

Welding for Design Engineers



GOODERHAM CENTRE
FOR INDUSTRIAL LEARNING

Training today for the needs of the future.

Welding for Design Engineers

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Chapter 1

Introduction

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1.0 Introduction

This book has been mainly developed for civil engineers. For more than a century, civil engineering students have been taught the design of reinforced concrete structures and riveted steel structures. Welded construction was relatively novel in the 1920s and 1930s, but really took off during the Second World War. To provide the basic design knowledge of welding during those years of rapid development, the Canadian Welding Bureau, in the late 1940s, undertook the task of disseminating the knowledge of welding construction. The Bureau compiled and administered a series of correspondence home study courses, known all over the world, which form the foundation of the CWB/Gooderham Centre for Industrial Learning home study modules today.

This volume encompasses the educational materials developed during the past five decades and specifically directs it toward civil engineering applications. Efforts have been made to condense vast amounts of technological information into this volume. Additional reading materials have been referenced at the end of each chapter for the reader to pursue further study.

The following news item appeared in the Engineering New Record in 1985 and 1987. It is a reminder to our fellow engineers of what could happen with a seemingly correct decision, but one made without thorough understanding of the implications of structural application.

In 1985 in Uster near Zurich, Switzerland, the collapse of a suspended concrete ceiling over an indoor swimming pool resulted in 12 people killed and 2 injured. Two years later the investigators reported that the acidic vapour (containing chlorine ions) coated the stainless steel hangers supporting the ceiling and led to pitting, stress corrosion and cracking. This problem has been written up in books which are well known among welding and corrosion engineers, but the typical structural engineers would not have these references. The design engineer should have called an expert when dealing with materials outside their experience, so said the expert.

The lesson of this story is the importance of having a knowledge of welding engineering. The design engineers should be familiar with it as they are with concrete. Hopefully, after studying this volume, the reader should be able to solve welding problems, or otherwise know when it's necessary to consult a welding expert.

The main purpose of this book is to be used both as a primer for civil engineers who are searching for welding knowledge, and as an important sourcebook for welding information.

1.1 Historical Background

Until very recently, the only method available to join metals was by forge welding, which requires two pieces of metal to be heated and then pressed or hammered together to develop a metallurgical bond between the two. Modern welding technology can trace its origins to the first half of the nineteenth century, when advances in electrical technology such as the production of an arc between two carbon electrodes and the invention of the electric generator took place. By the end of the nineteenth century, these advances had led to the development of three welding processes:

- ◆ arc welding
- ◆ resistance welding
- ◆ oxy-acetylene welding

The arc welding process in its numerous variations is now the most important and widely used welding process.

The first major patent for arc welding was awarded in the United Kingdom to Russians, Benardos and Olszewski in 1885, who employed a carbon electrode as the positive pole to obtain an arc with the workpiece (negative pole). The arc heated the workpiece (comprised of two adjoining pieces of lead or iron) so that they locally melted and fused with each other. Soon thereafter, in 1889, Slavinoff, from Russia, and Coffin, from the United States, were able to substitute a metal electrode for the carbon electrode.

A significant advancement in welding came with the use of consumable metal electrodes. Carbon electrodes previously in use could not provide filler metal. Further advances and applications of the metal arc welding process depended on the development of improved metal electrodes for greater arc stability, and a means of shielding the molten pool from contamination from the air surrounding the arc, which embrittled the weld metal.

The earliest effort in this regard was the application of coating or covering to the metal electrode. Kjellberg of Sweden applied the coating by dipping iron wires in a thick mixture of carbonates and silicates, and then letting them dry. The British were the first to attempt application of the arc welding technology on significant scales as a substitute for riveting in the fabrication of ships. In the United States, around the time of the start of World War I, German ships interned in New York harbour and scuttled by their crews were rapidly brought back into service by effecting repairs using arc welding. The first all-welded ship, the Fulagar, was launched by the British in 1920.

During the 1920s, arc welding was applied for fabrication of heavy wall-pressure vessels and buildings. In Canada, a 500 foot long, three span bridge having an all-welded construction was erected in Toronto in 1923. However, widespread use of arc welding had to wait until 1927 when an extrusion process to economically apply covering to the electrode was developed. For welding stainless steel, electrode coverings that reduced the amount of hydrogen in the weld metal or that contained more easily ionized ingredients for arc stabilization were developed soon after.

In 1930, Robinoff was awarded a patent for submerged arc welding (welding under powder or flux, continuous wire without any covering) of longitudinal seams in pipes. Being a highly productive, mechanized process, it is still a very popular welding process today.

The use of externally applied gases, instead of slag and gases formed from the electrode covering, to shield the weld pool in arc welding had also been investigated. During the 1920s, Hobart and Devers in the United States experimented with argon and helium as shielding gases and this was a precursor to the development of the gas tungsten arc welding process used for welding of magnesium, aluminum and stainless steel, during World War II. Their work also demonstrated the use of continuous wire being fed through a nozzle for arc welding with external inert shielding gases, and this was later developed into the gas metal arc welding process in 1948 at Battelle Memorial Institute. Availability of smaller diameter wires and constant voltage power sources made this process more popular for joining non-ferrous metals and alloys. Application of gas metal arc welding to steels had to await the introduction of carbon dioxide as a shielding gas in 1953. Since then, there have been numerous developments of gas mixtures containing argon, helium, oxygen and carbon dioxide for gas metal arc welding of steels.

Another significant innovation in the 1950s was the development of tubular wires that contained fluxing agents on the inside. The gases generated by the decomposition of the fluxing agents as well as an externally applied gas are used for shielding the pool from atmospheric contamination. Initially known as the Dualshield process, it is known as flux cored arc welding today. Other variations of tubular wires that have a significant usage today include self shielded flux cored arc welding wires, i.e., without using the external gas shield; and metal cored arc welding wires with metal powder and some arc stabilizing materials inside and used with external shielding gas.

Welding processes other than those using an arc heat for welding have also been developed over the years since the last part of the nineteenth century. Briefly, these can be summarized as follows:

- ◆ resistance welding and its variations (spot welding, seam welding, projection welding, flash butt welding) over the period 1885 to 1900
- ◆ thermit welding for joining rails in 1903
- ◆ electroslog welding during the 1950s
- ◆ electrogas welding in 1961
- ◆ plasma arc welding in 1957
- ◆ electron beam welding in the late 1950s
- ◆ laser welding in the early 1970s

1.2 Grouping of Welding Processes

There are many ways in which welding processes may be grouped and different countries have adopted various classification schemes based on the application of heat, whether external pressure is applied, the type of energy involved (mechanical, electrothermic, thermochemical), etc. The American Welding Society (AWS) groups welding processes based primarily on the mode of energy transfer, and secondarily on the influence of capillary action in effecting distribution of filler metal in the joint (as in brazing and soldering).

AWS defines welding as “a joining process that produces coalescence (i.e. growing together) of materials by heating them 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 material”. In the AWS approach, welding processes are grouped into the following major categories:

- | | |
|-----------------------------|--|
| ◆ arc welding (AW) | ◆ soldering (S) |
| ◆ solid state welding (SSW) | ◆ brazing (B) |
| ◆ resistance welding (RW) | ◆ other welding |
| ◆ oxyfuel gas welding (OFW) | ◆ allied processes (such as cutting, thermal spraying) |

Arc welding processes are, by far, the most commonly used in the welding industry and are, therefore, the main focus in this book. However, arc welding involves melting and most metals, when melted in air, become contaminated with oxides and nitrides through contact with the oxygen and nitrogen in the air. This contamination may result in a poor quality weld. Most arc welding processes have some means of shielding (protecting) the molten metal from the air or some other means of removing the harmful effects of oxygen and nitrogen. The two main methods of arc shielding are:

- ◆ flux shielding
- ◆ gas shielding

Most of the arc welding processes are distinguished principally by the method of shielding or the way in which it is applied.

The exact selection of an arc welding process for a particular application involves several considerations including:

- ◆ Is the process suitable for welding the metal or alloy involved? In the required thickness and position?
- ◆ Would the welded joint have the required quality and physical (mechanical, corrosion) properties?
- ◆ Is it the most economical of the available choices?
- ◆ Are the equipment and skilled welders available for the chosen process?

1.3 The Welding Arc

Most metals and alloys conduct electricity at room temperature due to the presence of free electrons. A considerable amount of heat can be produced from the flow of the current in a circuit. Typical examples of this heating effect, also called resistance heating, are tungsten filament bulbs and heating coils in ovens. In comparison, gases like oxygen, nitrogen, carbon dioxide, etc. do not conduct any electricity at room temperature. However, if sufficient energy is applied to a gas it also can become conductive. When sufficient voltage is applied to a gas it can be **ionized** – changed into positively charged ions and negatively charged electrons. The electrons move in response to the applied voltage to produce a current flow and this movement of electrons allows the initiation of an arc. The current flow causes resistance heating in the gas which promotes further ionization and increased current flow. As long as the voltage source is able to supply the necessary voltage and the current needed by the arc, it can be sustained in a stable manner and used for welding applications.

Based on the above principle, a conventional arc is formed between two non-consumable electrodes in a gas or vapour medium when an appropriate voltage, depending on the electrode material and gas phase, is applied to the electrodes. As seen in **Figure 1.1**, one of the two electrodes forms a positive terminal of the electrical circuit and is called the anode; the negative terminal of the circuit is called the cathode. When an arc is created, electrons are evaporated from the cathode and transferred to the anode through the ionized gas in between. Flow of electrons is the same thing as flow of current or electricity.

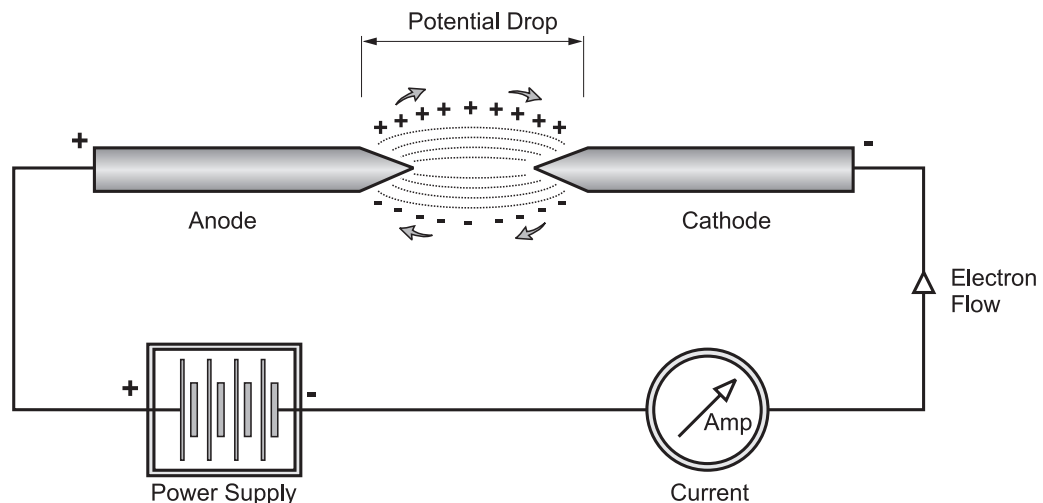


Figure 1.1: An arc between two electrodes.

A welding arc is formed when a fairly high current (10 to 2000 A) is forced to flow across a gap between two electrodes at relatively low voltage (10 to 50 V). A welding arc is intensely hot with temperatures exceeding 3000°C (see **Figure 1.2**) and forms a concentrated heat source suitable for melting most metals rapidly. The intense heat of the welding arc causes the filler metal to melt and when added to the locally hot melted workpiece, it forms the weld fusion zone. Its subsequent freezing (solidification) produces the bond (weld) between the workpieces. Arc welding processes do not require application of pressure to cause fusion.

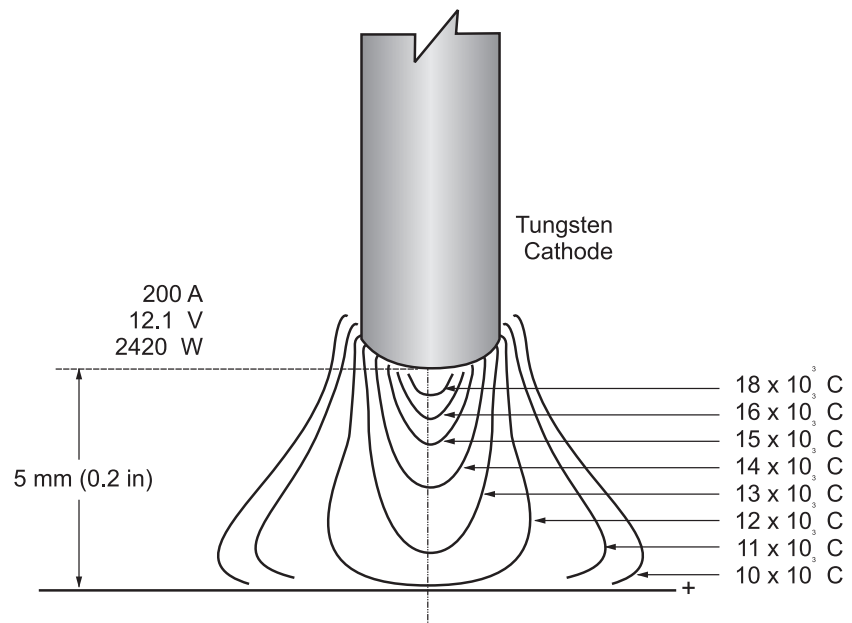


Figure 1.2: Temperature distribution in a 200 A arc in argon (from AWS Welding Handbook, Vol. 1).

In welding, the arc may be established between an electrode and the workpiece, or between two electrodes.

When the workpiece is one of the electrodes of the electrical circuit, the other electrode may be consumable or nonconsumable. A consumable electrode is designed to melt and add filler material to the welding joint.

The electrical current for welding is provided by a “power source” that draws high-voltage electric power from the main transformer and converts it into higher current and lower voltage suitable for welding (**Figure 1.3**). Power sources are broadly classified as constant current or constant voltage type, and the static volt/ampere output characteristics for these two types of power sources are shown in **Figure 1.4**.

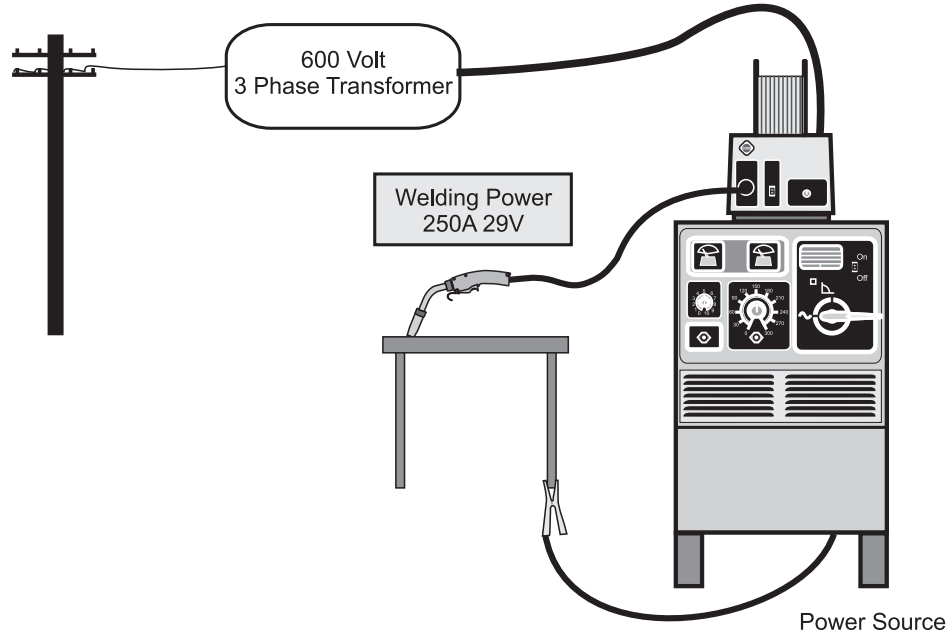


Figure 1.3: Transforming electrical power.

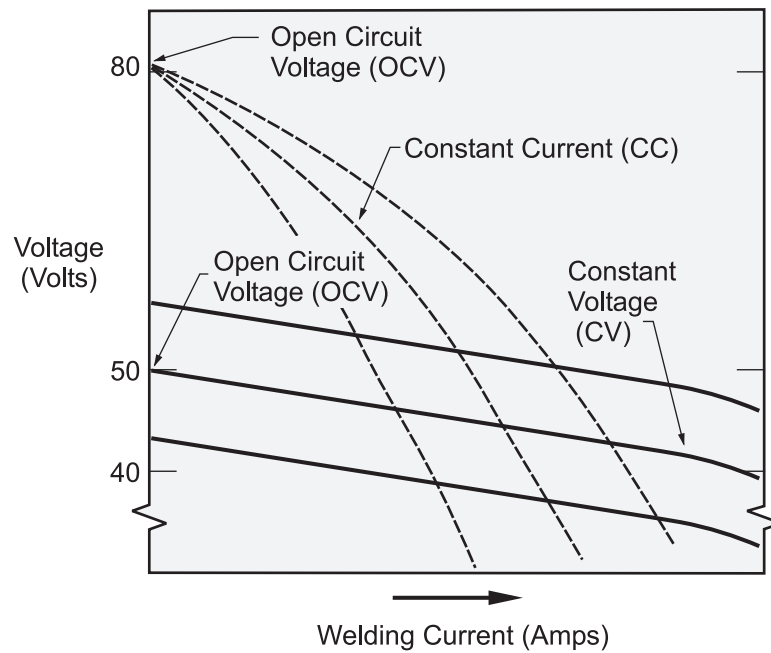


Figure 1.4: Characteristic volt/ampere curve for welding power sources.

1.3.1 Arc Efficiency

The welding arc provides the intense heat needed to locally melt the workpiece and the filler metal. In fact, all the electrical energy supplied by the power source is converted into heat (current x voltage). Some energy is lost in the electrical leads, and therefore the energy available for welding is the product of the current (I) and voltage drop between the electrode where the current enters it and the weld pool (V). For example, with 400 A current and 25 V drop from the contact tip to the weld pool, the arc energy is 10,000 Joules/second. This arc energy is partly used up in heating the electrode, melting the consumable electrode or the separately added filler metal in a nonconsumable electrode process, and heating and locally melting the workpiece. The rest of the heat is lost by conduction, convection, radiation, spatter, etc. The proportion of the energy that is available to melt the electrode/filler metal and the workpiece is termed the arc efficiency.

The arc efficiency for some of the commonly used arc welding processes varies between 20% and 90%.

For a given process, factors like welding in a deep groove, arc length, etc. also influence the arc efficiency. Higher arc efficiency usually means that for a given arc energy, a greater amount of weld metal is deposited and the workpiece cools at a comparatively slower rate.

1.3.2 Voltage Distribution Along the Arc

In any welding set up, there is a continuous drop in voltage from the lower-most point of contact between the contact tip and the wire, to the molten weld pool or the workpiece. **Figure 1.5** schematically shows that this voltage drop occurs in four steps.

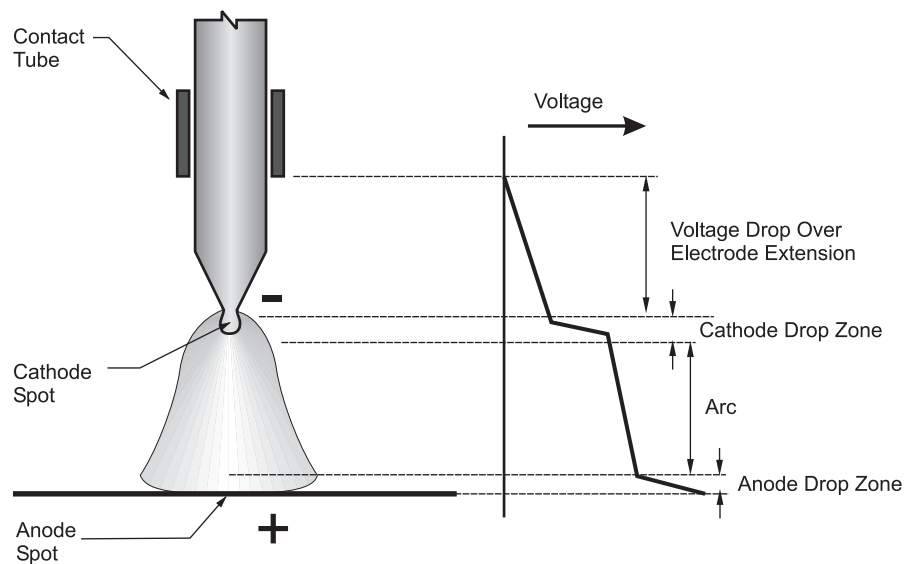


Figure 1.5: Voltage drop in the region of the welding arc.

First, there is a drop in voltage over the electrode extension, that is the length of electrode between the point of electrical contact with the contact tip, and its melting tip, also called cathode spot for the current flow direction shown in the sketch. The magnitude of this voltage drop depends on the electrode extension and the wire diameter as well as the current; a longer electrode extension, a smaller wire diameter or higher current all increase the voltage drop over the electrode extension length.

The voltage drop over the arc length, that is the distance between the cathode spot and the anode spot (the molten weld pool surface in **Figure 1.5**) takes place in three steps. Right next to the anode and cathode spots are small, thin, gaseous regions called the anode drop zone and cathode drop zone, respectively, and over these zones there can be a significant drop in voltage, in the range of 1 to 12 V depending on the electrode material.

In between the two drop zones, there is the arc column with a relatively small drop in voltage, of the order of 1 to 2 V per centimetre length of the arc column. There is a jet-like flow of ionized gases in the arc column that gives it some stiffness and force (resistance to deflection). This enables the welder to manipulate the gun and direct the molten metal to be deposited at the desired location in the weld joint. Shorter arcs have greater stiffness than longer arcs.

Arc length is a critical and controllable parameter, which is directly related to the arc voltage. Arc voltage depends on the space between electrodes; electrode composition, diameter and extension; shielding gas composition; metal thickness; joint design; welding position, etc. The voltage measured at the power supply is greater than the arc voltage. Output voltage represents the sum of arc voltage and the voltage drop in the remaining part of the electrical circuit. The longer the electrical cables the greater will be the difference between the voltage read at the power supply gauge and the actual arc voltage.

1.3.3 Magnetic Field Associated with a Welding Arc

When an electric current passes through a conductor, a magnetic field is created that surrounds the conductor (**Figure 1.6**). Unless this magnetic field is balanced in all directions, the welding arc will tend to be deflected from its normal axial orientation in line with the electrode. This phenomenon is called arc blow. It is more likely to be present during welding of magnetic materials (steels) and can cause incomplete fusion types of flaws in welds.

Some degree of imbalance in the magnetic field is always present. The path of the magnetic flux in the workpiece is continuous behind the arc and discontinuous ahead, due to the change in the direction of the current as it goes from workpiece to electrode (**Figure 1.7**). Since a shorter arc is stiffer, it is also less susceptible to arc blow.

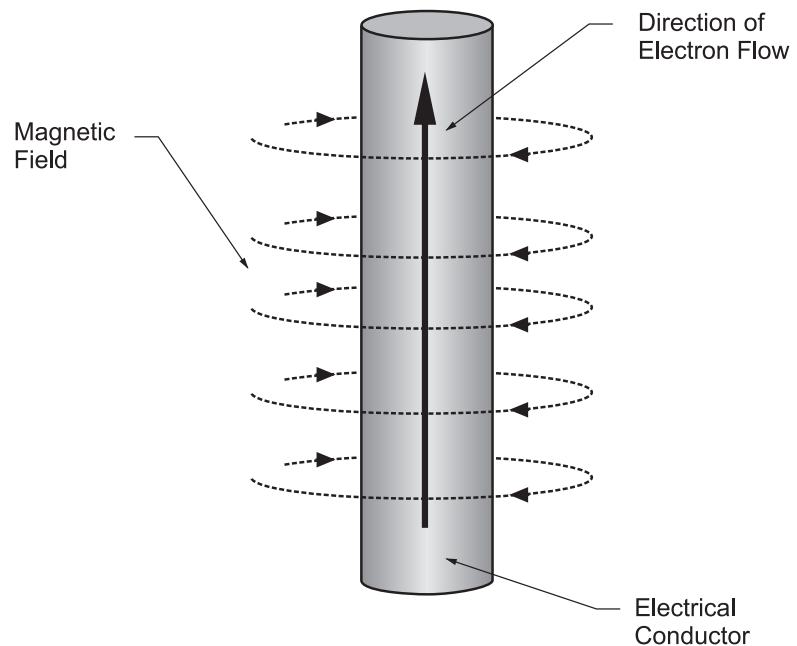


Figure 1.6: Magnetic field surrounding a current carrying conductor.

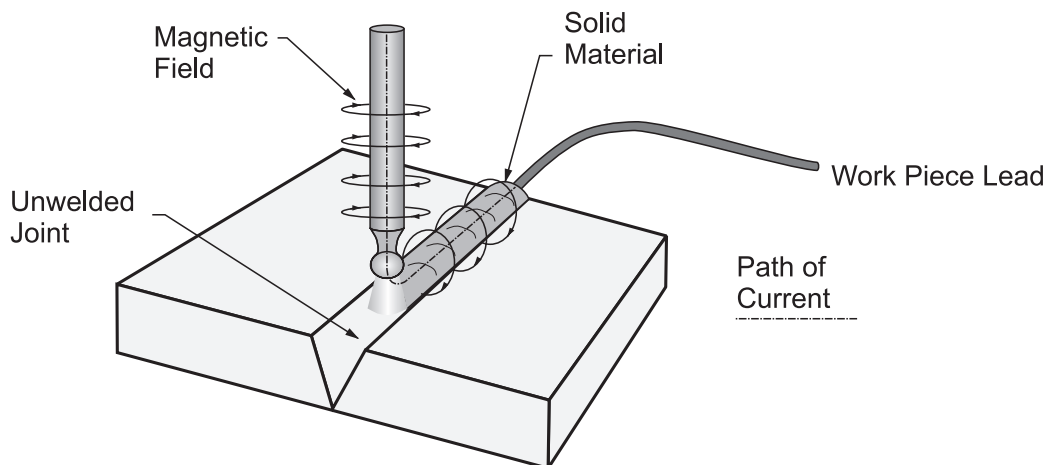


Figure 1.7: Imbalance in the magnetic field due to change in the direction of current and part unwelded joint.

The magnetic field introduced by the current flowing in the electrode also plays a role in metal transfer. When the tip of the electrode melts, there are several forces that act at the molten tip. These include surface tension, gravity, plasma jet and electromagnetic pinch force. Surface tension tends to prevent the detachment of the liquid drop at the electrode tip, irrespective of the welding position. Gravity supports droplet detachment when welding in the flat (downhand) position and attempts to prevent it in the overhead position. The plasma jet in most situations tries to detach and propel the molten drop across the arc column to the workpiece.

The electromagnetic pinch force helps in the process of detaching the molten metal drops from the electrode tip. Generally, when there is some necking between the molten tip and the unmelted electrode, the magnetic field introduces a pinch force acting in both directions away from the neck (**Figure 1.8**). This helps to separate the drop from the electrode. Since this pinch force increases as the square of the current, smaller and smaller drops are detached as the current increases.

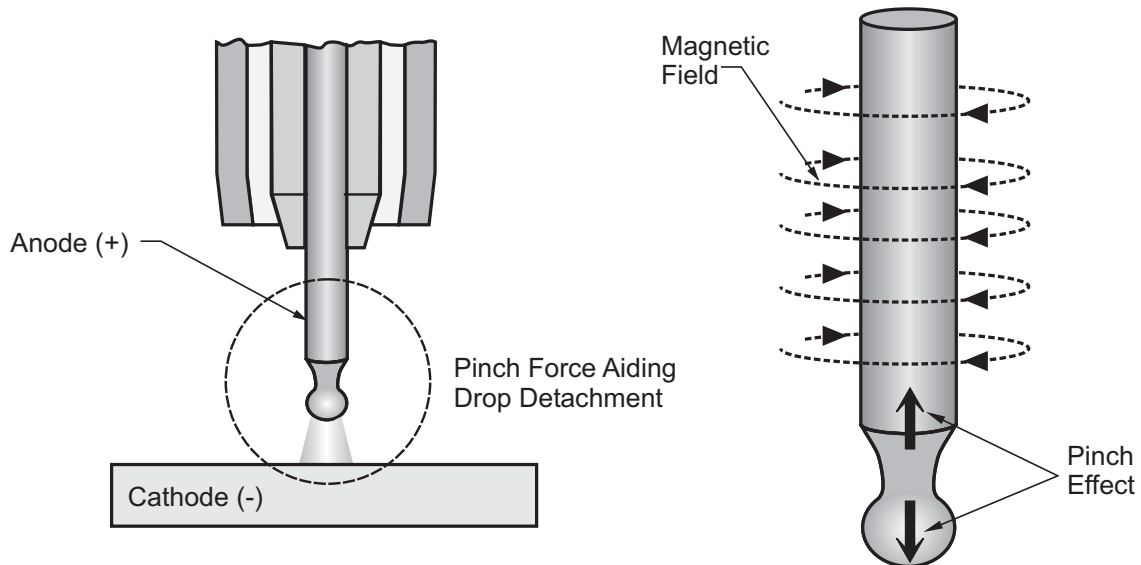


Figure 1.8: Detachment of molten metal drop due to pinch force.

1.3.4 Effect of Polarity

The electric current used in a welding arc may be either direct current (DC) or alternating current (AC). Direct current flows constantly in one direction. Alternating current is continually changing direction. When direct current is used for welding, the welding electrode (consumable or nonconsumable) can be the positive pole or negative pole in the electrical circuit. The workpiece will have the opposite polarity. These two arrangements for current flow are called DC electrode positive (DCEP) and DC electrode negative (DCEN), respectively (**Figure 1.9**). The type of current selected and its polarity can have a significant influence on the shape and penetration of the weld bead .

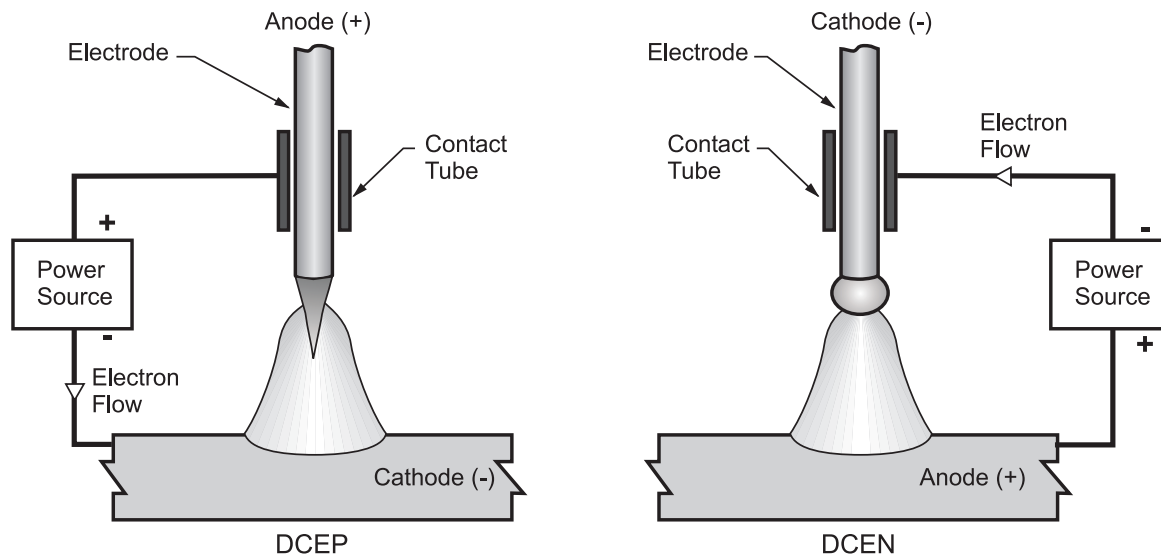


Figure 1.9: DCEP and DCEN arrangements for electrical leads.

For example, in gas tungsten arc (GTA) welding, a nonconsumable electrode welding process, direct current electrode negative (DCEN) is the polarity used most often. Electrons are easily emitted from the tungsten electrode (cathode). When the electrons travel through the arc they accelerate to very high speed. About 70% of the arc heat is released at the workpiece (anode or positive pole) due to electrons striking the surface at high speed. This produces a weld bead with greater penetration. When the polarity is reversed (DCEP) the workpiece becomes the cathode. The weld pool cannot easily emit electrons because the molten pool is at a much lower temperature than the tungsten and will resist the release of electrons. While DCEP is helpful in cleaning the weld pool by removing the oxides, about 70% of the arc heat is now generated at the electrode (anode). This reduces the life of the tungsten electrode and the weld bead has reduced penetration. The use of alternating current provides arc characteristics that are average of those for DCEN and DCEP (**Figure 1.10**).

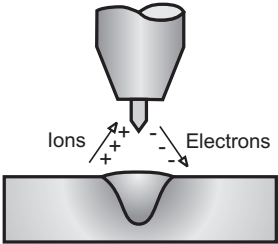
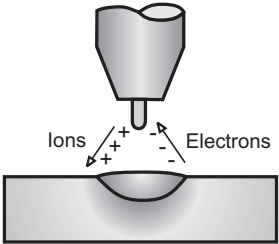
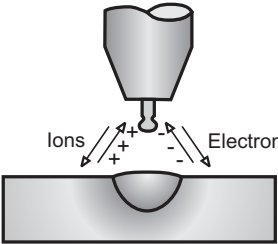
Current Type	DCEN	DCEP	AC (balanced)
Electrode Polarity	Negative	Positive	
Electron and Ion Flow			
Penetration Characteristics			
Heat Balance in the Arc (approx.)	Work End: 70% Electrode End: 30%	Work End: 30% Electrode End: 70%	Work End: 50% Electrode End: 50%
Penetration	Deep, Narrow	Shallow, Wide	Medium

Figure 1.10: Effect of current type and polarity in GTA welding (from AWS Handbook, Vol. 2).

The heat balance in consumable electrode processes differs from that in tungsten arcs. Thus, a greater amount of heat is generated at the cathode rather than the anode.

When using the gas metal arc process, direct current electrode positive is the polarity of choice as it leads to greater heat generation at the workpiece (cathode) and therefore greater penetration. Conversely, DCEN polarity produces more heat at the electrode (cathode), and therefore increases the electrode melt-off rate and reduces penetration.

1.3.5 Effect of Electrode Extension (Stickout)

When an electric current flows through a conductor, a certain amount of heat is generated due to the current having to overcome the electrical resistance of the conductor. This is called resistance heating and it is proportional to $I^2 \times R$ where I is the current and R is conductor resistance. The resistance, R , increases with the length of the conductor and decreases as the diameter increases.

In continuous wire consumable electrode welding, the electrode extension (**Figure 1.5**) represents an electrical conductor through which a fairly high welding current passes. When the electrode extension is increased, its resistance increases and therefore the magnitude of resistance heating also increases. As a result, for the same welding current, the consumable wire melts at a faster rate and thus increases the deposition rate for the same arc energy. However, this heating effect means that less heat is available to heat and melt the workpiece. Consequently, penetration is reduced and the risk of incomplete fusion type of flaws is increased. Also, due to an increase in voltage drop over a longer electrode extension, a higher voltage setting is usually needed to maintain a constant arc length as with the shorter electrode extension.

The effect of electrode extension for individual arc welding processes is addressed later.

1.3.6 Hydrogen in Weld Metals

Invariably, there is some amount of hydrogen present in the solidified and cooled weld zone. This hydrogen is introduced by the arc heat breaking down the moisture present in and around the welding arc. Possible sources of this moisture include the electrode covering, flux, shielding gas, atmospheric humidity and condensation on the work pieces.

When welding steels, absorbed hydrogen can cause cracking (this will be discussed further in Chapter 9). Therefore, in welding carbon and low alloy steels, martensitic stainless steels, etc., an important consideration in selecting the welding process and filler metals is the amount of hydrogen that might be introduced into the weld zone. Non-ferrous materials react differently to hydrogen.

1.4 Health and Safety

Like most manufacturing and fabrication processes, the welding operation presents various hazards to the health and safety of the welder and personnel working near a welding operation. These hazards include:

- | | |
|--------------------|--|
| ◆ Fire hazards | ◆ Smoke and fumes |
| ◆ Electrical shock | ◆ Compressed gases |
| ◆ Arc radiation | ◆ Other hazards related to specific processes, locations, etc. |

These hazards are well recognized and when proper precautions are taken, welding is a safe operation. It is therefore extremely important that before performing any welding operation the operator be fully aware of these precautions as well as be knowledgeable about the equipment to be used and its operation. The reader is referred to Module 1 for detailed guidance on the health and safety aspects of welding, and is strongly urged to have the knowledge therein before performing any welding.

As engineering personnel, you are always in an oversight position on the construction site. Safety is everybody's concern, especially for engineers.

1.5 Welding Terms and Definitions

Some of the terms frequently used in this book are briefly described below to assist the reader in better understanding the contents of this book.

Acceptance Criteria	A defined set of parameters against which the features of a product or component may be judged.
Acceptance Weld	A weld that meets all the requirements and acceptance criteria prescribed by the applicable welding code, standard, and/or specification.
Active Flux	A flux for submerged arc welding that causes changes in weld metal composition that depends on the welding parameters used, especially voltage.
Alloy	A metallic material made up of two or more elements, where at least one is a metal.
Alternating Current	Current flow in an electrical circuit where its direction (and therefore, direction of electron flow) continually reverses itself, usually at a pre-determined frequency.
Angle of Bevel	See preferred term "Bevel Angle".
Arc Blow	The deflection of an arc from its normal path because of magnetic forces.
Arc Force	The axial force developed by an arc plasma.
Arc Length	The distance from the tip of the welding electrode to the weld pool.
Arc Plasma	A gas that has been heated by an arc to at least a partially ionized condition, enabling it to conduct an electric current.
Arc Voltage	The voltage across the welding arc.
Arc Welding Gun	A device used to transfer current to a continuously fed consumable electrode, guide the electrode and direct the shielding gas and the arc.
Arc Welding Torch	A device used to transfer current to a fixed electrode, position the electrode and direct the shielding gas and the arc.
Autogenous Weld	A fusion weld made without addition of filler metal.

Back Gouge	To remove base metal and/or unfused weld metal from the unwelded root side of a joint to create a suitable groove for weld metal to be deposited. See also GTSM.
Backing Ring	Joint backing in the form of a ring, generally used in welding pipe.
Backing Strip	Joint backing in the form of a strip.
Backing Weld	Joint backing in the form of a weld.
Bare Electrode	A filler metal electrode that is manufactured as a wire, strip or bar with no coating or covering other than that which is incidental to its manufacture or preservation.
Barium Titanate	A polarized ceramic material used to create a piezoelectric signal in transducers (probes) for ultrasonic inspection. See also Piezoelectric Crystal, Probe and Quartz.
Base Metal	The metal (material) to be welded, brazed, soldered or cut.
Bead	See preferred term "Weld Bead".
Beam Angle	The angle at which a sound beam enters a material during ultrasonic inspection.
Bevel	An angular type of edge preparation.
Bevel Angle	The angle formed between the prepared edge of a member and a plane perpendicular to the surface of a member.
BHN	Brinell Hardness Number: In the Brinell Hardness Test, a number which denotes a material's hardness, correlating directly to the diameter of the indentation obtained by the test.
Buildup	A surfacing operation where material is deposited on the surface to restore dimensions.
Butt Joint	A joint between two members aligned in approximately the same plane.
Chill Ring	See preferred term "Backing Ring".
Cobalt 60 (Co 60)	A radioactive isotope that emits gamma rays for use in Gamma-Radiography. See also Radioisotope.

Code	A document often considered synonymous with standard or specification, however, more often it will be found to further incorporate rules of good practice by which the results required by a standard or specification may be obtained. In the USA, “code” is used as an equivalent to “standard” in Canada.
Coefficient of Absorption	A nuclear property of a material characterizing its ability to absorb radiation.
Cold Crack	A crack caused by the presence of hydrogen in the weld zone and that occurs at relatively low temperatures as the weld cools, usually below 100°C.
Complete Joint Penetration	Joint penetration in which the weld metal completely fills the groove and is fused to the base metal throughout its total thickness.
Compression	The type of force which tends to press an object, or a surface of an object, together.
Concave Weld Surface	A weld surface that has a cross-sectional profile curved like the inner surface of a circle.
Consumable Electrode	An electrode that melts and provides metal to fill the joint.
Covered Electrode	A composite filler metal electrode consisting of a core of a steel rod to which a covering sufficient to provide a slag layer on the weld bead has been applied. The covering may contain materials providing such functions as shielding from the ambient air, cleansing the weld metal, arc stabilization, or source of metallic addition to the weld.
Convex Weld Surface	A weld surface that has a cross-sectional profile curved like the outer surface of a circle.
Crater	A depression in the weld face at the termination of a weld bead.
Defect	A discontinuity that has been evaluated and determined to exceed the application acceptance criteria of the relevant code, standard and/or specification, i.e., rejectable discontinuity. See also discontinuity and flaw.
Deflection	The movement of a structure or object, usually referring to a beam or column, as a result of being subjected to a load.
Deposition Rate	The weight of material deposited in a unit of time.

Deposition Efficiency	The ratio of the weight of filler metal deposited in the weld metal to the weight of the filler metal melted, expressed as a percentage.
Depth of Fusion	The distance that weld fusion extends into the base metal or previous pass from the surface melted during welding.
Destructive Testing	Also known as Mechanical Testing, it is the process of testing a sample by loading until failure occurs. See Module 12, Mechanical Testing of Welds.
Developer	In Liquid Penetrant Inspection, the developing agent used, after the removal of excess penetrant, to “draw out” and form a contrasting background for the penetrant.
Direct Current Electrode Negative (DCEN)	An arrangement of direct current arc welding leads in which the electrode is the negative pole and workpiece is the positive pole of the welding arc.
Direct Current Electrode Positive (DCEP)	An arrangement of direct current arc welding leads where the electrode is the positive pole and workpiece is the negative pole of the welding arc.
Discontinuity	Any disruption in the normal physical or compositional features of a part. A discontinuity is not necessarily a defect.
Drag Angle	When the electrode points towards the start of the weld, the angle between the electrode center line and the seam center line in the direction of travel.
Ductility	A term referring to a material’s ability to be plastically deformed without fracturing.
Duty Cycle	The percentage of time during a specified test period that a power source can be operated at the rated output without overheating.
Dwell Time	In Liquid Penetrant Inspection, the time that the penetrant is in contact with the material being inspected.
Effective Throat	The minimum distance from the root of the weld to its face, less any reinforcement. See also “Size of Weld”.
Elastic Limit	The maximum limit of stress a material is able to be subjected to without being permanently deformed. See also “Yield Point”.
Elastic Deformation	The non-permanent change in an object’s dimensions while being subjected to stress that is below the elastic limit.

Electrode	A component of the electrical circuit that terminates at the arc, molten conductive slag, or base metal.
Electrode Extension	The length of unmelted electrode extending beyond the end of the contact tube.
Electrode Setback	The distance the electrode is recessed behind the constricting orifice of the plasma arc torch, measured from the outer face of the nozzle.
Elongation	In tensile testing, a term used to describe the increase in distance between gauge marks on the test specimen after testing. It is usually expressed as a percentage of the original gauge length.
Essential Variables	A variable that if changed would affect the mechanical properties of the deposited weld metal and/or weldment. A change in an essential variable of a prescribed welding procedure would require re-qualification.
Fatigue	A phenomena usually resulting in fracture caused by repeated or fluctuating stresses which, at a maximum, are below the ultimate tensile strength of the material. These failures are progressive, begin as minute cracks and propagate due to the action of the cyclical stresses.
Fatigue Failure	Failure of an object or weldment as the result of fatigue.
Fatigue Strength	The maximum stress per specified number of cycles that can be sustained without occurrence of failure.
Feather Edge	See preferred term "Root Edge".
Ferrous Alloy	A metal composition consisting primarily of iron and one or more other elements.
Filler Metal	The metal or alloy to be added in making a welded joint.
Flat Position	The welding position when welding is performed on the upper side of the joint and the weld face is approximately horizontal.
Flaw	Synonymous with defect, a flaw is an unacceptable discontinuity. See also "Discontinuity".
Fluorescent Method	For either Liquid Penetrant Inspection or Magnetic Particle Inspection, the use of a detecting media that is fluorescent under ultra-violet (black) light.

Flux	A material used to provide a slag cover on the molten weld pool to prevent its contamination from the atmosphere and control the amount of impurities in the weld metal.
Fusion (Fusion Welding)	The melting together of filler metal and base metal, or base metal only, to produce a weld.
Gamma Radiography	A radiographic technique which utilizes the gamma radiation by the decay of a radioisotope to produce an image on a recording media. See also "Gamma Rays" and "Radioisotope".
Gamma Rays	The electromagnetic radiation emitted by the decay of radioisotopes, such as Cobalt 60 and Iridium 192, used in Gamma Radiography.
Groove Angle	The total included angle of the groove between parts to be joined by a groove weld.
Groove Radius	The radius used to form the shape of a J or U-groove weld joint.
Groove Type	The geometric configuration of a groove.
Gouge to Sound Metal (GTSM)	The process of back gouging to a depth to where sound weld metal, previously deposited from the other side, is achieved so that a weld with complete fusion through the root is obtained.
Hardness	The relative resistance of a metal to plastic deformation. May also refer to resistance to abrasion, scratching or indentation.
Heat Affected Zone	The portion of the base metal adjacent to the weld metal whose mechanical properties or microstructure have been changed due to the heat of welding.
Heat Treatment	A procedure or combination of procedures involving the heating of a metal or alloy to a predetermined temperature and then cooling it at some specified rate so as to obtain desired properties.
Horizontal Position (fillet weld)	The welding position when a fillet weld is deposited on the upper side of an approximately horizontal surface and against an approximately vertical surface.
Horizontal Position (groove weld)	The welding position when the axis of the weld is approximately on a horizontal plane, and the weld face lies in an approximately vertical plane.

Incomplete Fusion	A weld discontinuity formed when the weld metal does not completely fuse with the substrate (base metal or previous weld beads).
Included Angle	See preferred term “Groove Angle”.
Inert Gas	A gas that does not participate in any chemical reaction at all.
Inspection Cycle	The complete cycle involved in inspection beginning with the examination of drawings, specifications, weld procedures, consumables, equipment, operator qualifications, etc., through to fit-up and pre-weld operations. Inspection during welding should ensure that deviation from the weld procedure does not occur. The inspection cycle is not complete until all aspects of fabrication, including repair work, final dimension checks, and heat treatment, have been finished.
Ionizing Radiation	Electromagnetic radiation of sufficient energy to cause electrons to be stripped from the atoms they strike. Typically capable of damaging cellular tissue.
Iridium 192 (Ir 192)	A radioactive isotope which emits gamma rays for use in Gamma Radiography. See also “Cobalt 60”.
Joint Build-Up Sequence	The order in which the weld beads of a multi-pass weld are deposited with respect to the cross-section of the joint.
Joint Design	The joint geometry together with the required shape, dimensions and strength of the welded joint.
Joint Geometry	The shape of the joint to be welded and its dimensions.
Joint Penetration	The distance that the weld metal extends from its top surface (excluding reinforcement) into the joint.
Joint Welding Sequence	See preferred term “Joint Build-Up Sequence”.
Lack of Fusion	See preferred term “Incomplete Fusion”.
Land	See preferred term “Root Face”.
Layer	A stratum of weld metal or surfacing material. The layer may consist of one or more weld beads laid side by side.

Longitudinal Waves	In ultrasonic inspection, sound waves in which the particle motion or vibration within the test materials is in the same direction as the propagated wave.
Manual Welding	Welding performed by a welder who holds and manipulates the torch, gun or the electrode holder, and moves the arc/weld pool along the weld joint.
Mechanized Welding	Welding performed with the torch or gun held and moved along by a mechanical device, with the operator making occasional adjustments based on visual observation of the weld.
Melting Rate	The mass or length of electrode melted in a unit time.
Modulus of Elasticity	Also known as Young's Modulus, it is the ratio of stress, below the elastic limit, to strain. In essence, it is the measure of the stiffness or rigidity of a material.
Necking	The reduction of the cross-sectional area of a material, in a localized area, when in tension. Necking begins to occur when the ultimate tensile strength of the material has been exceeded.
Nonconsumable Electrode	An electrode that does not melt but sustains the welding arc.
Non-Destructive Testing (NDT)	Any of several examination methods where a component or assembly is evaluated without damaging or otherwise lessening its intended service life.
Open Circuit Voltage	The voltage between the output terminals of a power source when no current is being drawn from it.
Overhead Position	The welding position where welding is performed from the underside of the joint.
Partial Penetration Joint	A joint where the design does not require the weld throat to equal the workpiece thickness.
Pass	A single progression of a welding or surfacing operation along a joint, weld deposit or substrata. The result of a pass is a weld bead, layer or spray deposit.
Penetrameter	In Radiography, a device used for the validation of the technique's image quality. Penetrameters are made from similar material as the test specimen and its thickness is relative to the thickness of the test piece. Also known as an Image Quality Indicator.

Penetrant	In Liquid Penetrant Inspection, a liquid that has the ability to enter extremely small surface openings by capillary action.
Penetrating Ability	In Radiography, the ability of a particular technique to penetrate a certain object. This depends primarily on wavelength, with shorter wavelengths having greater penetration.
Permanent Set	The amount of plastic deformation remaining in a material after the stress causing the deformation has been removed.
Piezoelectric Crystal	A material used in Ultrasonic probes (transducers) capable of producing a Piezoelectric Effect. See also "Barium Titanate", "Piezoelectric Effect", "Probe" and "Quartz".
Piezoelectric Effect	In Ultrasonic Inspection, the property of certain materials to generate mechanical vibrations when subjected to electrical pulses, and vice versa. See also "Piezoelectric Crystals".
Porosity	Round or oblong discontinuities in weld metal formed as a result of entrapment of gas during weld metal solidification.
Probe	A device used in Ultrasonic Inspection, consisting of a Piezoelectric Crystal, which may transmit and/or receive sound pulses and convert these into either mechanical vibrations or electrical pulses. See also "Piezoelectric Crystal".
Procedure Qualification Record	A record of welding parameters used to produce a sound weld in a specified material in accordance with a welding procedure specification, such that the weld also meets the specified mechanical property requirements.
Prod Method	In Magnetic Particle Inspection, the method utilizing a prod that can locate surface and sub-surface indications parallel to the alignment of the poles of the prod.
Quartz	A material used to create a piezoelectric signal (effect) in transducers (probes) for ultrasonic inspection. See also "Barium Titanate", "Piezoelectric Crystal" and "Probe".
Radiography Sensitivity	The ease at which images of fine object features can be detected.
Radiographic Technique	The entire Radiographic method used during testing in terms of radiant energy used, wavelength, Source-to-Film distance, film used, material and material thickness, etc.

Radiography (RT)	A Non-Destructive Testing Method in which radiant energy is used in the form of either X-rays or Gamma-rays for the volumetric examination of opaque objects. See also "Gamma Radiography", "Radiographic Technique" and "X-Ray Radiography".
Radioisotope	A naturally or artificially produced isotope that releases ionizing radiation during its decay. See also "Cobalt 60" and "Iridium 192".
Root	See preferred term "Root of Joint" or "Root of Weld".
Root Edge	A root face with zero width.
Root Face	Portion of a bevelled edge preparation that is left substantially perpendicular to the workpiece surface, usually to prevent burn through.
Root Gap	See preferred term "Root Opening".
Root of Joint	The portion of a joint to be welded where the members are closest to each other. In a cross-section, the root of the joint may be either a point, a line or an area.
Root of Weld	The points as shown in cross-section at which the back of the weld intersects the base metal surfaces.
Root Opening	The separation between the members to be joined at the root of the joint.
Semi-automatic Welding	Welding operation where the filler metal is fed automatically into the weld pool but a welder holding a gun or torch controls the travel speed, travel angle and the work angle.
Shear	The type of force that produces an opposite but parallel sliding motion between two parts in the same plane.
Shear Waves	In Ultrasonic Inspection, sound waves in which the particle motion or vibration within the test material is perpendicular to the direction of the propagated wave. See also "Wavelength".
Shielding Gas	Gas delivered through a welding gun or torch with the objective of protecting the arc and the weld metal from atmospheric contamination.
Single-Welded Joint	In arc or gas welding, any joint welded from one side only.

Size of Weld	Groove Weld: The joint penetration (depth of bevel plus root penetration when specified). The size of a complete penetration groove weld and its effective throat are one and the same. Fillet Weld: The leg lengths of the largest right-angle triangle that can be inscribed within the fillet weld cross-section.
Slag	A glassy substance formed on top of the weld metal as a result of melting of the flux and its reaction with the weld metal.
Slope	Quantitative measure of the incline of the power source volt\ampere curve.
Slugging	The act of adding a separate piece, or pieces, of material in a joint before or during welding that results in a welded joint not complying with design, drawing or specification requirements.
Source-to-Film Distance	In Radiography, the distance between the source of radiation and the recording medium (film).
Space Strip	A metal strip or bar prepared for a groove weld, and inserted in the root of a joint to serve as a backing and to maintain the root opening during welding. It can also bridge an exceptionally wide gap due to poor fit-up.
Specification	A document that usually sets forth in some detail the requirements and/or acceptance criteria demanded by a buyer for a certain product. It may be, or become the basis of a contractual agreement between the buyer and the supplier. See also "Code" and "Standard".
Standard	A document by which a product may be judged. In terms of welding, a standard generally summarizes the requirements for processes, procedures, consumables, materials, inspection, acceptance criteria, etc. See also "Code" and "Specification".
Strain	A measure of the change in dimensions of a body due to the presence of stress.
Stress	The internal force induced in a material to counter-balance an externally applied force. Mathematically, it is the applied force divided by cross-sectional area, and is represented by the Greek letter sigma, σ .
Stress/Strain Curve	A graph that plots the stress (y-axis) against the strain (x-axis) of a material during a tensile test.

Surface Tension	Force at the surface of liquid that tries to reduce its surface area and prevents it from wetting the solid that it is in contact with.
Surfacing	Use of a welding process to deposit a layer of a similar or different material on the surface of a workpiece to restore dimensions or to achieve desired properties (corrosion resistance, wear resistance, etc.).
Tensile Strength	See preferred term “Ultimate Tensile Strength”.
Tension	The type of force that tends to pull an object, or a surface of an object, in opposite directions.
Toughness	The ability of a metal to absorb energy and deform plastically before fracturing.
Transition Curve	A graph that plots the energy value obtained in an impact toughness test (y-axis) versus specified temperatures (x-axis).
Transition Temperature	The temperature at which the transition curve shows a sharp change in toughness.
Travel Angle	The angle between the electrode axis and the perpendicular to the weld axis in a plane defined by the electrode and weld axis.
Ultimate Tensile Strength	The maximum stress from tension that a material can withstand without fracture. Mathematically, it is the maximum load applied divided by the original cross-sectional area.
Undercut	A groove or a notch formed in the base metal adjacent to a weld toe.
Volt\Ampere Curve	A graphical representation of the voltage-current relationship for a given power source when a steady load is placed on it.
Wavelength	The distance a wave travels through one complete cycle. See also “Longitudinal Waves” and “Shear Waves”.
Weld Bead	A weld deposit resulting from a pass.
Weld Face	The surface of the weld opposite to the root.
Weld Metal	That part of an arc weld that was completely molten at one time during welding.

Weld Pool	The molten metal, prior to its solidification, under and adjacent to the arc.
Weld Reinforcement	Weld metal in excess of the quantity required to fill a joint.
Weld Root	The region of a weld pass where the underside of a weld bead meets the base metal.
Welding Head	A part of a completely mechanized welding equipment set-up that incorporates the gun or the torch, wire feeder and wire spool.
Welding Inspector	A person specially trained in any applicable aspect of welding, fabrication and inspection of weldable materials in terms of judging a weldment's compliance against a prescribed acceptance criteria.
Welding Leads	Cables that are part of the electrical circuit and connect the power source to the electrode (electrode lead) and to the workpiece (workpiece lead).
Welding Procedure	The details of materials, joint geometry, welding consumables, welding parameters, preheat/interpass temperature/postweld heat treatment, etc., and related practices and procedures for the production of welds.
Weldment	Any fabricated component or unit to which welding has been applied.
Wetting	Phenomenon that allows liquid weld metal to easily spread over and fuse with the base metal.
Wire Feed Speed	The rate (length per unit time) at which wire is fed and melted in welding.
Workpiece	The member that is to be welded.
X-Ray Radiography	Radiographic method in which X-rays are utilized to produce a permanent image on a recording medium. See also "Gamma Rays" and "Radioisotope".
X-Rays	In Radiography, a form of relatively high radiant energy, created by the bombardment of electrons on a material at high voltage. See also "Radiography" and "X-Ray Radiography".

Yield Point	The first point at which a material under load experiences an increase in strain without an increase in stress. It is the stress levels at which plastic deformation begins. Not all metals exhibit a definite yield point. See also "Elastic Limit".
Yield Strength	The stress at which the yield point is reached. Mathematically, it is the load applied at the yield point divided by the original cross-sectional area.
Yoke	In Magnetic Particle Inspection, a device used to locate surface and sub-surface indications transverse to the alignment of the pole.
Young's Modulus	See preferred term "Modulus of Elasticity".

Chapter 2

Welding Codes and Standards

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2.1 Introduction

The heading of this chapter may give the reader an impression that the subject is dry and full of legal jargons. Not if you are just starting your design career and the senior engineer assigns you a welding design project, in which one component is as shown in **Figure 2.1**. You are to calculate the fillet size required for the Tee-joint given:

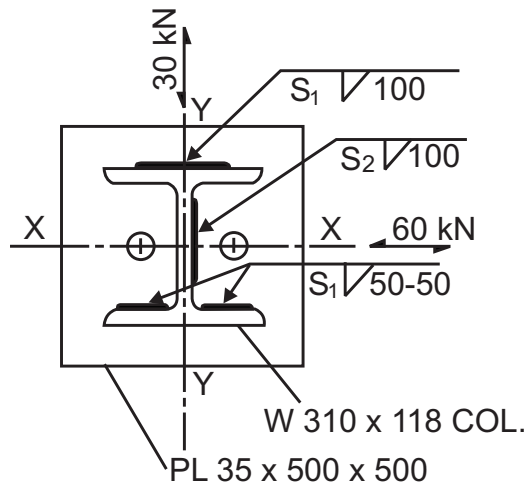


Figure 2.1

For simplicity, it is assumed that the flange welds resist shear in the X-X direction and web weld resists shear in the Y-Y direction. The length of welds are given:

E4918 electrode, 1 mm fillet = 0.156 kN/mm

Flange welds:

$$S_1 = \frac{60 \text{ kN}}{200 \times 0.156} \cong 2.0 \text{ mm}$$

Web welds:

$$S_2 = \frac{30 \text{ kN}}{100 \times 0.156} \cong 2.0 \text{ mm}$$

What is the weld size you would indicate on your design sketch – 2.0 mm? If you do, you are wrong. Why? Because the code, CSA W59 or AWS D1.1 and others stipulate that the minimum fillet size for 35 mm thick plate is 8 mm. Why?

The answer to this question involves a lot more consideration than just the simple strength calculation. It involves welding heat input, cooling rate, welding metallurgy, weld mechanics, weld cracking, and last but not least, practicality. It is impossible to lay down a fillet weld that small in a structural fabrication shop. If you do show 2.0 mm fillet on your design sketch, the draftsman will know that you have no welding design experience.

We need codes and standards to legally protect our professional career and, most importantly, to ensure public safety.

Note also that construction specifications always specify conditions such as the following:

- ◆ The welding fabrication must be done in accordance with CSA W59 or AWS D1.1.
- ◆ Welders and welding operators shall be qualified by the Canadian Welding Bureau (CWB) according to CSA W47.1.
- ◆ Electrodes used on this project shall be of the E49XX series and certified by the CWB.
- ◆ Inspection shall be done according to CSA W59 by CWB certified companies and personnel.

As another example, the following clauses are part of the requirements by CAN/CSA – S16-01 “Limit States Design of Steel Structures”.

16.6.17.3

Fabricators and erectors of welded construction covered by this standard shall be certified by the Canadian Welding Bureau in Division 1 or Division 2 to the requirements of CSA Standard W47.1 or W55.3, or both, as applicable. Specific welding procedures for joist fabrication shall be approved by the Canadian Welding Bureau.

16.9.5 *Installation of Steel Deck*

16.9.5.2

- (a) *The installer of steel deck to be fastened to joists by arc spot welding shall be certified by the Canadian Welding Bureau to the requirements of CSA Standard W47.1.*
- (b) *The installation welding procedures shall be approved by the Canadian Welding Bureau.*
- (c) *The welders shall have current qualifications for arc spot welding issued by the Canadian Welding Bureau.*

24.3 *Fabricator and Erector Qualification*

Fabricators and erectors responsible for making welds for structures fabricated or erected under this Standard shall be certified by the Canadian Welding Bureau to the requirements of CSA Standard W47.1 (Division 1 or Division 2), or CSA Standard W55.3, or both, as applicable. Part of the work may be sublet to Division 3 fabricators, however, the Division 1 or Division 2 fabricator or erector shall retain responsibility for the sublet work.

31.5 *Third-Party Welding Inspection*

When third-party welding inspection is specified, welding inspection shall be performed by firms certified to CSA Standard W178.1, except that visual inspection may be performed by persons certified to Level 2 or 3 of CSA Standard W178.2.

The design engineers responsible for preparing the construction documents must be familiar with all the relevant clauses in the structural steel design and welding specifications. The fabricator's engineers responsible for welding design and procedures must also be familiar with both the applicable welding and structural steel specifications to produce a satisfactory structure.

Codes and standards set the level of acceptable quality so that the owner knows what quality product to expect and the engineers know what specifications govern the design, fabrication and erection. It is the common technical (and legal) language among owners, contractors, architects and engineers. It forms an important part of all engineering contractual documents.

Some of the major codes or specifications pertaining to welding fabrication will be mentioned with brief outlines in the following paragraphs.

2.2 Purpose of Standards

In this time of rapid development of new technologies, standards can be said to fulfill the all-important task of harnessing these developments into product performance or service-oriented regulatory constraints, setting levels of acceptable quality while taking a responsible stand on the protection of public interest.

The ultimate objective of standardization is to build confidence in the user (public), and in so doing, stimulate production and commercial activity and in turn greatly enhance the economic well being of the country.

In more specific terms, the functions of standards is:

- ◆ to ensure public safety
- ◆ to educate – by setting general rules for guidance of producers and consumers
- ◆ to simplify – by reducing the range of variations in sizes, processes and hence the stock and related record-keeping services
- ◆ to conserve – by saving time and materials through ready and official acceptance of developments permitting the use of more advanced design methods and the attainment of higher production efficiencies
- ◆ to certify – by serving as hallmarks of quality and value

The Canadian structural welding standard system merits special mention. Its uniqueness lies in the successful combination of advanced material and design standards and their well conceived integration with Canada's certification standards. Since 1947, the certification standards have established a solid foundation of technological capability in welding engineering and supervisory personnel for the Canadian welding industry. The superior performance record of welded steel structures in this country is a direct result.

2.3 Development of Standards

Most national standards are generated through the voluntary efforts of all segments of society, government and industry, producers and consumers, institutions and individuals.

In most Western countries, the governments freely relinquish their prerogative to impose control or direction on the standardization system. However, some feel compelled to design a mechanism to prevent overlap and duplication in the system, to develop procedural methods to coordinate its output, and at the same time ensure the widest possible national acceptance of standards.

This particular function is fulfilled:

- ◆ in Canada by the Standards Council of Canada (SCC), established by an Act of Parliament;
- ◆ in the USA by the American National Standards Institute (ANSI)

Most of the standards of the Western world are voluntary standards. That means:

- ◆ they are developed with the voluntary cooperation of all concerned
- ◆ the use of the standard by those affected (meaning the specifiers) is also totally voluntary (unless otherwise mandated)

Such standards, however, become mandatory when so designated by a pertinent regulatory authority or when specified contractually.

The standards are also consensus standards, meaning that everyone affected by the development or use of a standard has an opportunity to participate in the development of these standards, either directly or indirectly through representation or through public review.

Since a balanced representation on a committee is of overriding importance, it will serve the purpose to identify the most common interest groups. These particular groups, or rather the individual members of each group, are defined by the Standards Council of Canada as follows:

1. **Producer:** in the context of a standards-writing committee, a producer is a representative of an organization involved with the manufacture or promotion of the product, material or service of concern to that committee.
2. **User:** in the context of a standards-writing committee, a user is an individual or a representative of an organization concerned with the use or application of the product, material or service of concern to that committee.
3. **General Interest:** in the context of a standards-writing committee, a general-interest member is an individual or a representative of an organization who is not associated with the production, distribution, direct use or regulation of the product. This category is intended to include professional and lay people employed by academic and scientific institutions, safety associations, etc.
4. **Consumer:** in the context of a standards-writing committee, a consumer is an individual who uses goods and services to satisfy his needs and desires, rather than to resell them or produce other goods with them.

Standards are developed in many different types of organizations:

- ◆ companies
- ◆ trade associations
- ◆ governmental agencies
- ◆ technical and professional societies

Therefore, there are many degrees of consensus involved in developing a voluntary standard. By no means must all standards originate from the consensus system. Some are intended for use only within a company, an industry or governmental agency.

However, a standard dealing with a commodity servicing an open market should be developed by a full consensus procedure. Its balanced interest representation will:

- ◆ permit it to attain a high level of credibility
- ◆ make it eligible for recognition as a national standard

2.4 Administration of Standards

The term “administration” is taken strictly to imply an ongoing activity on the part of an agency, to which a standard has given a clear mandate to monitor the maintenance of its requirements.

The classical example of such standards are the Canadian Standards Association (CSA) welding certification standards, whether concerned with products (e.g., electrodes) or organizations (e.g., fabricators, inspectors or inspection companies). The Canadian Welding Bureau (CWB), Certification Division (a Division of the CWB Group – Industry Services) is charged with the task of administering and monitoring these standards. It is the responsibility of CWB to monitor, through an appropriate mechanism, the manufacturer’s or the company’s adherence to the full conditions of the standard under which certification has been granted.

There are other administrative models. In Canada, the area of boilers and pressure vessels is under the jurisdiction of provincial governments. The designated departments of the appropriate ministries perform a function similar to the responsibility of CWB (to monitor), but the extent of this function is defined by the applicable Pressure Vessel Act.

In the United States, boiler and pressure vessels are governed by ASME codes (American Society of Mechanical Engineers).

In some European countries, agencies have been established to fulfill the functions similar to those performed by the CWB. The assignment of these agencies may also include an inspection function.

In Canada, the CWB certifies welding inspectors and welding inspection organizations.

2.5 CSA Standard W47.1 Certification of Companies for Fusion Welding of Steel

2.5.1 General

The CSA W47.1 Standard becomes the foremost qualification code in structural welding in Canada. The Standard specifies the conditions and personnel qualification requirements that shall be met for a company to become certified.

Company certification under W47.1 is a unique concept that has been implemented not only by the Canadian welding industry, but also in many countries around the world. It is administered by the Canadian Welding Bureau (CWB).

The first edition was published in 1947 as CSA W47, and since then other editions have been published in 1973, 1983, 1992 and 2003. The CSA W47 Standard is re-numbered as CSA W47.1 to differentiate it from CSA W47.2, which is the standard for Certification of Companies for Fusion Welding of Aluminum.

CSA W47.1 Standard is mandated in Canada (and therefore W47.1 company certification) through various CSA Design Standards such as those for buildings and bridges, which are similarly mandated by the National Building Code of Canada (NBCC), and by Provincial Building Codes or Bridge Codes.

All major governing design specifications in Canada make certification to W47.1 Standard a mandatory requirement. For example, as stated in the introduction of CSA S16-01, Limit States Design of Steel Structures.

CSA W47.1 Standard is interlinked with other welding Standards, e.g., CSA W59 – Welded Steel Construction (Metal Arc Welding), and the CSA W48 Standard – Filler Metals and Allied Materials for Metal Arc Welding.

Although company certification to W47.1 is a mandatory requirement of Canadian structural fabricating companies, where not mandated in welded manufacturing, it is frequently required as a quality control measure.

The following is a brief outline of the Standard. Consult the text for full details.

- 1) The W47.1 Standard is explicitly concerned with certification of companies. It is not a product standard and cannot be used to either evaluate or approve products. Consequently, it is not intended to supersede or encroach on codes or other jurisdictions governing the manufacture of specific products such as pressure vessels (ASME, API, CSA-B51).
- 2) Although the basic provisions of the code can be construed to indirectly constitute some measure of quality assurance, it must be stressed that it remains the responsibility of the purchaser (owner) to ensure, through adequate inspection, that the required quality of welded fabrication is attained.

- 3) Canadian Welding Bureau (CWB) representatives audit certified companies periodically, the sole objective being to monitor each company's compliance with the conditions of CSA W47.1 Standard. These CWB audits are not to be construed as inspection of welds or inspection of welded products, and they do not diminish the need for inspection by others as stated above.
- 4) Canadian Welding Bureau is not a government organization, nor a division of CSA. CWB is a federally incorporated, "not for profit" organization.

The uniqueness of the certification system under CSA W47.1 lies in the principles for qualification of the company, including specifically:

- ◆ the employment of qualified welders
- ◆ the employment of qualified welding supervisors
- ◆ the employment of qualified welding engineers (full time or retained)
- ◆ the approval of welding procedures
- ◆ the administration of the Standard by a single independent third party (CWB)

2.5.2 Company Certification to CSA Standard W47.1

The following is a brief explanation of the procedural steps a candidate company has to take in order to acquire the CSA W47.1 certification status:

1) Make Formal Application

W47.1 specifies "Each company applying for certification shall make formal application to the Bureau". The application is signed by the CEO and applies only to the plant or site identified in the application.

The company must indicate in which division it wishes to be certified:

- ◆ Division 1: the company shall employ a welding engineer on a full-time basis.
- ◆ Division 2: the company shall employ a welding engineer on a part-time basis.
- ◆ Division 3: the company is not required to employ or retain a welding engineer.

It should be noted that a full time qualified welding supervisor must be employed by all divisions.

2) CEO Shall Designate Key Personnel

The CEO shall designate engineering, shop and field supervisory and quality control personnel, giving them the authority to act and be responsible to the company in their respective work areas. These persons shall be designated on a form signed by the CEO.

3) Resumes for Designated Welding Engineer and Welding Supervisors

Work Experience Required by Welding Engineers: A minimum of five years of welding-related experience is required. When the engineer responsible is retained, he/she shall report in writing through the company to the Bureau on his/her effective participation in the company's welding operations.

Work Experience Required by Welding Supervisors: A certified company (for all divisions) shall have at least one full time welding supervisor. Each supervisor shall meet the following criteria for work experience:

- ◆ The welding supervisor shall have a minimum of five years of welding-related experience, a thorough knowledge of company's welding procedures, be able to read drawings, interpret welding symbols, know weld faults, quality control and inspection methods.

Educational Requirements – Engineering Personnel: Each engineer shall be a member of a professional engineering association. The educational requirements for the engineering personnel include the academic background and tangible evidence of additional courses of study involving examinations on a number of welding-related areas. Briefly, the additional courses of study would include subjects such as:

- ◆ Weldability of metals; fatigue and brittle fractures; welding procedures and practices; welded joints and connections; welding processes, equipment and materials; weld faults; and methods of control of quality.
- ◆ Additionally, engineers shall have knowledge of the applicable welding codes and standards.

Educational and Practical Requirements – Welding Supervisors

Educational Requirements: Each welding supervisor shall have knowledge of applicable CSA welding standards (e.g., CSA W47.1 and CSA W59) pertaining to his/her normal work. Additionally, each supervisor shall have a knowledge of weld faults, quality control and inspection methods, and be able to read and interpret drawings, all pertaining to his/her normal work.

Practical Requirements: Each welding supervisor shall have practical welding related experience; and shall have a thorough knowledge of the company's welding procedure specifications and related welding procedure data sheets. The supervisor shall be familiar with the operation of the various types of welding equipment related to his/her work with the company.

4) List of Welding Equipment and Any Quality Control System Used

The equipment list will define the welding scope of the company's operations, and will assist the Bureau when assessing the qualifications of designated welding personnel.

5) Provide a List of Welding Personnel

This list refers to the welders, welding operators and tack welders. Before company certification can be granted, each welder, welding operator and tack welder shall be qualified for the welding process(es) and welding position(s) in which he/she welds. (See also Welder Qualification).

6) Provide a File on Company's Welding Standards

The company shall prepare a set of Welding Standards, including Welding Procedure Specifications (WPS), and related Welding Procedure Data Sheets (WPDS), which shall be submitted to the Bureau for acceptance/approval.

Welding procedures, using joints designated as prequalified in the applicable governing standard or code, and which satisfy procedural stipulations as they apply to the welding process, shall be accepted by the Bureau.

Welding procedures which do not meet the aforementioned conditions, and for which sufficient testing information has not been accumulated, shall undergo procedure qualification testing in accordance with the provisions of the W47.1 Standard. Welding of the test assemblies shall be witnessed by the Bureau's representative.

7) Qualification of Welders and Welding Operators (Performance Tests)

W47.1 describes specific plate test assemblies for the qualification of welders, welding operators and tack welders. There is also a pipe test assembly for welder qualification. Qualification by welding non-standard test assemblies may be allowed where special welding conditions exist due to equipment or plant operations. Qualification is governed by classification, welding process, mode of process application and position of welding (see the following paragraphs).

The Bureau's representative shall witness all welding personnel qualification tests, and shall issue a record showing each person's welding qualification. The welding qualification issued for a welder/operator is subject to special validating conditions, and is recognized only while the welder/operator or tack welder is employed by a company certified under CSA W47.1.

After certification, the company shall report to the Bureau, showing names and qualifications of all welding personnel (tack welders, welders and welding operators).

8) Welding Processes

CSA W47.1 addresses the following welding processes:

- ◆ shielded metal arc welding (SMAW)
- ◆ flux-cored arc welding (FCAW)
- ◆ metal cored arc welding (MCAW)
- ◆ gas metal arc welding (GMAW)
- ◆ submerged arc welding (SAW)
- ◆ gas tungsten arc welding (GTAW)
- ◆ electroslag welding (ESW)
- ◆ electrogas welding (EGW)

2.6 CSA Standard W47.2 Certification of Companies for Fusion Welding of Aluminum

2.6.1 General

This standard specifies requirements for certification of companies engaged in fusion welding of aluminum alloys and erection of aluminum structures. It is similar to the CSA W47.1 Standard.

2.6.2 Similarity Between W47.1 and W47.2

- 1) The concept of three divisions with the same distinguishing criteria applicable.
- 2) The certification and administration procedures to be followed by the Bureau with identical obligations on the part of the company for maintaining the condition of certification (reporting of changes in welding personnel and welding procedures).
- 3) The educational and practical experience requirements for the engineering and supervisory personnel in Divisions 1 and 2, but with the years of experience for the latter increased to 4 in case of Division 3.
- 4) The requirements related to Welding Procedure Specification and Welding Procedure Data Sheets.

2.6.3 Major Differing Provisions Between W47.1 and W47.2

- 1) The application of the Standard is restricted to:
 - i) commercial fabrication of aluminum structures and their repair - specialized product fabrication is totally excluded (pressure vessels)
 - ii) thickness 3 mm or greater
- 2) The welding processes are limited to include only:
 - ◆ gas metal arc welding (GMAW)
 - ◆ gas tungsten arc welding (GTAW)
 - ◆ plasma arc welding (PAW)
 - ◆ arc and capacitor discharge process for stud welding (SW)
- 3) Essential variables related to each of the welding processes are listed and base metal alloy groupings as another variable clearly tabulated.
- 4) Welding Procedure Qualifications include plate and pipe test assemblies for groove welds and plate assemblies for fillet welds. In case of pipe assemblies a “6G” – (inclined 45° to the horizontal) non-rotating pipe has been introduced. A fracture test has been added to normal W47.1 procedural tests.
- 5) The concept of performance levels has been introduced for welder qualification:

Level I	designating fillet welding only
Level II	designating welding of groove joints either from both sides or from one side with backing
Level III	designating welding of groove joints from one side without backing for the full thickness of material
- 6) In addition to the performance levels the qualification of welders and welding operators is governed by:
 - ◆ the welding process
 - ◆ mode of process application (semi-automatic, automatic)
 - ◆ type of weld and position
 - ◆ the filler metal alloy group in the case of the GMAW process
- 7) Pipe and plate test assemblies are provided for with a “fracture test”.
- 8) While in W47.1 qualification for F, H, V, OH was designated as for example “class F” qualification, the W47.2 Standard uses the term “category F”.

2.7 CSA W48-01 Filler Metals and Allied Materials for Metal Arc Welding

The CSA W48 Electrode Standard is a companion to the W59 and W47.1 Standards.

Fabricators undertaking work specified to CSA Standard W59, Welded Steel Construction, are required to use welding electrodes and filler metals conforming to CSA or equivalent standards.

The W48 Standard covers the specifications of the following types of electrodes:

- ◆ carbon steel covered electrodes for shielded metal arc welding
- ◆ chromium and chromium-nickel steel covered electrodes for shielded metal arc welding
- ◆ low-alloy steel covered electrodes for shielded metal arc welding
- ◆ solid carbon steel filler metals for gas shielded arc welding
- ◆ carbon steel electrodes for flux and metal cored arc welding
- ◆ fluxes and carbon steel electrodes for submerged arc welding

This standard prescribes certification requirements for electrodes for the given individual welding process.

The CSA W48 Standard is administered by the Canadian Welding Bureau, which is under obligation to publish lists of certified electrodes at yearly intervals.

The objective of certification under the CSA W48 Standard is to demonstrate the properties of weld metal deposited in a standard joint under specified and controlled welding conditions.

The CWB Module 6 – Electrodes and Consumables, covers this standard in more detail.

2.8 CSA Standard W59 Welded Steel Construction – Metal Arc Welding

2.8.1 General

The CSA W59 Standard is considered to be the primary steel welding standard in Canada. As already pointed out, it is directly linked with the CSA Standards W47.1 and W48 dealing with certification of companies and filler metals respectively, and because of its stipulations involving the other two, may be considered greatly responsible for the resounding success of structural welding quality throughout Canada.

In conjunction with the CSA W178.1 qualification code for welding inspection organizations and individual inspectors there is in Canada an encompassing framework of standards and an extremely well-integrated system of certification and qualifications, all geared to provide a reliable measure of assurance of safe performance of welded structures in service and hence of public safety.

W59 Includes:

- ◆ workmanship standards and technique
- ◆ prequalified details of joints and welding processes
- ◆ inspection procedures and acceptance criteria
- ◆ design strengths under static and cyclic loadings for welds for allowable stress and limit states design methods
- ◆ allowable stress ranges for fatigue loading

It should be noted that Clauses 1 to 10 of the Standard cover the requirements common to all types of structures and:

- ◆ Clause 11 governs welding of statically loaded structures
- ◆ Clause 12 governs welding of cyclically loaded structures

It should be further noted that in these two clauses, provisions are included for:

- ◆ the allowable stress design (ASD) method
- ◆ the limit states design (LSD) method

This is in view of both methods being used in current engineering practice, although the phasing out of the ASD method in other governing CSA design standards (S16-01) indicates that the LSD design approach will eventually become the preferred design method.

2.8.2 Review

A number of provisions in the Standard are of significance in that they clearly define the extent of its coverage and the specifications mandated upon the designer, the fabricator and the inspection agency. These are briefly discussed next, occasionally with explanatory background reasoning for their inclusion into the Standard where feasible or deemed necessary.

- 1) Clear statement is made with respect to types of steel structures excluded from the coverage. Reference is made to the distinct requirements provided by other regulatory authorities exercising jurisdiction and having specific expertise pertinent to related, given products (e.g., water pipes – American Water Works Association AWWA, pressure vessels – ASME, API).

2) Applicable welding processes are those used in actual fabrication operations:

- ◆ shielded metal arc welding (SMAW)
- ◆ flux cored arc welding (FCAW)
- ◆ metal cored arc welding (MCAW)
- ◆ gas metal arc welding (GMAW)
- ◆ submerged arc welding (SAW)
- ◆ gas tungsten arc welding (GTAW)
- ◆ electroslag welding (ESW)
- ◆ electrogas welding (EGW)
- ◆ stud welding (SW)

A further requirement of the Standard is that the filler metals (consumables) for each process be approved either in accordance with the provisions of the CSA W48 electrode standard series or when not applicable in accordance with the pertinent provisions of the CSA W47.1 Standard.

3) Pre-approved materials, meaning those acceptable without reservation, are identified as steels, whose specified minimum yield strength does not exceed 700 MPa (100 ksi). A comprehensive listing of the eligible steels together with their CSA or ASTM designation is provided.

4) An important requirement of the Standard is directed towards the technological capability of the fabricator. It requires the fabricator:

- ◆ to be either certified under the provisions of the CSA W47.1 Standard, or
- ◆ to demonstrate competency to produce welded structures of desired quality and soundness to the engineer, the professionally qualified, designated representative of the regulatory authority or of the purchaser, as applicable.

Although this requirement appears optional, the fact is that in almost all types of steel structures it can be said to be mandatory by virtue of other, governing design standards demanding certification to the W47.1 standard. As a matter of fact, imposed on this fundamental requirement is the additional stipulation in the CSA S16-01 Standard “Steel Structures for Buildings” that only fabricators certified to Division 1 and 2 under the CSA W47.1 standard are eligible to undertake work on any steel structures the design of which is governed by S16-01.

5) With respect to inspection, the Standard stipulates that preferably, organizations certified to CSA W178 “Qualification Code for Welding Inspection Organizations” be used. The non-mandatory certification to W47.1 (point 4) and to W178 (point 5) was prompted by “no trade restriction” considerations.

- 6) Fundamental concepts in strength calculations of welded joints and connections are provided. These concepts are of basic importance in assessing the capacity (ASD) or the resistance (LSD) of welds for which pertinent formulae are tabulated in Clauses 11 and 12 and which involve:
- ◆ types of welds, types of groove welds
 - ◆ their minimum and effective sizes together with separate provisions for fillet welds, plug and slot welds
- 7) Requirements governing the workmanship and welding technique of the fabricator are included:
- ◆ conditions for matching filler-base materials for welding of corrosion resistant steels
 - ◆ maximum exposure times and subsequent storage and conditioning of electrodes, especially those of the low hydrogen type
 - ◆ specified limits of acceptability of planar discontinuities in base material and recommended action for repair of edge discontinuities
 - ◆ preparation of material for welding with tolerance limits for assembly and fit-up of structural elements
 - ◆ workmanship tolerances for the preparation and fit-up of groove welded joints
 - ◆ provisions for tack welds, temporary welds and seal welds
 - ◆ details of welding procedures and techniques for each welding process
 - ◆ extensive treatment of stud welding
 - ◆ recommended sequences in assembly and welding aiming at minimizing distortion and residual stresses
 - ◆ preheat and interpass temperatures as tabulated are related to steel designations (Carbon equivalent – expressing their weldability), thickness of material, and low hydrogen or non-low hydrogen electrodes or processes.
 - ◆ conditions permitting reduction of preheat temperatures for minimum single pass SAW fillet sizes
 - ◆ dimensional tolerances for finished welded structural elements
 - ◆ acceptable profiles of fillet and groove welds
 - ◆ corrective action for defective welds
 - ◆ requirements for stress relief, when specified. These refer to temperature, holding time and rates of heating and cooling

- 8) Requirements, with respect to welding inspection include:
- ◆ an emphasis on advanced communications between the inspection organizations and the fabricators as well as timely scheduling of inspection
 - ◆ a clear statement of the obligations of the fabricator in matters arising from results of inspection
 - ◆ conformance of nondestructive (NDT) procedures to pertinent clauses of the Standard and applicable ASTM codes
- 9) Repair and strengthening of existing structures.
- 10) The concept of “prequalification” applies to SMAW, FCAW, MCAW, GMAW and SAW welding processes.
- 11) As already pointed out, Clause 11 includes all design and construction provisions for statically loaded structures. Clause 12 covers the requirements for cyclically loaded structures with particular emphasis on fatigue, the inherent mode of behaviour under fluctuating loads typical of bridges and crane runways.

2.9 CSA Standard W59.2 Welded Aluminum Construction

2.9.1 General

This standard is similar to CSA W59 (for steel construction) in format but specifies the requirements for welded aluminum construction for general applications. For special applications such as pressure vessels, pipelines or the aviation industry, other standards applicable to that specific type of fabrication should be used. This standard gives provisions for the following welding processes:

- ◆ gas metal arc welding (GMAW)
- ◆ gas tungsten arc welding (GTAW)
- ◆ plasma arc welding (PAW)
- ◆ stud welding (arc and capacitor discharge process) (SW)

The Standard gives guidelines of design of welded connections, joint geometries, filler alloy selection, filler metal alloy groupings and base metal alloy groupings. Inspection methods and acceptance criteria are also provided. The appendix lists the physical properties and the mechanical properties of alloys with various tempers, which is very important information for design engineers.

2.10 CSA Standard S6

Design of Highway Bridges

CSA Standard S6 is a comprehensive design standard encompassing all essential engineering considerations, with separate coverage requirements for steel-reinforced and pre-stressed concrete, and timber. In the steel section, a separate clause on “welds”:

- ◆ invokes the provisions of the CSA Standard W59 – Welded Steel Construction
- ◆ reserves fabrication only for companies certified to CSA Standard W47.1 – Certification of Companies for Fusion Welding of Steel
- ◆ requires inspection to be performed by either the designer or inspection organizations certified to CSA Standard W178.1 – Qualification Code for Welding Inspection Organizations

Although the mandatory use of electrodes certified to the CSA W48 Standard is inherent in the W59 and the W47.1 Standards, the S6 Standard calls for their certification separately for greater emphasis.

2.11 CAN/CSA-S16-01

Limit States Design of Steel Structures

S16-01 covers a wide scope with rules and requirements for design, fabrication and erection of steel structures, with considerable attention given to joining and fastening material by welds and bolts.

This is a limit states design Standard for steel structures. The current edition at the time of this writing was preceded by seven working stress design editions dating back to 1924, and six limit states design editions beginning with the 1974 edition. The Standard is prepared in SI (metric) units. In accordance with the provisions in the Standard, the working stress design method has been officially withdrawn.

It should be noted that this National Standard of Canada, CAN/CSA-S16-01, has been adopted by the National Building Code of Canada as a reference Standard for steel structures, thereby further reflecting its dominant position among the governing Canadian design standards.

Although primary attention of S16-01 is directed to statically loaded structures, it includes provisions for the design of fatigue loaded structures. Since the latter provisions appear in a number of other CSA Standards (e.g., W59, S6), it is of importance to note that though a concerted and coordinated inter-committee effort these provisions have been kept identical in all pertinent standards.

The comprehensive design requirements of the Standard are said to incorporate the latest research recommendations. Exhaustive design coverage is given to beams and girders, open web steel joists, composite beams and columns, built-up members and connections involving welds and bolts.

With respect to welding, reference is made to the CSA Standard W59 and W55.3 for design and practice in arc welding and resistance welding respectively, while for the same types of welding processes, certification of fabricators is required either to the CSA W47.1 (Division 1 and 2 for primary contractors) or the CSA W55.3 Standards.

Workmanship requirements include fabrication tolerances, erection and inspection.

Appendices provide explanatory background information or complementary information.

2.12 CSA Standard W186-M1990 Welding of Reinforcing Bars in Reinforced Concrete Construction

2.12.1 General

It should be first stressed that the W186 Standard is primarily a combined welding design and certification standard, which in addition prescribes workmanship and inspection requirements.

Its scope of application expressed in terms of welding is precisely defined by types of joints and connections, types of welding processes and types of base materials.

2.12.2 Review

With respect to joints and connections, it covers welding of reinforcing bars either directly to one another or through splice members or to structural steel members used in anchorages in pre-cast or cast-in-place concrete construction.

The accepted welding processes include the:

- ◆ shielded metal arc welding (SMAW)
- ◆ gas metal arc welding (GMAW)
- ◆ flux cored arc welding (FCAW)

together with:

- ◆ pressure gas welding (PGW)
- ◆ thermit welding (TW)

In case of the first three, emphasis is put on low-hydrogen or controlled-hydrogen electrode classifications. All electrodes for these processes are required to be certified to the CSA W48 Standard while filler metals for the last two processes are subject to procedure qualification as prescribed in the Standard.

Base materials are identified by referencing pertinent reinforcing steels of the CSA G30 Standard series while a number of structural steels are listed under their CSA G40.21 or ASTM designations.

The administration of the Standard and specifically of its certification program is left with the Canadian Welding Bureau with the usual requirements for the Bureau to check on the maintenance of code conditions and to publish lists of certified fabricators.

The detailed and comprehensive design provisions of the Standard are based on the limit states (LSD) principles with the SI (metric) units used throughout. Described are types of bar splices, types of bar to structural steel anchorage connections together with types of welds used (grooves and fillets). Special attention is given to flare grooves (welds between two round bars in a longitudinal lap joint and welds between a round bar and flat plate also in a lap joint). The effective sizes and lengths of all types of welds are established.

The minimum factored resistances of joints are defined and a number of formulae delivering these resistances provided. Included are also formulae precluding any other predictable or possible modes of failure associated with a given joint configuration. A comprehensive tabulation of design applications relating bar or plate material to electrode classifications for all possible types of welds is provided.

The provisions for workmanship are based on principles of good welding practice. Low temperature limitations for welding, preparation, assembly requirements and the mandatory use of approved welding procedures with emphasis on proper application of preheat are clearly specified. Options for welding of galvanized steel are offered. Storage and conditioning of electrodes and the quality of welds are covered.

In the part on certification, the Standard has adopted identical requirements to those in the W47.1 Standard. They include:

- 1) qualified:
 - ◆ engineering personnel, employed or retained
 - ◆ supervisory personnel
 - ◆ welding personnel
- 2) approved welding procedures
- 3) adequate welding equipment

However, of great significance is the fact that fabricators already certified in Divisions 1 or 2 of CSA W47.1 are accepted as certified under the W186 Standard with only a few additional requirements related mainly to welding procedure qualifications and welder qualification for flare groove welding.

Conditions attached to the qualification of the engineering and supervisory personnel include educational and practical experience requirements. However, in each case as already stated, pertinent qualification under W47.1 is given almost full recognition under this Standard.

Welding procedure qualifications are covered with appropriate test assemblies and types of tests together with specified ranges of acceptable test results.

Qualification of welders is given similar comprehensive coverage with validity extended to two years. Qualification on flare grooves is taken as acceptable for fillet welds while fillet qualifications under the W47.1 Standard are also considered valid.

For other than visual inspection, the Standard requires the use of inspection organizations certified to the CSA W178.1 Standard.

In one of the appendices, typical design solutions are provided for guidance of the designer. All classical types of joints and welds are used to illustrate the calculation procedures.

2.13 CSA Standard W178.1 Qualification Code for Welding Inspection Organizations

2.13.1 General

The W178.1 Standard uses the qualification concept of the W47.1 Standard and hence encompasses the full organization or its respective division performing welding inspection. As a national standard administered by the Canadian Welding Bureau, it serves to ensure uniform and reliable inspection capabilities of companies engaged in quality control of welded structures.

In view of the growing national and international appreciation of quality in the manufacturing process, the competency of inspection services assumes ever-increasing importance. Design sophistication and advanced exploration of material capabilities further substantiate this importance.

The W178.1 Standard, although clearly written for certification of independent inspection organizations, does not preclude its application to the manufacturer's or fabricator's own inspection systems. Its main objective is to set basic requirements for obtaining and maintaining certification in any of the clearly identified inspection service categories.

2.13.2 Review

The administration provisions define the responsibilities as well as the extent of authority of the Bureau at the time of granting of certification and during the subsequent surveillance of the company's adherence to the conditions of certification.

Included are provisions for specific cases where retention by contract of qualified personnel and equipment is necessary for a given company to fully meet the requirements of the Standard. Clear reference is also made to the Bureau's obligation to periodically publish lists of certified companies to serve the industry. On the other hand, the companies are required to immediately report any changes in personnel and equipment.

Eleven separate categories of certification are provided for selection by the companies. These relate to distinctive product or group of products oriented fabrications. The specific requirements for certification include the following:

- 1) Standard inspection procedures providing clear instructions with respect to execution of the basic and most common inspection functions such as checking the qualification of welding personnel, determining the availability of approved welding procedures, identifying base and filler materials, establishing the extent of inspection prior to and during welding together with acceptance inspection and preparation of reports.
- 2) Standard testing procedures covering all destructive and non-destructive methods contemplated for use by the company.
- 3) Inspection personnel who meet the qualification requirements of the Standard
- 4) Suitable inspection equipment and test facilities.

The Standard distinguishes between the following three levels of inspection personnel:

- ◆ certified welding division supervisors
- ◆ certified welding inspectors
- ◆ qualified operators for test facilities and equipment

It sets specific educational, training and experience criteria for each level. Mobility of qualified personnel within certified companies is permitted.

In the case of radiographic and ultrasonic inspection methods (anticipated for use in service by the company) certification as senior industrial radiographers and senior ultrasonic operators in accordance with the respective Canadian General Standards Board (CGSB) specifications is required.

The very demanding educational requirements for the division supervisor extend to his/her knowledge of principles and application of welding processes, through understanding of inspection methods, weld discontinuities and the applicable welding codes and standards. He/she may be required to demonstrate his/her knowledge by means of examinations. Reference is made to acceptable courses of study, upon successful completion of which the foregoing requirements may be partly reduced.

With respect to the second personnel level, separate provisions are made for junior and senior welding inspectors with the former to perform routine inspection but under the supervision of the responsible senior personnel. Obviously, less demanding educational requirements are set for the junior inspector level requiring some knowledge related to welding and experience in certain capacities.

In the case of senior inspectors, the Standard stipulates more advanced educational requirements, extending to a proven ability to interpret drawings and inspection results, to understanding governing codes, and to demonstrate acceptable familiarity with the qualification system of welders and welding procedures. A longer period of practical welding fabrication or welding inspection is also stipulated.

These superior qualification requirements for the senior key inspection personnel are thought to add markedly to their capability to properly carry out their inspection responsibilities.

With respect to operators of other testing equipment like that for the Magnetic Particle or Liquid Penetrant methods, certification to pertinent CGSB specifications is required, while in the case of other equipment the qualification is left to the discretion of the Bureau.

2.14 CSA W178.2 Certification of Welding Inspectors

2.14.1 General

The main objective of the W178.2 Standard is to provide further assistance to the industry's efforts to produce quality products by providing welding inspection personnel certified individually with qualified skills and capability.

Effectively supporting this main objective is the fact that the prospective applicants need not be members of an inspection organization. This adds a good measure of flexibility to the setting of the manufacturer's own quality programs.

Recognizing the fact that the integrity of inspection is largely dependent on the theoretical knowledge and practical experience on the part of those performing it, the W178.2 Standard establishes appropriate educational and experience criteria considered adequate to ensure the required level of inspection competence. In its scope it also logically provides a link with the W178.1 Standard.

The administration of the Standard is entrusted with the Canadian Welding Bureau, relying on its best professional judgment in the implementation of all those provisions, where such judgment is necessary. Although not explicitly required by the Standard, the Bureau publishes a list of certified welding inspectors at proper time intervals to serve the manufacturing industry.

2.14.2 Review

The Standard sets certification requirements for three levels of inspector personnel (levels 1, 2 and 3) in an ascending order of competence with some provisions for trainees. It defines the responsibilities together with the related competency requirements for each inspector level. In the case of radiographic, ultrasonic, magnetic particle, and liquid penetrant inspection methods, certification to appropriate Canadian General Standards Board (CGSB) specifications is mandatory.

Experience in welded fabrication or welding inspection in one or more capacities of several listed for each area, is required. The years of experience increase with each level and are directly related to educational requirements in a manner that allows for reduction in time with more advanced and substantial educational backgrounds.

In addition to practical tests on visual detection and identification of faults, open book examinations are specified on inspection standards for any category of products (10 listed) for which certification is sought. Closed book examinations are specified for welding, inspection and metallurgy with the required extent of knowledge duly apportioned for each level.

It is important to note that suitable recognition is given to inspection personnel employed by companies certified under the W178.1 Standard. Certification in Level 2 is granted to inspectors qualified by the American Welding Society when certain conditions are met, and AWS provides reciprocal recognition.

Submission of evidence of satisfactory vision is required. Duration of validity is set for 3 years with procedures for renewal fully described.

Finally, the code of ethics is invoked to further stress the importance that the Standard attaches to the integrity of welding inspectors.

2.15 National Building Code of Canada (NBC)

The National Building Code of Canada is published by the National Research Council. Prepared by the Canadian Commission on Building and Fire Codes, it comprises nine parts serving as models of technical requirements with respect to public health and safety in buildings, and is suitable for adoption by appropriate legislative authorities in Canada. In Canada, under the terms of the “Constitution Act”, provincial and territorial governments are responsible for the regulation of buildings, and therefore, the NBC has become the basis for provincial building codes. It also has been widely accepted in municipal bylaws. In its subsection on steel in Part 4 “Structural Design”, the NBC requires buildings and their structural members to conform to CAN/CSA-S16-01 Standard, Limit States Design of Steel Structures.

Additionally, in its Appendix, a reference identifies the specific clause in S16-01 that requires fabricators and erectors of welded structural steel to be certified to the requirements of CSA Standard W47.1, Certification of Companies for Fusion Welding of Steel, in either Division 1 or Division 2. The User’s Guide – NBC, Structural Commentaries (Part 4), has detailed coverage on topics such as:

- ◆ serviceability criteria for deflections and vibrations
- ◆ wind loads
- ◆ snow and rain loads
- ◆ effects of earthquakes
- ◆ foundations

2.15.1 Provincial Building Code

Each province or major metropolitan has its own building code which, in large measure, is based on the National Building Code. There may be minor variations that may be more stringent.

2.16 CSA Standard Z662 Oil and Gas Pipeline Systems

The purpose of CSA Standard Z662 is to establish essential requirements and minimum standards for the design, construction and operation of oil and gas industry pipeline systems. These requirements and standards apply to conditions normally encountered (as opposed to abnormal or unusual conditions) in the oil and gas industry. This Standard is published in SI (metric) units, and its first publication in 1994 combined and superseded the two CSA Standards Z183 and Z184, Oil Pipeline Systems and Gas Pipeline Systems respectively.

This Standard's clause on "Joining" includes an extensive coverage on welding (arc welding, gas welding, explosion welding and roll welding). It stipulates its own welding procedures and welder qualifications together with details of essential variables, test assemblies, preparation of test specimens, inspection and testing of production welds, and acceptance criteria. Arc welding consumables shall be in accordance with the requirements of the CSA W48 Standard, which is administered by the Canadian Welding Bureau – Certification Division. Therefore, the welding consumables shall be certified by the Bureau.

Other clauses in the Standard relate to:

- ◆ materials
- ◆ installation
- ◆ pressure testing
- ◆ corrosion control
- ◆ operating, maintenance and upgrading
- ◆ offshore steel pipelines
- ◆ gas distribution systems
- ◆ plastic pipelines
- ◆ oilfield steam distribution pipeline systems

There are also eight (8) non-mandatory appendices to CSA Standard Z662, including one on Limit States Design.

2.17 ASME – American Society of Mechanical Engineers

ASME, through its Council on Codes and Standards, is recognized worldwide as a major standards-setting organization. Founded in 1880 as an educational and technical society, it continues to pursue its basic objectives through dissemination of technical information and promotion of economic, reliable and safe practices in a wide area of product-oriented engineering and manufacturing activities.

One of the avenues used most effectively towards this objective is standards development. ASME directs this particular activity through its ten Code and Standards Boards, which exercise full jurisdiction over the standards-generating committees, each responsible for a specific area of standards development. To ensure full implementation of the standards, it uses accredited companies for certification of compliance with its codes.

Of primary interest is the Pressure Technology Board and specifically the Pressure Vessel Codes under the auspices of the ASME Boiler and Pressure Vessel Code Committee. The function of the committee is to establish rules of safety covering design, fabrication, inspection and testing of boilers, pressure vessels and associated equipment during original construction. In formulating these rules, consideration by the committee is given to the needs of the manufacturers, users, inspectors and regulatory agencies. The objective of the rules is to provide a margin of deterioration in service so as to ensure a reasonably long and safe period of usefulness. Advances in material technology and new experience are also considered.

The ASME Boiler and Pressure Vessel Code is published every three years. It has been adopted in 46 states in the USA, numerous municipalities, all provinces in Canada (see CSA B.51) and is used in several other countries. Addenda are published regularly to maintain an updated status of the code.

For general information, the following are the 11 sections of the ANSI/ASME Boiler and Pressure Vessel Code:

- I) Power Boilers
- II) Material Specifications
 - Part A – Ferrous Materials
 - Part B – Nonferrous Materials
 - Part C – Welding Rods, Electrodes and Filler Metals
- III) Subsection NCA – General Requirements for Division 1 and Division 2
 - Division 1
 - Subsection NB – Class 1 Components
 - Subsection NC – Class 2 Components
 - Subsection ND – Class 3 Components
 - Subsection NE – Class MC Components
 - Subsection NF – Component Supports
 - Subsection NG – Core Support Structures
 - Appendices
 - Division 2 Code for Concrete Reactor Vessels and Containments
- IV) Heating Boilers
- V) Nondestructive Examination
- VI) Recommended Rules for Care and Operation of Heating Boilers
- VII) Recommended Rules for Care of Power Boilers
- VIII) Pressure Vessels
 - Division 1
 - Division 2 – Alternate Rules
- IX) Welding and Brazing Qualifications
- X) Fiberglass-Reinforced Plastic Pressure Vessels
- XI) Rules for Inservice Inspection of Nuclear Power Plant Components

Of greater interest is section IX and its part dealing with welding procedures and performance qualifications. A cursory review of those in comparison with similar requirements in the CSA W47.1 Standard would reveal that, among others, differences exist in:

- ◆ the definition of essential variables, these being more numerous and more restrictive in W47.1
- ◆ section IX listing a separate set of variables where impact testing is a part of procedure qualification
- ◆ performance qualification, with section IX:
 - i) providing for a 6G assembly (inclined pipe section)
 - ii) ruling differently on the extent of validity on basis of a test in one given position
 - iii) not specifying a mandatory time limit for check testing
 - iv) not permitting mobility for qualified welders

2.18 American Welding Society (AWS)

The American Welding Society was founded in 1919. It has gained wide national and international recognition over the years for its contribution to the transfer of welding technology, a service that is essential to research, development and application engineering, as well as to manufacturers and users.

One of the most successful activities is the Society's outstanding input into the formulation of standards. As an accredited standards-developing organization under ANSI guidelines, the AWS can publish, within the prescribed rules, American National Standards (ANS) pertaining to welding.

Balanced representation on committees is strictly enforced, and a two level review is provided as follows:

- 1) by the Technical Activities Committee (TAC), for technical content and adherence to rule of operation, and
- 2) by the Technical Council for publication

There are 22 technical AWS committees responsible for more than 100 standards covering a wide range of areas related to welding.

It should be noted that there is a strong and active Canadian participation on the AWS committees. This participation is dictated by the desire to keep welding standards in both countries at the same advanced level and without any major differences, to effectively support the high volume of trade between them.

2.19 AWS Codes of D Series

The AWS Code of D Series numbers from D1.1 to D18.2. The frequently referred ones relevant to structural fabrication are listed below:

- D1.1 Structural Welding Code – Steel
- D1.2 Structural Welding Code – Aluminum
- D1.3 Structural Welding Code – Sheet Metal
- D1.4 Structural Welding Code – Reinforcing Steel
- D1.5 Bridge Welding Code
- D1.6 Structural Welding Code – Stainless Steel
- D3.6 Specification for Underwater Welding

2.20 AWS A5 Specifications: Filler Metal Specifications

The AWS A5 Specifications consist of 32 specifications which cover a wide range of alloys for various welding processes. The following specifications are more relevant to fabrication shops:

AWS A5.7-84R	Specification for Copper and Copper Alloy Bare Welding Rods and Electrodes
AWS A5.9-93	Specification for Bare Stainless Steel Welding Electrodes and Rods
AWS A5.10:1999	Specification for Bare Aluminum and Aluminum Alloy Welding Electrodes and Rods
AWS A5.11/A5.11M-97	Specification for Nickel and Nickel Alloy Welding Electrodes for Shielded Metal Arc Welding
AWS A5.14/A5.14M-97	Specification for Nickel and Nickel Alloy Bare Welding Electrodes and Rods
AWS A5.22-95	Specification for Stainless Steel Electrodes for Flux Cored Arc Welding and Stainless Steel Rods for Gas Tungsten Arc Welding

AWS A5.23/A5.23M-97	Specification for Low Alloy Steel Electrodes and Fluxes for Submerged Arc Welding
AWS A5.28-96	Specification for Low Alloy Steel Electrodes and Rods for Gas Shielded Arc Welding
AWS A5.29-1998	Specification for Low Alloy Steel Electrodes for Flux Cored Arc Welding

2.21 ANSI/AWS-D1.1 Structural Welding Code – Steel

As the most prominent of the D1 series, this Code provides comprehensive rules pertaining to the construction of welded steel structures. It covers the design and strength of welds, qualification requirements for welding procedures and welding personnel, workmanship, inspection and quality acceptance criteria.

The Code consists of eight sections, annexes and commentary as follows:

Section 1	General Requirements
Section 2	Design of Welded Connections
Section 3	Prequalification of WPSs
Section 4	Qualification
Section 5	Fabrication
Section 6	Inspection
Section 7	Stud Welding
Section 8	Strengthening and Repairing Existing Structures
Annexes and Commentary	

The Code covers only arc welding processes and incorporates the concept of prequalified welding procedures in conjunction with the use of prequalified joint details.

It is comparable to the CSA Standard W59 – Welded Steel Construction, except for its extensive coverage of tubular structures and its requirements for qualification of welding procedures and welding personnel.

It should be noted that it is a conformance code. It is up to the fabricators to voluntarily adopt and conform to it and the AWS does not monitor and enforce their adherence as does the Canadian Welding Bureau on CSA W59 and W47 with certified companies.

The AWS D1.1 Code, with its commentary, has been published on a yearly basis. As an authoritative document, it enjoys worldwide recognition.

2.22 ISO Standards

International Standards Organization

The ISO Standards were originated by European Common Market Countries. They are now adopted by some North American companies as well. The Standards give guidelines for quality control in industrial and business operations.

The Standard that covers arc welding operations is ISO 2553. Since standards will eventually be globalized, we should all know something about ISO 2553. Although the content of the Standard is not as extensive as CSA W47.1/W59 and AWS D1.1, the Table of Contents is shown below to give an outline of ISO 2553:

Welded, Brazed & Soldered Joints – Symbolic Representation of Drawings

Contents

1. Scope
2. Normative References
3. General
4. Symbols
 - 4.1 Elementary Symbols
 - 4.2 Combination of Elementary Symbols
 - 4.3 Supplementary Symbols
5. Positions of Symbols on Drawings
 - 5.1 General
 - 5.2 Relationship Between the Arrow Line and the Joint
 - 5.3 Position of the Arrow Line
 - 5.4 Position of the Reference Line
 - 5.5 Position of the Symbol with Regard to the Reference Line
6. Dimensioning of Welds
 - 6.1 General Rules
 - 6.2 Main Dimensions to Be Shown
7. Complimentary Indications
 - 7.1 Peripheral Welds
 - 7.2 Field or Site Welds
 - 7.3 Indication of the Welding Process
 - 7.4 Sequence of the Information In-the-Tail of the Reference Mark
8. Examples of Application of Spot and Seam Joints

ISO 3834 Quality Systems for Welding

ISO 9606 Welder Qualification Procedure

Chapter 3

Weld Joints and Welding Symbols

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3.1 Introduction

Welding consists of joining two or more pieces of metal by the application of heat and sometimes pressure. In electric arc welding, the heat comes from an electric arc and no pressure is employed to fuse the metal parts. In most applications of arc welding, filler metal is added to the joint which is specially prepared in certain shapes, like a mold, to receive the molten filler metal. In some applications, the metal parts are fused together without additional filler metal.

Since welding is related to making joints, the student should first be familiar with the terminology of welds and joints. Not only must the names of these joints and welds be familiarized, but also the systems by which they are technically represented. It is through the correct usage of the terminology that we can communicate with each other in this field in the most effective and exact manner.

This chapter is the abridged version of the following CWB Modules. Students are advised to study them for more detailed information.

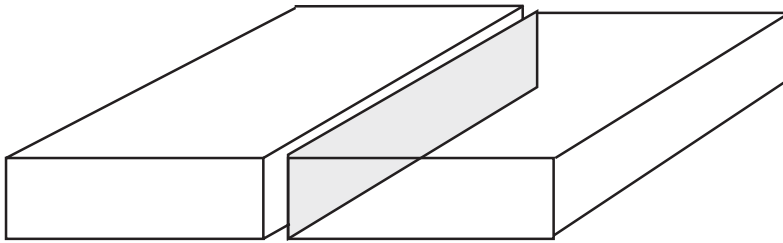
Module 2	Engineering Drawings, Basic Joints and Preparation for Welding
Module 3	Symbols for Welding

3.2 Definition of Joint

JOINT: The junction of members or the edges of members which are to be joined or have been joined.

The following figures show various joints and it can be seen that an alternative description of a joint might refer to the “faying surfaces which are in contact”. While this is not entirely correct, it will assist the student in deciding on the joint which is present under certain conditions.

Look at the joint shown in **Figure 3.1** and at the same time, consider the definition of the word “joint” and also the “faying surfaces which are in contact”.



The student should realize that there is only one joint shown in **Figure 3.1**, and that joint extends the whole length of the plate.

Figure 3.1

Now, look at **Figure 3.2**, the assembly consisting of three plates. Consider the number of joints and select your answer from the following:

- | | |
|---------------|-----------|
| 1 joint only? | 2 joints? |
| 3 joints? | 4 joints? |

Check your answer.

ANSWERS

COMMENTS ON ANSWERS

- | | |
|--------------|---|
| 1 joint only | No. You are thinking of one assembly which after welding will form one weldment. A weldment is an assembly whose component parts are joined by welding. |
| 2 joints | This answer is correct. The three plates form two joints. The actual joint is the faying area in contact with the centre plate. |
| 3 joints | No. You are considering three plates which form part of the assembly. |
| 4 joints | No. Perhaps you are considering each side of the joint. For example, there are four sides where fillet welds could be made. However, these are only two areas of faying surfaces. |

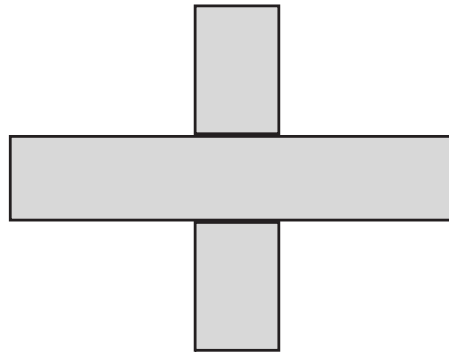
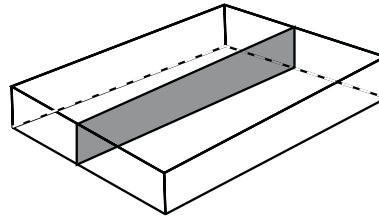
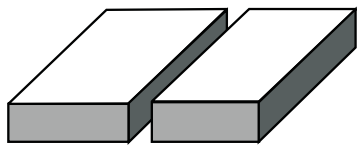


Figure 3.2: *The faying surfaces of these two joints have been marked by a thick black line.*

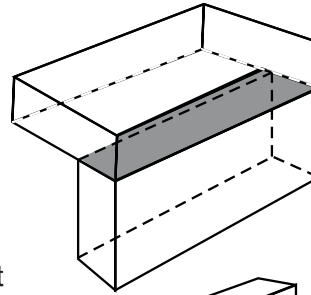
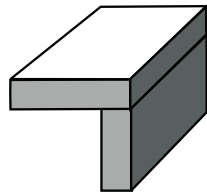
3.2.1 Types of Basic Joints

There are five basic joints, although many variations of these result from the manner of preparation and assembly. These five, illustrated in **Figure 3.3**, are termed butt joint, corner joint, tee joint, lap joint and edge joint.

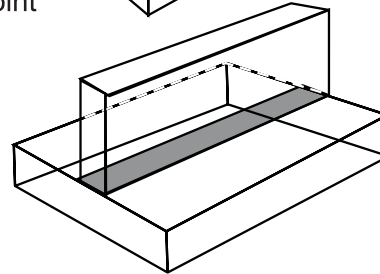
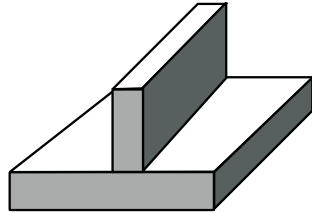
The actual joint is shown as a shaded area on the right side of each joint.



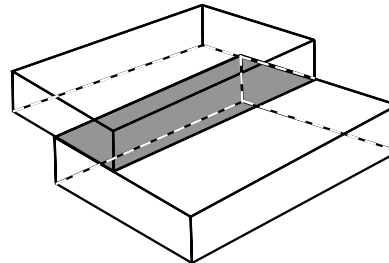
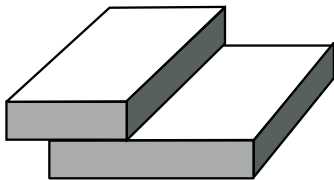
Butt Joint



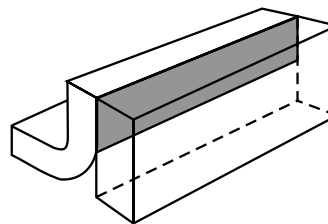
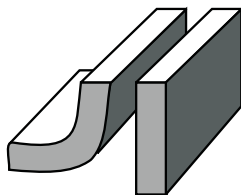
Corner Joint



Tee Joint



Lap Joint



Edge Joint

Figure 3.3: Five basic joints.

3.3 Definition of Weld

A localized coalescence of materials (metals or non-metals) produced either by heating the metals to suitable temperatures, with or without the application of pressure, or by the application of pressure alone, with or without the use of filler materials.

The word “coalescence” is used since coalescence is defined as “growing together, or growing into one body”. In welding metals, the metallic bond is formed as the weld is being made.

3.3.1 Basic Types of Welds

There are five basic types of welds which are:

- 1) groove weld
- 2) fillet weld
- 3) plug and slot welds
- 4) surfacing weld
- 5) flanged weld

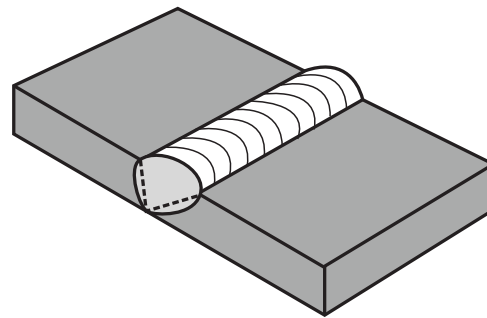


Figure 3.4: Groove weld.

1) Groove Weld

A groove weld is a weld made in a groove between the workpieces. There are many different shapes of grooves. **Figure 3.4** shows one type of groove weld.

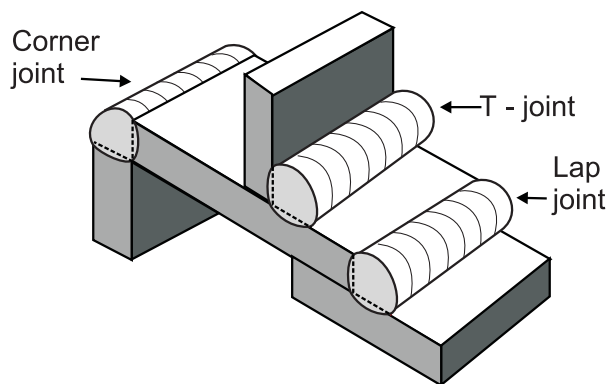


Figure 3.5: Fillet weld.

2) Fillet Weld

A fillet weld is a weld of approximately triangular cross-section joining two surfaces approximately at right angles to each other in a lap joint, T-joint or corner joint as shown in **Figure 3.5**.

3) Plug Weld and Slot Weld

A plug weld is a weld made in a circular hole in one member of a joint fusing that member to another member. A slot weld is similar to a plug weld except that the hole is elongated. See **Figure 3.6**.

In preparation for plug and slot welds, holes or slots are made in the upper plate. On relatively thinner material, such welds can be made without holes or slots and are called arc spot and arc seam welds, in which the upper sheet is melted and fused to the lower sheet.

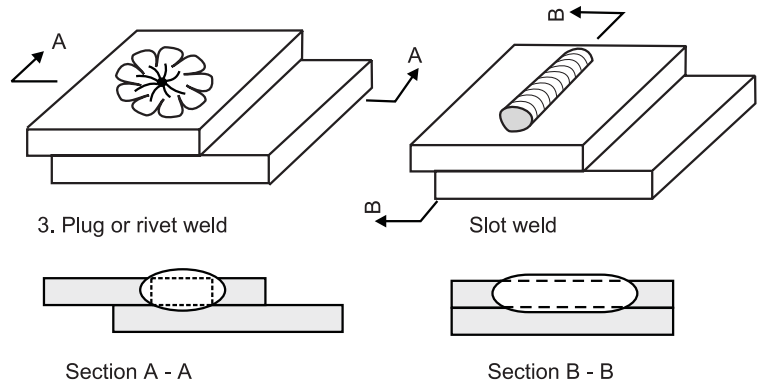


Figure 3.6: Plug weld and slot weld.

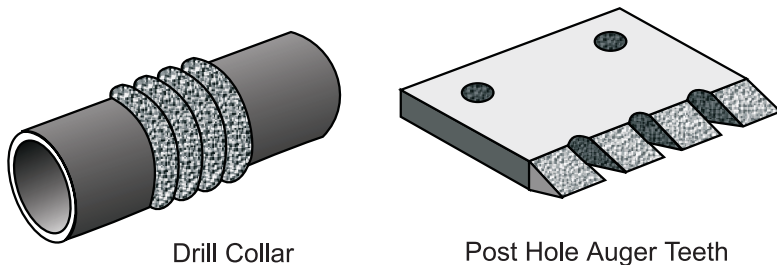


Figure 3.7: Surfacing weld.

4) Surfacing Welds

All welds are composed of one or more weld beads. A bead is a single run or pass of weld metal. A weld bead or beads may be applied to a surface, as opposed to making a joint, to obtain desired properties or dimensions. Such a weld is called “surfacing welds”, as shown in **Figure 3.7**.

5) Flanged Weld

Flanged weld is a group term which covers: corner-flange welds, edge welds and edge-flange welds. As shown in **Figure 3.8**, they are apparently neither groove welds nor fillet welds. They are not surfacing welds because these welds are forming joints along two members.

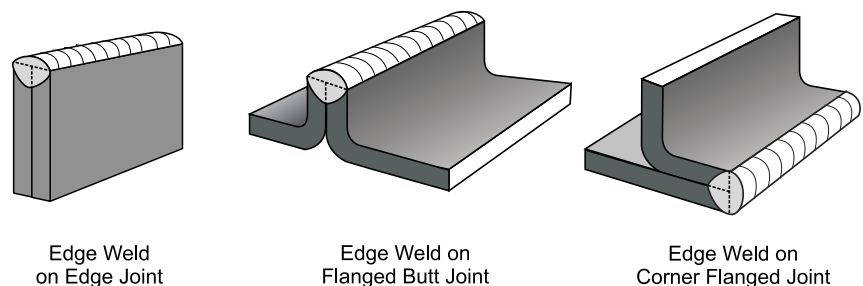


Figure 3.8: Flange welds.

3.4 Groove Weld

“A weld made in the groove between two members to be joined”.

Figure 3.9 shows the geometries and welding terms for typical groove weld joints. In order to describe the geometry of a joint, all the numerical data for plate thickness, bevel or groove angle, groove radius of J-groove, root face and root opening should be given.

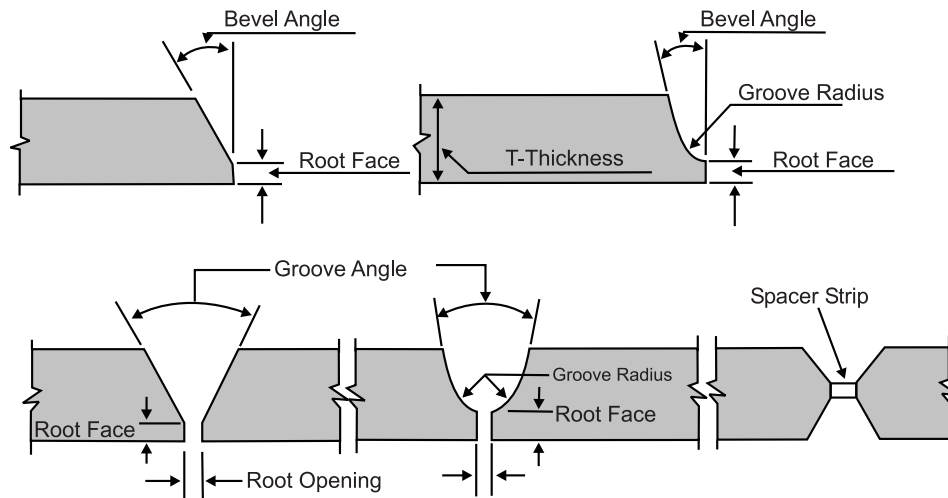
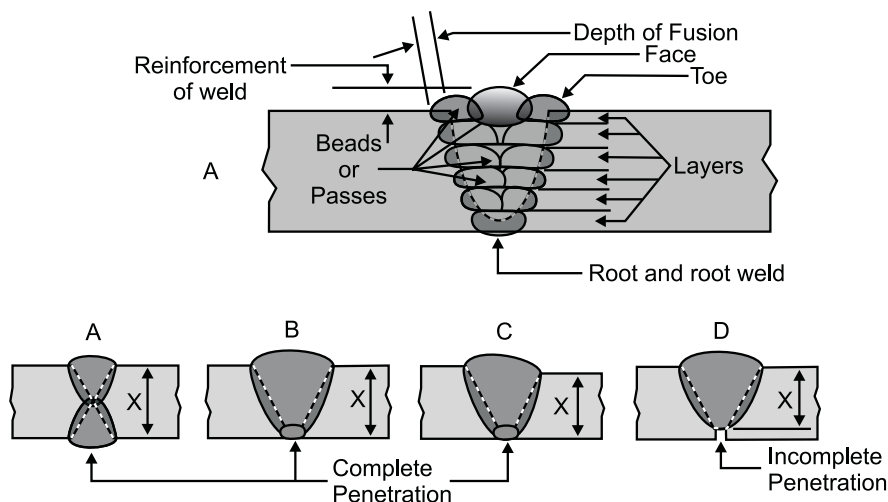


Figure 3.9

The above examples are shown on a single groove joint. All the terms are applicable to double groove joints as well.

Figure 3.10 shows more terms related to welds and joints.



Note: The weld size or effective throat (x) is defined in sketches A, B, C and D. Where joint penetration is complete as in A and B, the weld size is the thickness of the plate. Where the plates differ in thickness as in C, and joint penetration is complete, the weld size is the thickness of the thinner plate. Where joint penetration is incomplete as in D, the weld size is the depth of penetration.

Figure 3.10: Joint and welding terms.

3.4.1 Single Groove Welds

The terms “Single Weld” and “Double Weld” should be clarified. A square groove, when welded from one side, is called a single-square-groove weld as shown in **Figure 3.11**. When welded from both sides, it is called a double-square-groove weld (see **Figure 3.14**).

Figure 3.12 shows a bevel-groove weld that is chamfered on one side only, but welded from both sides. It is commonly considered as a single-bevel-groove weld.

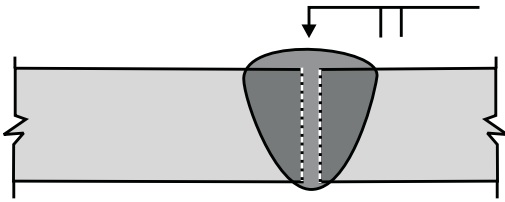


Figure 3.11: Square-groove weld.

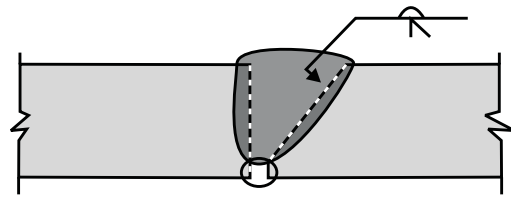
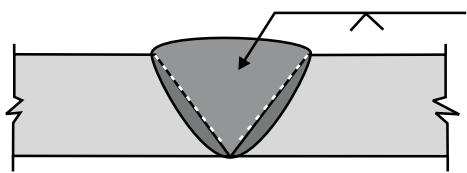
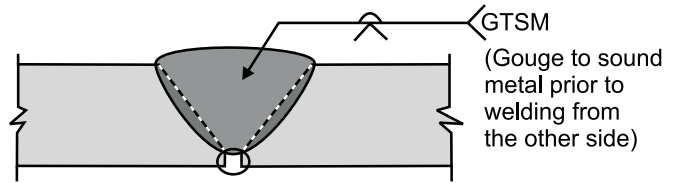


Figure 3.12: Single-bevel groove weld.

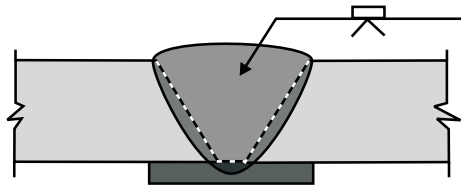
The following examples (**Figure 3.13**) are of single-V-groove welds.



Welded only from one side.



Welded and backgouged and welded from both sides.



Welded onto a backing strip.

Figure 3.13: Single V-groove welds.

3.4.2 Double Groove Welds

Double groove welds are shown in **Figure 3.14**. When welds are made from both sides of a square-groove joint or when both sides of the joint have been chamfered to form groove welds on both sides, then the term “*Double*” is used.

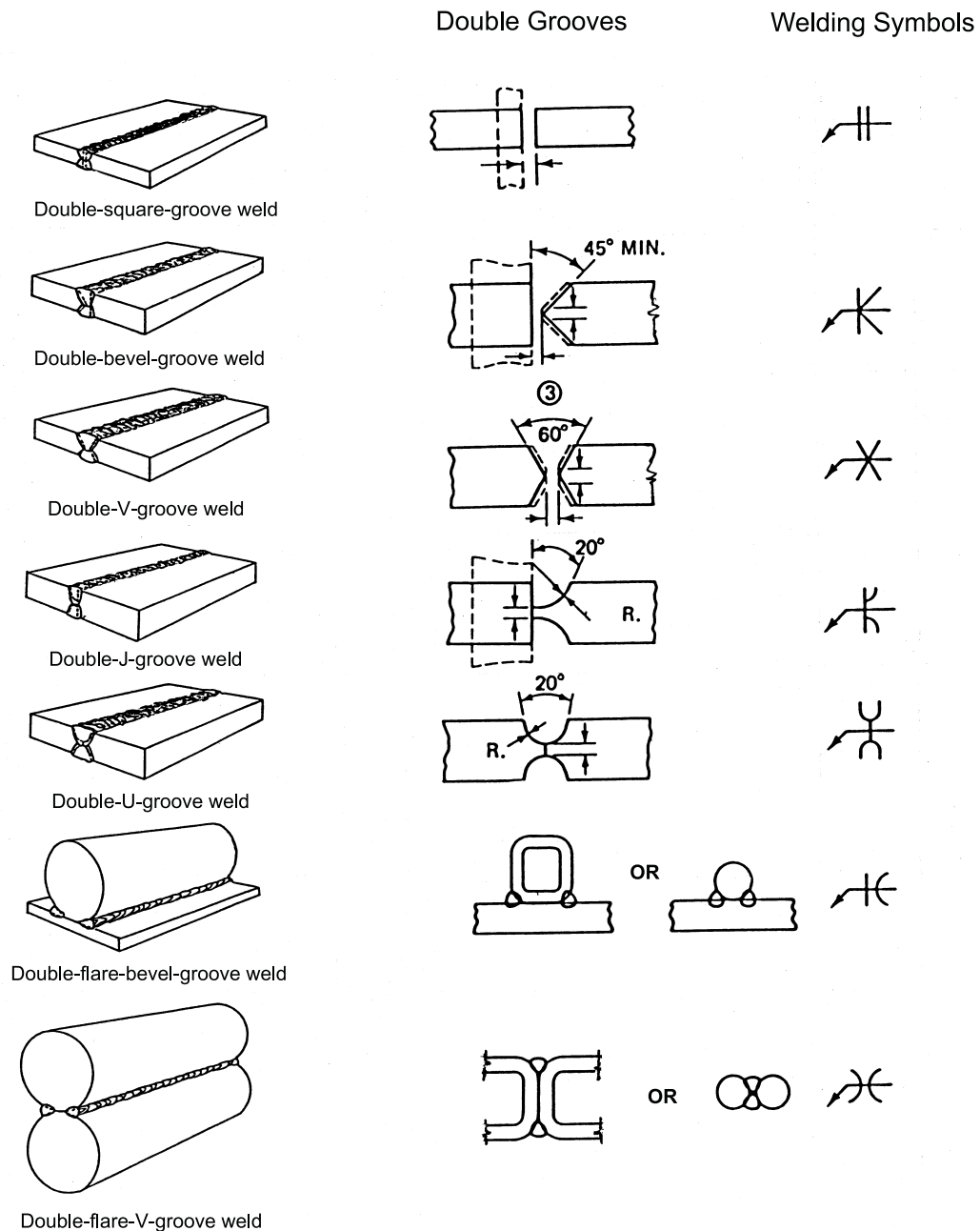


Figure 3.14: Double groove welds.

3.5 Prequalified Joints

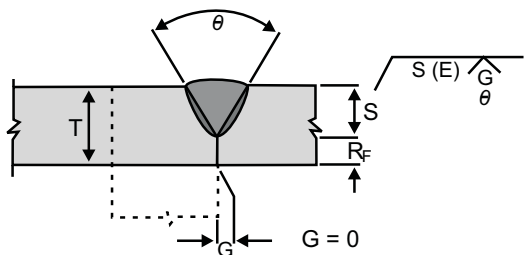
There are some groove weld joints that are designed as prequalified weld joints. These joints meet the requirements of: joint geometries, welding processes, welding positions, base metal and filler metal specifications.

The objective to designate certain joints as “prequalified” is to exclude these joints from the requirements of welding procedure qualification tests. Economy is a major factor for so doing. The accumulated experience of the welding industry over the years demonstrates that reliable good performance of these weld joints can be readily achieved under the prescribed conditions. Also, designers and fabricators are provided with the best tried and proven practice and they do not have to go through the trial and error process and welding procedure qualification tests. It should be noted that different welding codes and standards may differ slightly in the designation of prequalified joints.

There are prequalified joint designated in both complete joint penetration joints and partial joint penetration joints. Sample prequalified joints are shown in the following tables in which CSA W59 (Welded Steel Construction) and AWS D1.1 (Structural Welding Code) are referenced. It should be noted that certain joints are designated by AWS D1.1 as prequalified joints, but which are not prequalified in CSA W59. CSA W59 and AWS D1.1 should be consulted for the complete list of prequalified joints.

The student is reminded that there are other welding standards with prequalified joints that may be different from CSA W59 and AWS D1.1.

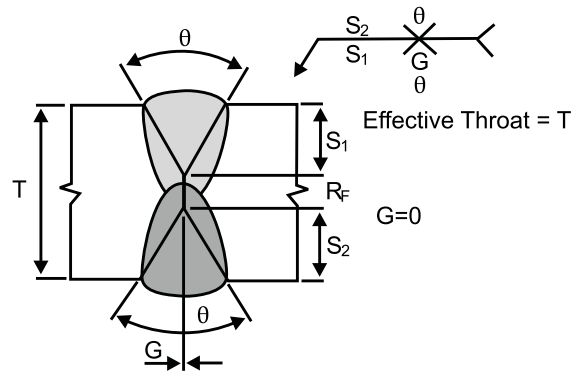
CSA W59

						
Welding Processes	Joint Designation	Base Metal Thickness T (mm)	Root Face R _F (mm)	Groove Angle	Permitted Welding Positions	Weld Size (mm)
SMAW	BC-P2b	≤13	3	45°#2<60°	F, O	S - 3
				60°	F, V, O	S
FCAW	BC-P2-FC	U	3	45°#2<60°	F	S - 3
				60°		S
SAW	BC-P2-S	U	6	60°	F	S

Tolerances are given in CSA W59, Clause 5.

Figure 3.15: Prequalified partial joint penetration groove welds (sample joint).

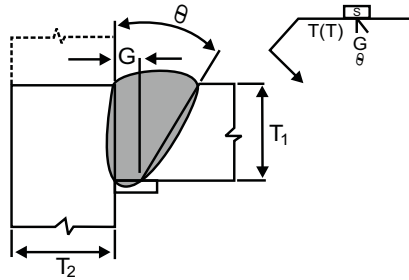
CSA W59



Welding Processes	Joint Designation	Base Metal Thickness T (mm)	Root Opening G (mm)	Groove Angle	Permitted Welding Positions	Weld Size (mm)
			Root Face R _F (mm)			
SMAW	B-U3b-(x)	U	0 - 3	45°	F, V, O	T
			2 (GTSM)			
FCAW	B-U3-FC (x)	U	0	45°	F	T
			3 (GTSM)			
SAW	B-U3C-S (x)	U	0	60°	F	T
			6 (NO GTSM) >6 (GTSM)			

Tolerances are given in CSA W59, Clause 5.
GMAW is not prequalified.
GTSM - Gouge to sound metal.

Figure 3.16: Prequalified complete joint penetration groove welds (sample joint).



Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation		Permitted Welding Positions	Gas Shielding for FCAW	Polarity
		T ₁	T ₂	Root Opening G	Groove Angle θ			
SMAW	B-U4b	U	-	12mm	20°	F, O Only	-	
				10	30°		-	
				6	45°	All	-	
FCAW	TC-U4b-FC	U	-	6	30°	F, H Only	Yes	
				5	45°			
				6	30°		No	SP ⁽²⁾
				5	45°			
				10	30°	F	No	RP ⁽³⁾
				6	45°	F, H		
SAW	TC-U4a-S	U	-	16	20°	F Only	-	
				10	30°			
				6	45°			

- (1) No prequalified joint for GMAW process.
 (2) SP - Straight polarity, electrode negative.
 (3) RP - Reverse polarity, electrode positive.
 (4) Split pass mandatory in root layer.

Figure 3.17

3.6 Positions of Welding

With metallic arc welding, it is possible to deposit weld metal in any position with some of the welding processes, so that a welder may make a joint that is below him, in front of him, above him, or at any intermediate positions between these welding positions.

The following welding positions are defined and frequently referred to by the welding industry:

3.6.1 Definitions

Terminology

Definitions

Flat Welding Position

The welding position used to weld from the upper side of the joint; the face of the weld is approximately horizontal, **Figure 3.18, 1G and 1F**.

Horizontal Welding Position

Fillet Weld – The position in which welding is performed on the upper side on an approximately horizontal surface and against an approximately vertical surface, **Figure 3.18, 2F**.

Groove Weld – The welding position in which the weld face lies in an approximately vertical plane and the weld axis at the point of welding is approximately horizontal. See **Figure 3.18, 2G**.

Overhead Welding Position

The position in which welding is performed from the under side of the joint, **Figure 3.18, 4G and 4F**.

Positioned Weld

A weld made in a joint which has been so placed as to facilitate making the weld.

Vertical Welding Position

The position of welding in which the axis of the weld is approximately vertical, **Figure 3.18, 3G and 3F**.

Positions of Pipe Welding

The position of a pipe joint in which welding is performed in the horizontal position and the pipe may or may not be rotated.

Horizontal Fixed Welding Position

The position of a pipe joint in which the axis of the pipe is approximately horizontal and the pipe is not rotated during welding.

Horizontal Rolled Welding Position

The position of a pipe joint in which the axis of the pipe is approximately horizontal and welding is performed in the flat position by rotating the pipe.

3.6.2 Designation of Welding Positions

This section will give the student a quick view of the welding positions with respect to groove and fillet welds made on plate material.

A weld is said to be made in the flat position, horizontal position, vertical position or overhead position depending on the position of the joint in relation to the floor. Welding techniques for the four positions of welding vary according to the positions the weld metal is deposited. It is possible to deposit weld layers of considerable volume in the flat and vertical positions but stringer beads are normally used for horizontal and overhead positions. These positions are better illustrated in **Figure 3.19** to augment some of the definitions given earlier. The number and letter combinations are used to designate each welding position for quick reference. The letter G stands for groove weld, letter F for fillet weld. The numbers 1, 2, 3 and 4 correspond to flat, horizontal, vertical and overhead positions respectively, as shown in **Figure 3.18**.

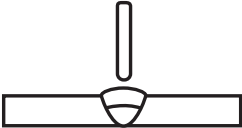
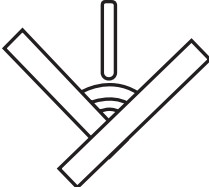
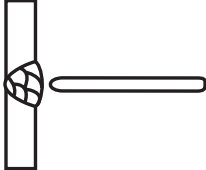
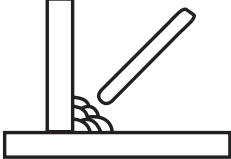
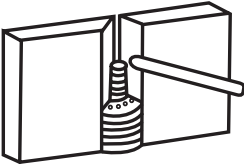
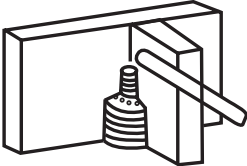
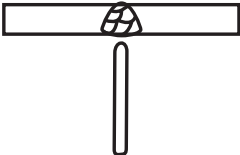
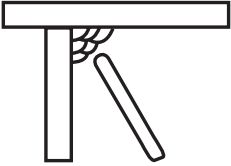
Position of Weld	Groove	Designation	Tee Joint Fillet	Designation
Flat		1G		1F
Horizontal		2G		2F
Vertical		3G		3F
Overhead		4G		4F

Figure 3.18: Positions of welding.

3.6.3 Positions of Groove Welds in Plate

Figure 3.18 shows the welding positions in the most exact manner, but in practical shop fabrication, the welding positions can be in any of the intermediate positions. **Figure 3.19** shows the sectors which are designated as certain welding positions. The sector angles are measured clockwise from the 0° point as shown. Within one sector, the centerline of a groove cross-section can vary from one radius to the other, and all the groove welds are considered in the same welding position. It is an approximation with the actual welding techniques considered in different positions.

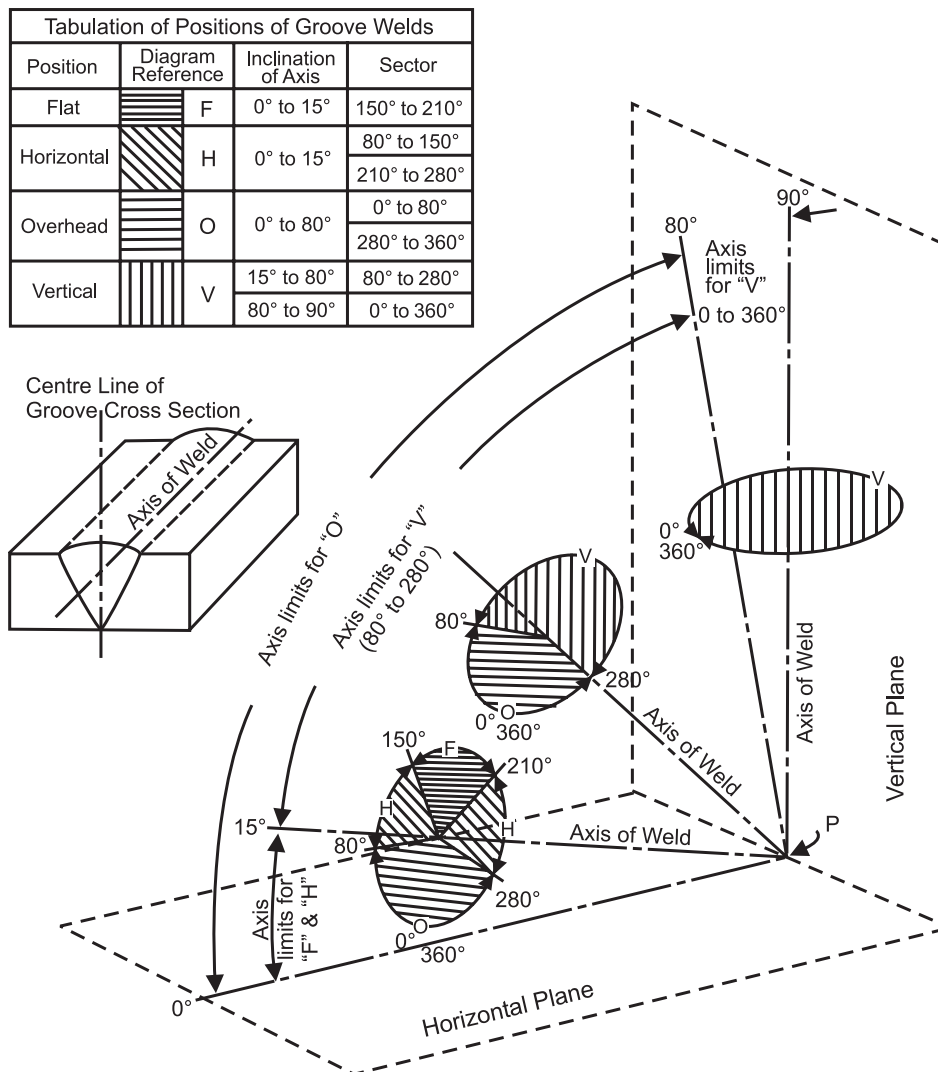


Figure 3.19: Positions of groove welds.

3.6.4 Positions of Groove Welds in Pipe

Positions of welds in pipe may vary from flat to overhead and all the positions in between if the pipe is not rotated. Also, the axis of the pipe may vary from 0° (horizontal) to 90° (vertical) and all the angles in between. **Figure 3.20** shows the welding positions around the circumference joint for pipe axis from 0° to 90° .

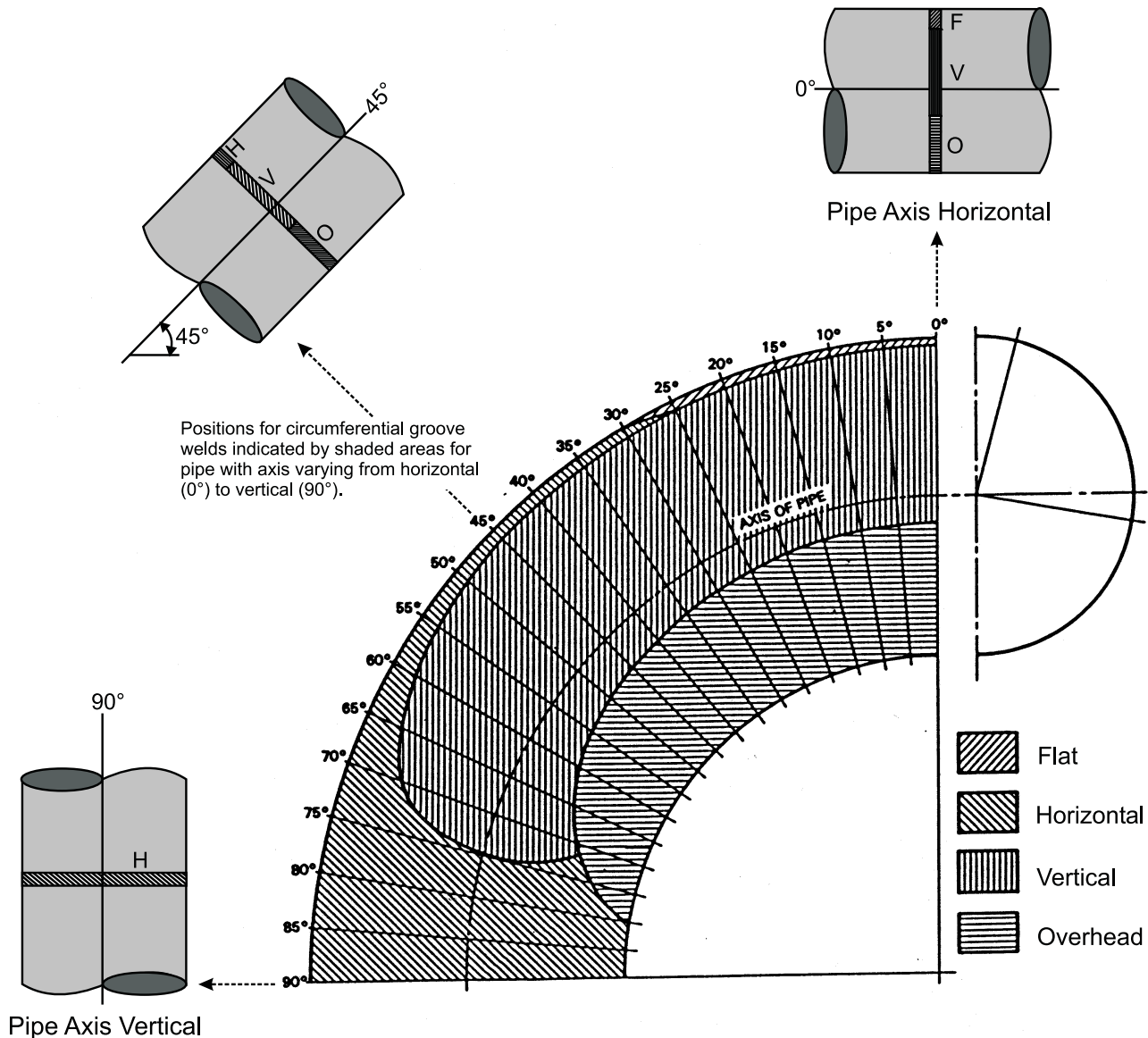


Figure 3.20: Welding position diagram for groove welds in pipe.

3.7 Joint Edge Preparation

Plate edges to be welded are prepared according to the joint configurations, be it square, bevelled or J-grooves. The CWB Module 2 – Engineering Drawings, Basic Joints and Preparation for Welding, gives the full description of this subject. The students are recommended to read Module 2 for methods of preparation. In this chapter, a brief description of the most common methods will be presented.

Oxyfuel cutting is the most common method used in structural steel fabrication shops. **Figure 3.21** shows the cutting torch positions for simple or compound cutting. It should be noted that the cutting is not done by the heat in the flame.

Briefly, the basic principle of oxygen cutting depends upon the simple fact that steel at red heat will oxidize rapidly or “burn” where a jet of oxygen is directed onto it. The ordinary cutting torch enables this to be done by providing both a heating flame and a pure oxygen jet – each with its own controls – the heating flame being used chiefly to preheat the steel where the cut is to be started, after which the oxygen jet does the cutting.

Only a small area needs to be preheated for starting the process since, as soon as oxidation commences, the combustion of the steel produces very intense local heat. This further preheats the metal around the oxidation point, enabling the oxygen jet to pierce almost any thickness of steel, or to make a cut in whichever direction the torch is moved. After the cut has started, the main function of the heating flame is to keep the oxide fluid (so that it will leave the cut easily) and to compensate for heat losses, especially at the upper edge. The pressure of the oxygen jet blows away the oxide fluid.

It should be pointed out that the cutting is not done by melting, although it appears that way. The process depends entirely on the combustion (that is, burning) of the steel in the path of the oxygen jet. On mild and normal welding quality steels, the process has no detrimental effect on the metal and there is no need to machine the cut surface before welding.

Smoothness of the cut edge is an important feature and this depends on the proper tip size, tip to work distance, oxygen pressure, and on the uniformity of speed with which the torch is moved. The movement may be made with the torch held in the hand (ie., manual cutting) or it can be mechanically propelled (machine cutting).

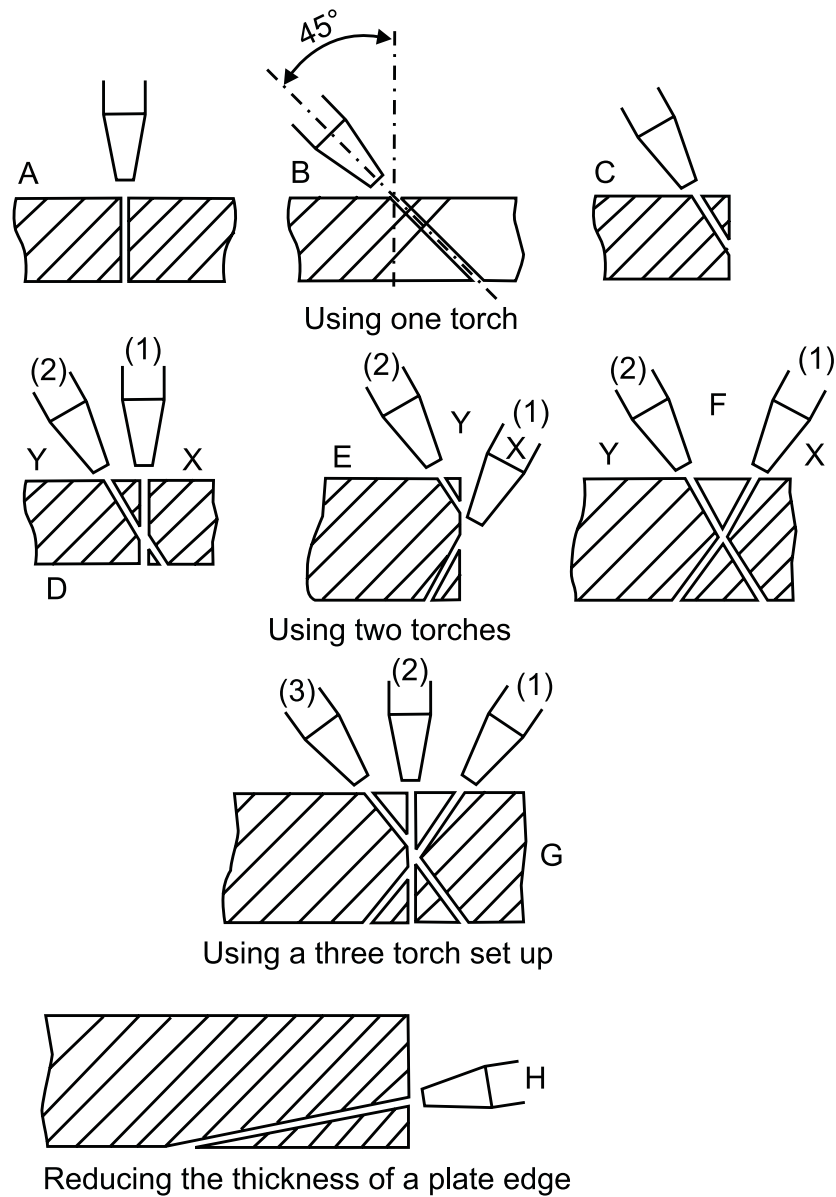


Figure 3.21: Use of oxygen cutting for preparing square and bevel edges.
 (Note - figures in brackets indicate order of the location of torches in the direction of cutting)

Another commonly used method is the air carbon arc gouging which is mainly used to make J- or U-grooves. J- or U-grooves can also be made by machining, which is much more costly than air carbon arc gouging. **Figure 3.22** shows how the joint is prepared.

Compressed air carbon arc, as the name implies, consists of melting the metal to be gouged or cut with an electric arc and blowing away the molten metal with a high-velocity jet of compressed air parallel to the electrode. Because it does not depend on oxidation, it works on metals which do not oxidize readily. The equipment used is a torch that directs a stream of air along the electrode and external to it. The torch is connected to an arc welding machine and an ordinary compressed-air line delivering approximately 100 lbs per sq. inch. Since the exact pressure is not critical, normally no regulator is necessary. The electrode used is a composition of carbon and graphite and is usually copper clad to increase its life and provide a uniform groove, as well as to reduce radiation heat. The shape of the electrode may be round or half round. DCRP is used for most applications, but in some materials DCSP is preferred. An electrode for alternating current is also available and this, when used with either AC or DCSP, gives improved results on certain applications.



Figure 3.22(a): Manual air carbon arc torch.



Figure 3.22(b): Principle of air carbon arc process.

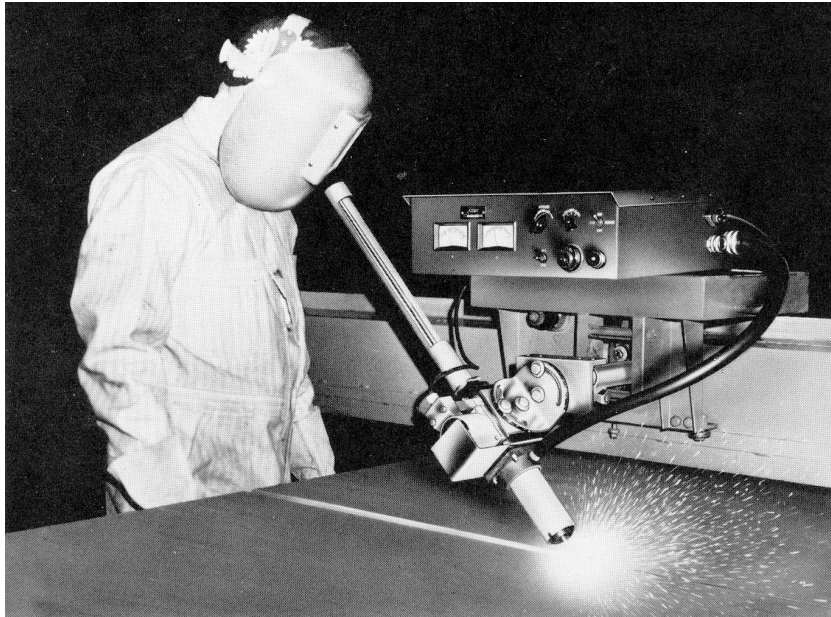


Figure 3.23: Automatic arc-air gouging machine.

There are also mechanical methods for joint preparation. For square edges, saw cut may be used. For bevel edges, specially designed edge bevellers are available. They can be mounted and self-propelled or a portable manual type can also be used as shown in **Figure 3.24**.



Figure 3.24(a): Rotary shear.
(Photo courtesy of Gullco International)



Figure 3.24(b): Portable beveller.

3.8 Fundamental Concepts of Welding Symbols

3.8.1 Weld Symbols, Supplementary Symbols, Welding Symbols

Definitions

In welding symbols terminology, there are several standard terms in common use. A clear understanding of these terms is very important to have any meaningful dialogue involving welding symbols.

These terms are:

- a) weld symbols
- b) supplementary symbols
- c) welding symbols

The definition of these terms and their interrelationship are described as follows:

- a) *Weld symbol* is a term used explicitly to designate a specific type of weld. The pertinent types of welds considered under the governing AWS A2.4 specification for “Symbols for Welding, Brazing and Nondestructive Examination” and the basic weld symbols are shown in **Figure 3.25**. Weld symbols such as these form an integral part of any typical welding symbol.

GROOVE WELDS							
Square	Scarf*	V	Bevel	U	J	Flare-V	Flare-Bevel

Fillet	Plug or Slot	Stud	Spot or Projection	Seam	Back or Backing	Surfacing	Flange	
							Edge	Corner

*Used predominantly in brazed joints - see section on Brazing.

Figure 3.25: Basic weld symbols.

- b) *Supplementary symbol*, as the term indicates, is used to provide complementary information to that given by the basic elements of a typical welding symbol.

Supplementary symbols are always used in conjunction with a welding symbol, and they are shown in **Figure 3.26**.

Weld all around	Field Weld	Melt Through	Consumable Insert (Square)	Backing or Spacer (Rectangle)	Contour		
					Flush or Flat	Convex	Concave

Figure 3.26: Supplementary symbols.

- c) *Welding symbol*, in turn, provides comprehensive information with respect to the geometry of preparation, fit-up and welding of joints. It is composed of a number of standard elements, including a weld symbol, and uses any of the applicable supplementary symbols to effectively complement such information.

All the basic elements of a typical welding symbol, including reference to supplementary symbols and their respective designated locations, are shown in **Figure 3.27**.

3.9 Basic Weld Symbols

Reference was already made to the primary purpose of a weld symbol. Its main and specific objective is to graphically identify each type of weld.

To assist in this identification, the shape of the symbol, whenever possible, is made to conveniently reflect the relative configuration of the fusion faces as represented by a vertical section through the joint.

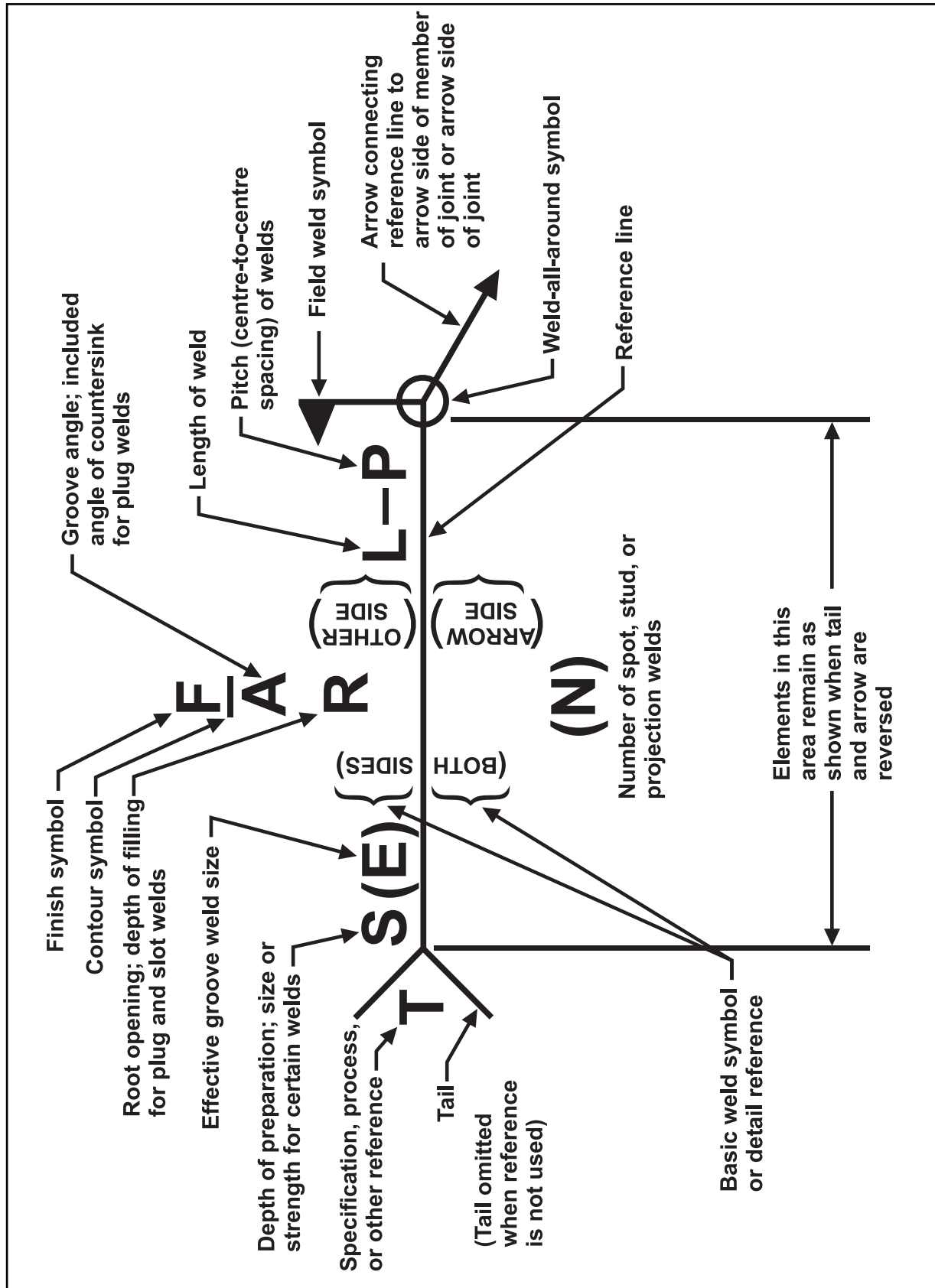


Figure 3.27: Standard location of elements of a welding symbol.

The following symbols (**Figure 3.28**) are some examples, with the viewing position indicated for correct placement:

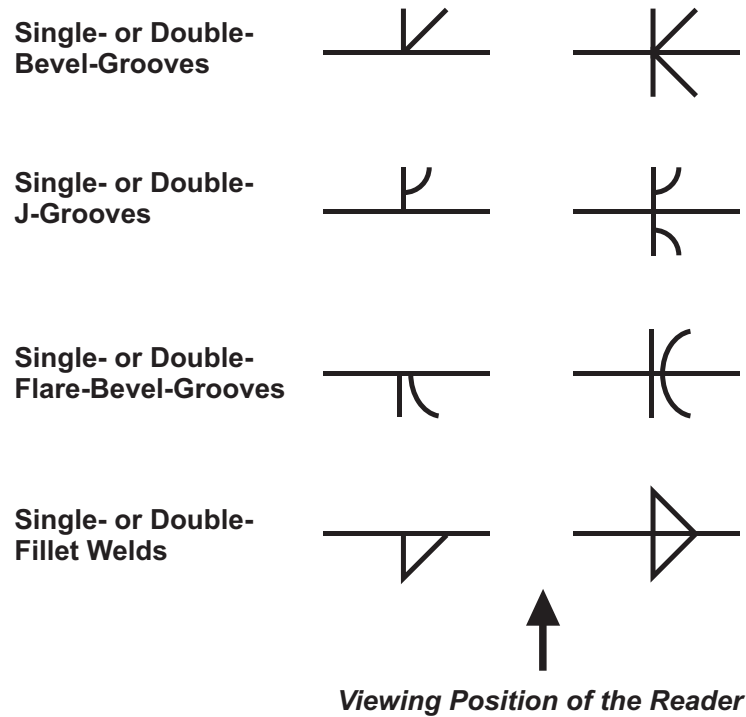


Figure 3.28: Correct placement of weld symbols.

Hence, all weld symbols as shown in **Figure 3.29**, viewed from the same position as in **Figure 3.28**, are incorrect.



Figure 3.29: Incorrect placement of weld symbols.

This rule points to the fact that proper attention must be given to the placement of a weld symbol on the reference line.

Several practical examples are given in the following pages to illustrate the application of basic weld symbols.

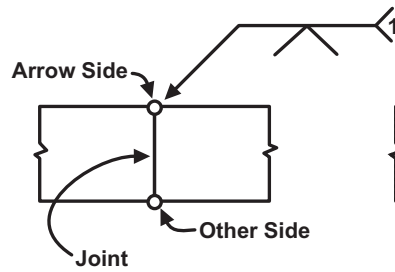
EXAMPLE 1

GROOVE WELD IN A BUTT JOINT

Required:
A Single-V-Groove Weld

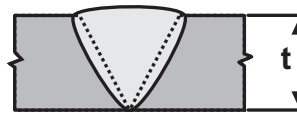


▼ ALTERNATIVE 1:

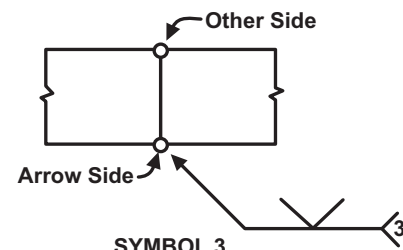


SYMBOL 1

indicates preparation to be made from the Arrow Side



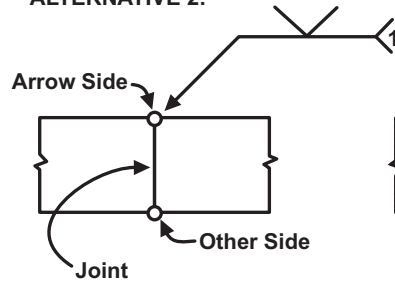
WELD



SYMBOL 3

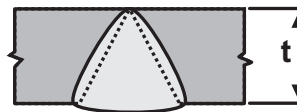
Preparation from the same side could have been obtained using Symbol 3 as shown

▼ ALTERNATIVE 2:

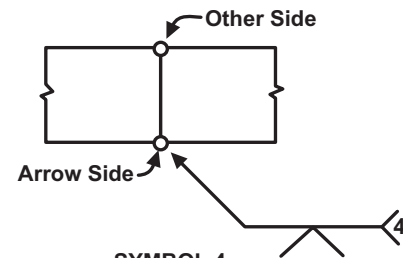


SYMBOL 2

indicates preparation from the Other Side



WELD

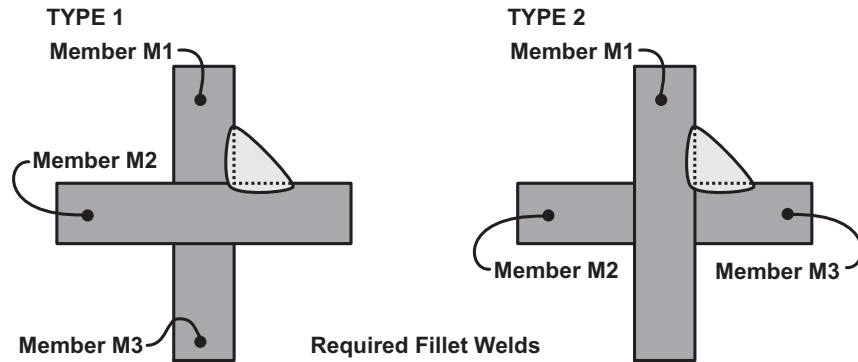


SYMBOL 4

Preparation from the same side could have been obtained using Symbol 4 as shown

EXAMPLE 2

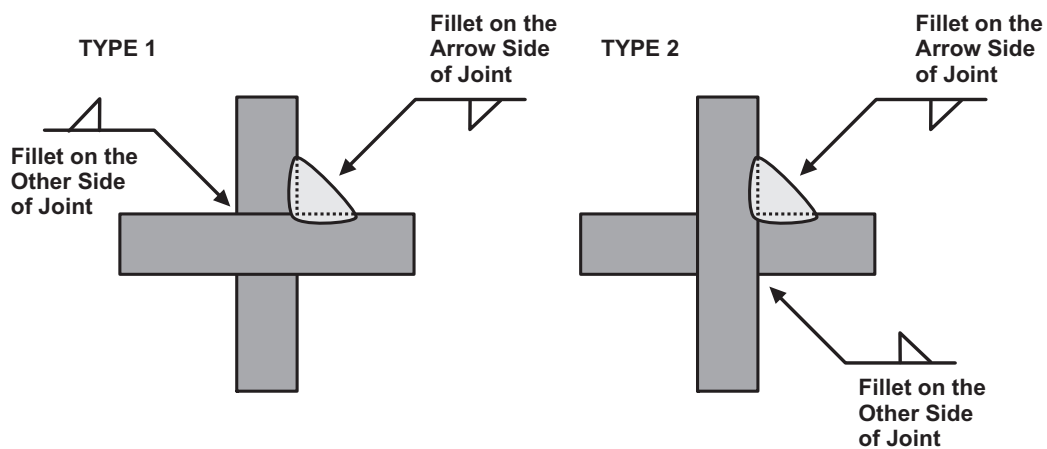
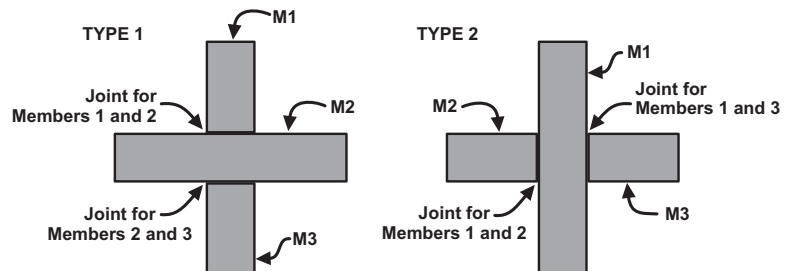
CRUCIFORM DOUBLE-T JOINTS



TYPE 1: - Member M1 is to be welded to member M2;

TYPE 2: - Member M1 is to be welded to member M3;

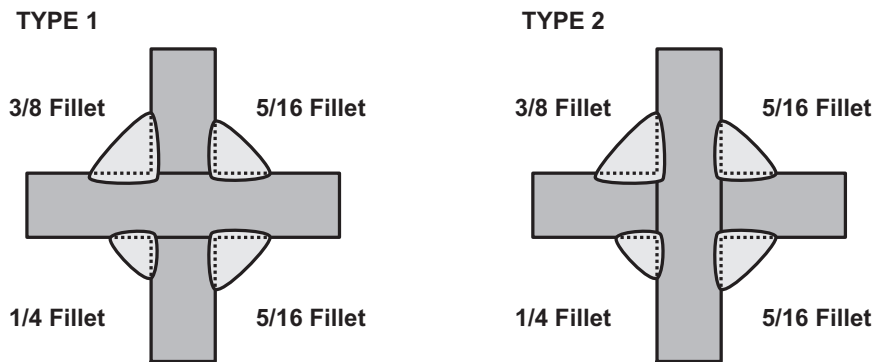
the common areas of contact and, therefore, the joint must be as shown.



Each pair of symbols calls correctly for the same weld.

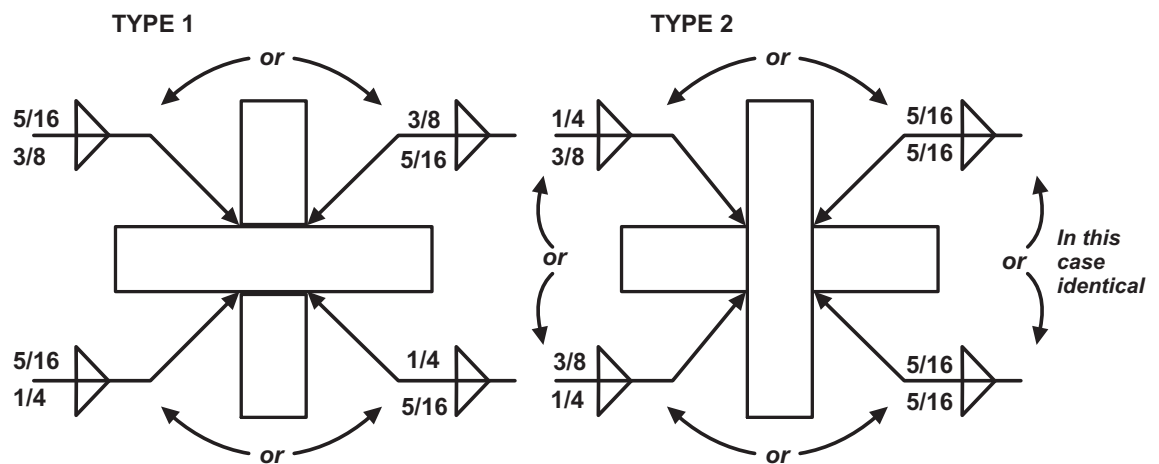
EXAMPLE 3

CRUCIFORM JOINTS SIMILAR TO THOSE IN EXAMPLE 2
BUT WITH FILLET SIZES SPECIFIED FOR EACH CORNER



Desired Welds
showing *identical* arrangement for each type

The correct double fillet welding symbols for each type, respectively, will be:



Appropriate Symbols
for the Desired Welds

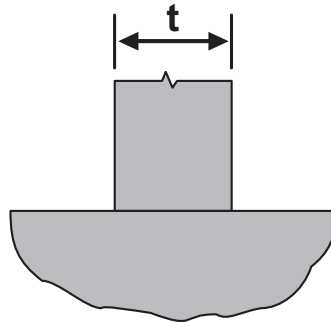
Either metric or imperial measurement may be applied

EXAMPLE 4

GROOVE WELD IN A T-JOINT

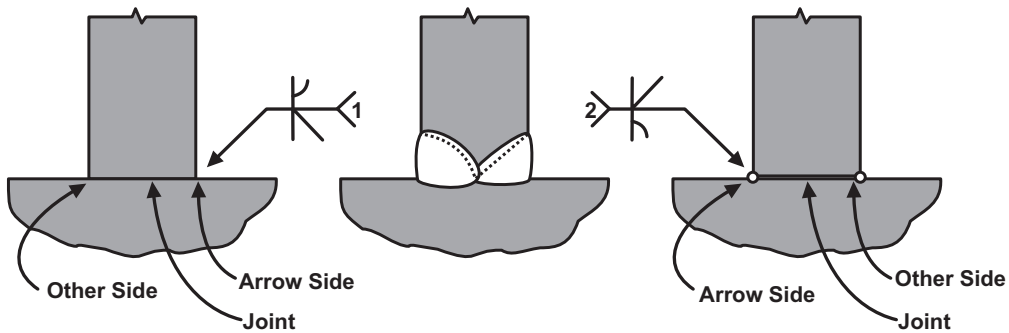
Required a combined
Bevel- and J-Groove Weld

(A hypothetical requirement
considered only for the
purpose of the exercise)



Assuming half a thickness preparation for each type of groove, the alternatives are:

ALTERNATIVE 1:



SYMBOL 1

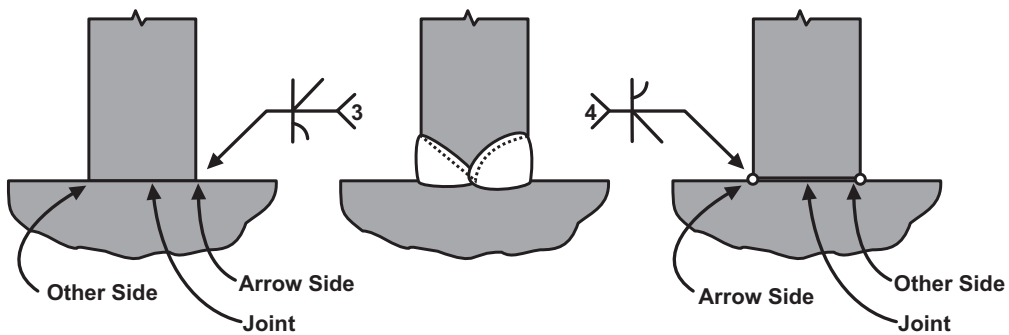
indicates bevel preparation from
Arrow Side and "I" preparation
for the *Other Side*

WELD

SYMBOL 2

Identical preparation of the joint
can be obtained using Symbol 2

ALTERNATIVE 2:



SYMBOL 3

indicates "J" preparation from the
Arrow Side and Bevel preparation
for the *Other Side*

WELD

SYMBOL 4

Identical preparation of the joint
can be obtained using Symbol 4

3.10 Supplementary Weld Symbols

As seen from **Figure 3.26**, supplementary weld symbols are used to convey specific requirements. One can again observe that their graphic designations bear a very close visual likeness to the effect they mean to achieve.

3.10.1 Field Weld Symbol

Welding in the field is generally understood to mean welding in a place other than that of initial construction. The erection phase of welded construction work will most likely involve welding in the field, or on site, as some may refer to it.

The weld symbol designating welding in the field must show a flag placed above and at right angle to the reference line at the junction with the arrow. The direction of the arrow is left optional. However, some may prefer to point it away from the arrow.

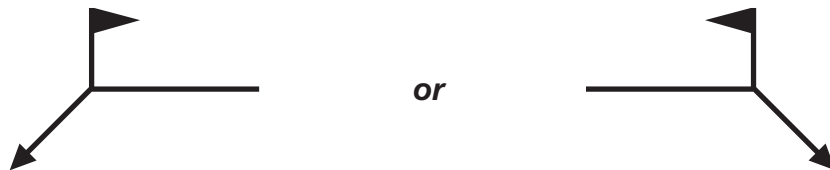


Figure 3.30

3.10.2 Melt-thru Symbol

Occasionally, there are conditions in a joint in which full or complete joint penetration is required that permit welding only from one side. As a visible manifestation of such penetration, a reinforcement may be specified for the other side.

This reinforcement may be conveniently expressed by a melt-thru symbol, together with its required height, or without it when a specific height is of no significance.

3.10.3 Contour Symbol and Finishing of Welds

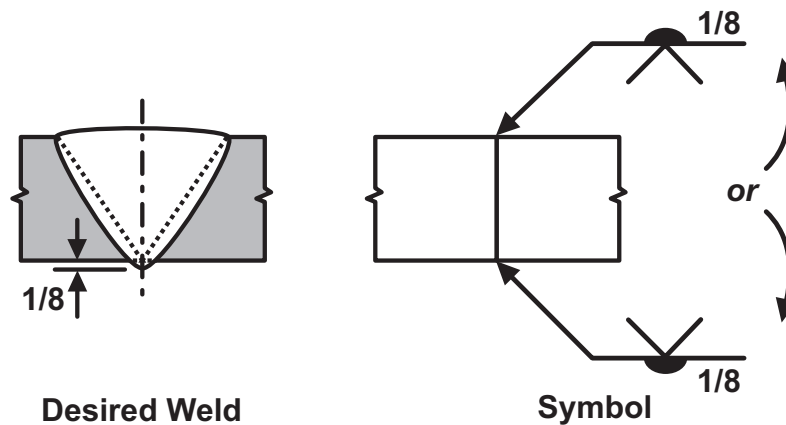
Sometimes it is required to specify the contour of the weld surface. It is important for certain structures or mechanical components to minimize stress concentrations. When mechanical means are intended to obtain the desired contour, the supplementary contour symbols should be used with the user's preferred mechanical means specified to obtain it.

The required contour of welds may be obtained without recourse to mechanical means. However, if such means are necessary to produce the required finish, the appropriate letter designation assigned to the following methods of finishing must be added to the contour symbol. It must be understood that these designations specify the method and not the degree of finish.

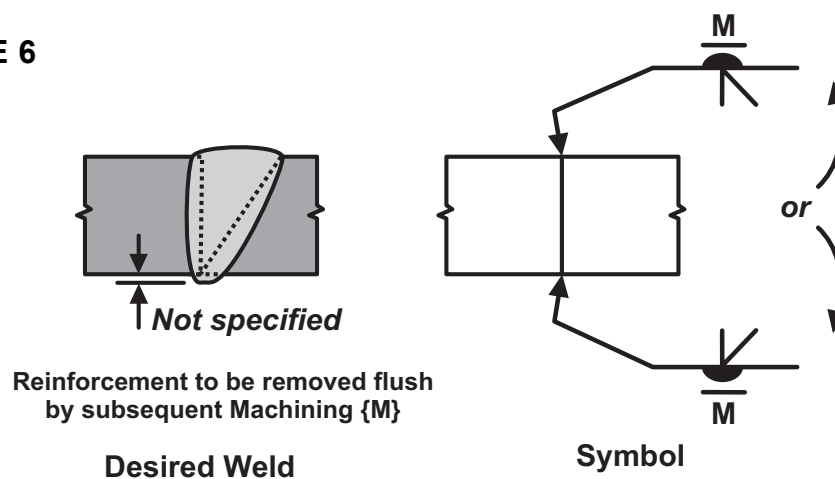
C – Chipping	G – Grinding
M – Machining	R – Rolling
H – Hammering	

The following sketches will illustrate these provisions:

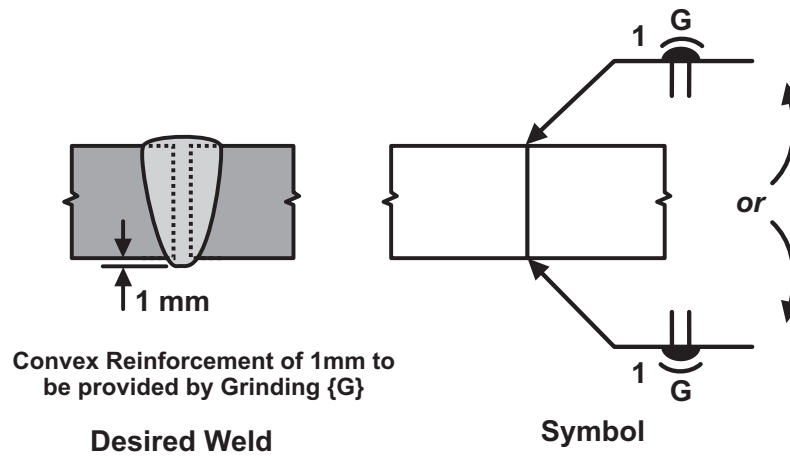
EXAMPLE 5



EXAMPLE 6



EXAMPLE 7



3.10.4 All-Around Weld Symbol

The all-around supplementary symbol must be shown in the welding symbol when a circumferential weld is required and abrupt changes in the direction of welding are involved. This procedure is well illustrated in the case of a hollow structural section (HSS), rectangular in profile and welded to a base plate.

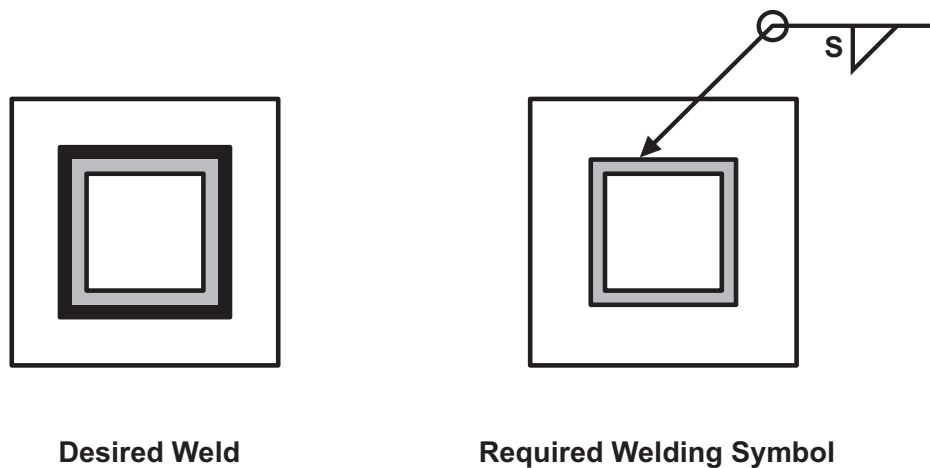
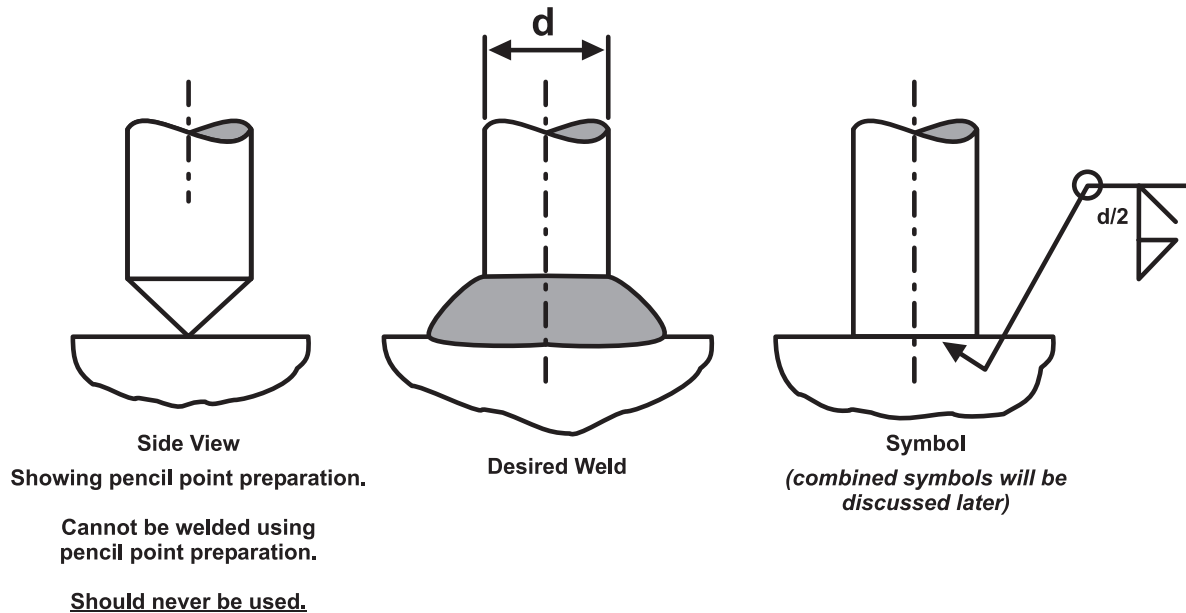


Figure 3.31

EXAMPLE 8

A ROUND BAR SIMILAR TO EXAMPLE 8 WELDED TO A BASE PLATE



3.11 Break in Arrow

In most cases of groove welds, both members to be joined require some form of preparation. Hence, the use of an ordinary welding symbol with an ordinary straight-line arrow is entirely satisfactory. However, such is not the case with groove welds requiring the preparation of only one member in the joint. If the preparation of one specific member is of importance, the welding symbol must have positive means to identify this member.

This is conveniently done by a break in the arrow, with the arrow pointing in the direction of the member to be chamfered.

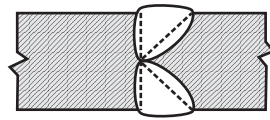
It should be noted that the arrow need not touch this particular member. The only matter of importance is the direction in which the arrow points (to the left or to the right).

The arrow need not be broken if the welding symbol is not used to specify which members have to be prepared. There are, of course, situations in which only one member can be prepared, in which case a break in the arrow is superfluous.

The following examples will illustrate the point.

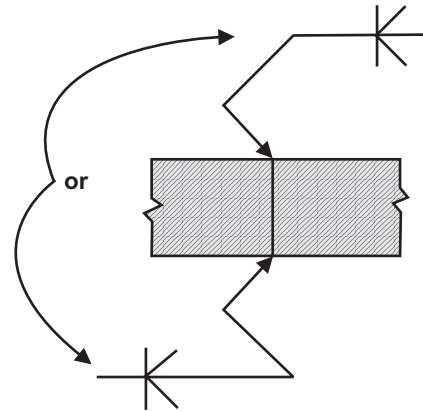
EXAMPLE 9

DOUBLE-BEVEL-GROOVE WELD IN A BUTT JOINT WITH THE CHAMFERED MEMBER SPECIFIED



Desired Weld

Preparation specified on the right-side member as shown

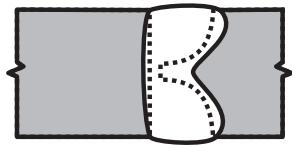
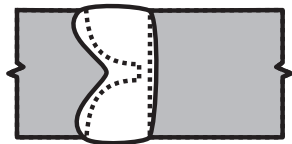


Symbol

The arrows point to the right member to be chamfered

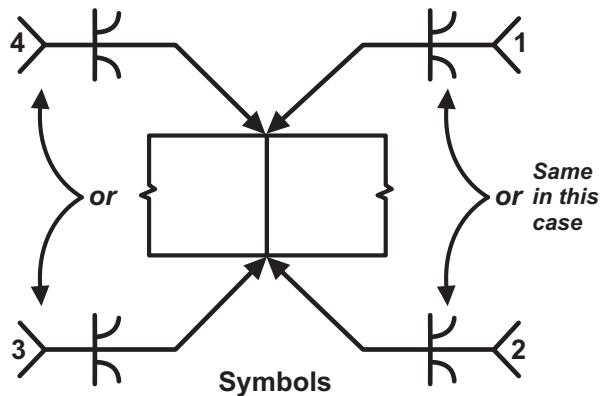
EXAMPLE 10

DOUBLE-J-GROOVE IN A BUTT JOINT WITH THE MEMBER TO BE CHAMFERED *NOT* SPECIFIED



Desired Weld

Either of the two are acceptable

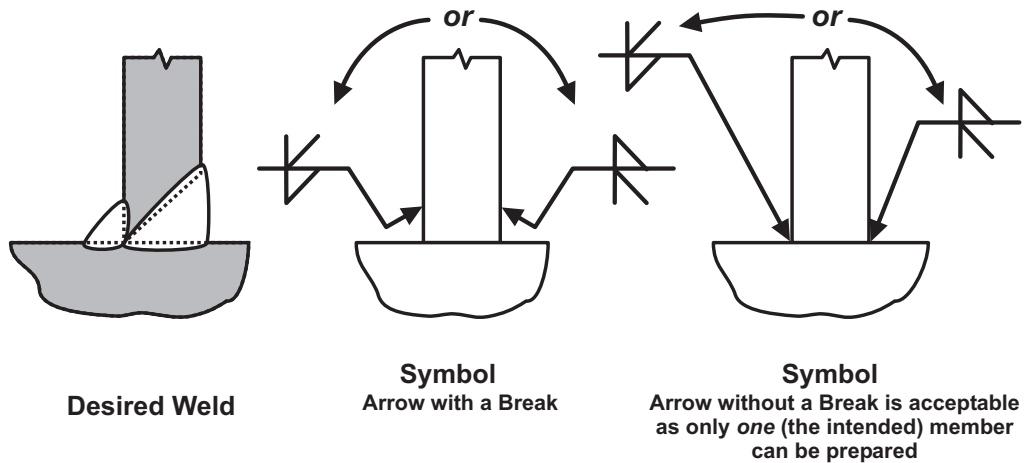


Symbols

Pointing the arrow to the left or to the right member as shown has *no significance* with regard as to which member is to be chamfered *because they are straight-line arrows without a break.*

EXAMPLE 11

SINGLE-BEVEL-GROOVE AND A FILLET WELD IN A T-JOINT



[As a matter of principal, it is recommended to use the arrow with a break]

3.12 Combined Weld Symbols

Normally, joints will require more than one type of weld symbol. Joints for which one type of weld symbol is sufficient are represented by welding symbols in **Figure 3.32**.

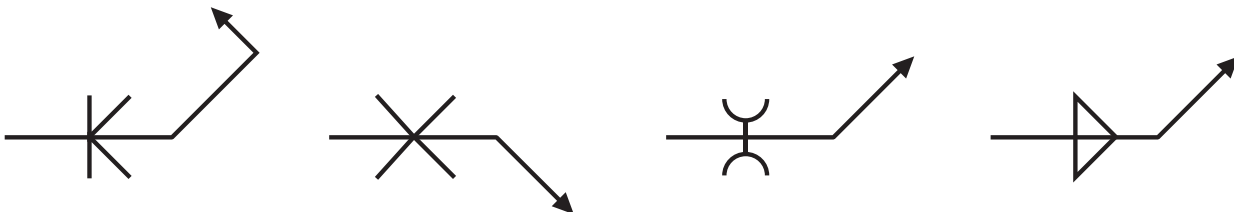


Figure 3.32

However, joints that require a combination of two or three different types of weld symbols are illustrated by the following welding symbols (**Figure 3.33**):

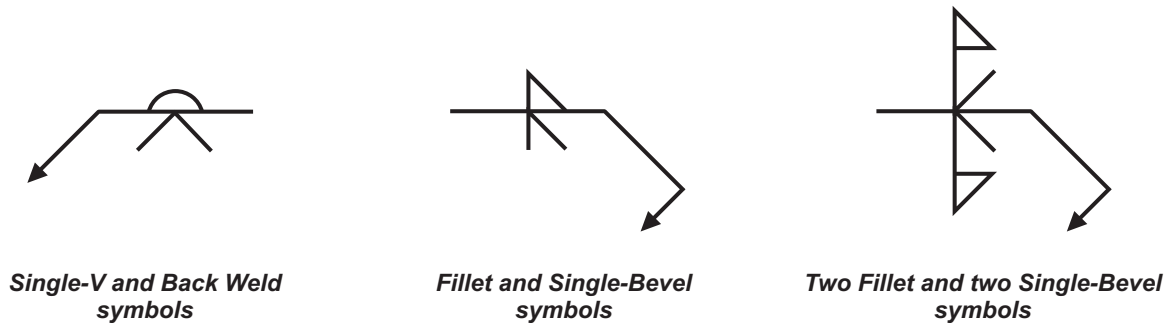
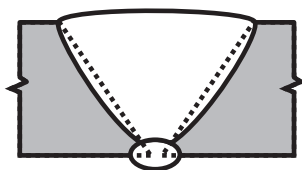


Figure 3.33

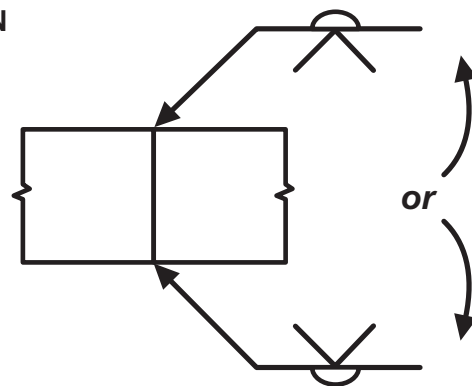
Each of the welds represented by the pertinent weld symbol must appear in the welding symbol, either in a single or in a combined arrangement.

EXAMPLE 12

A SIMPLE WELD SYMBOL COMBINATION



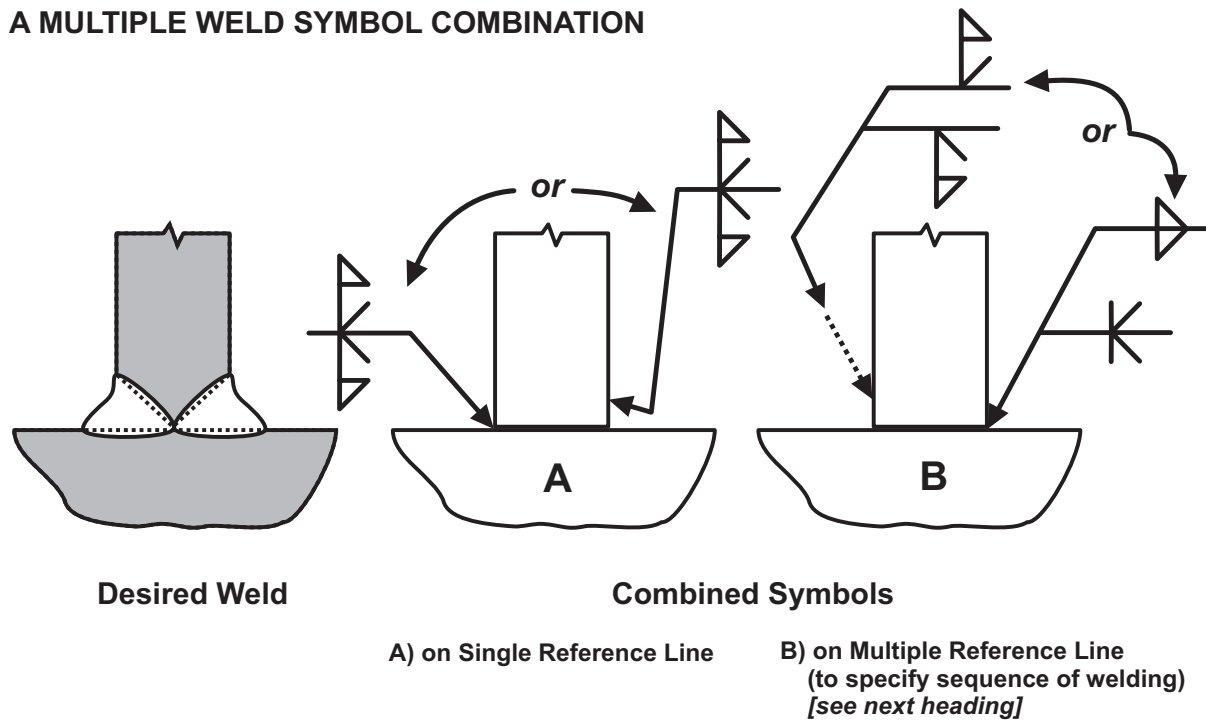
Desired Weld



Symbol
A combination of a V and
Back Weld symbols

EXAMPLE 13

A MULTIPLE WELD SYMBOL COMBINATION



3.13 Information in Tail of Welding Symbol

The tail of the welding symbol allows convenient placement of any type of information that will effectively complement the information conveyed by the other components of the symbol.

The conventions as used by individual companies and geared to their specific operations will have a great bearing on the type of information that each of them will consider sufficient in scope for their needs.

Such information may:

- 1) refer to a specific welding process, or
- 2) consist of a welding procedure specification number, or
- 3) show "typical" when the required weld is representative of all welds shown in the drawing

3.14 Extent of Welding Denoted by Symbols

When the length of a weld is not specified in the symbol, the welded length is the one between abrupt changes in the direction of welding.

The length of weld may also be designated by a dimensional length of hatching.

As its name implies, the all-around welding symbol specifies the weld all around the joint, regardless of the number of planes involved.

The section on fillet welds reviews all of the above variations to the extent of welding, as covered by a welding symbol with or without supporting dimensioning.

When intermittent welds are required in the length of a joint, they should be dimensioned by the welding symbol in a manner as shown and thoroughly discussed in the section on fillet welds.

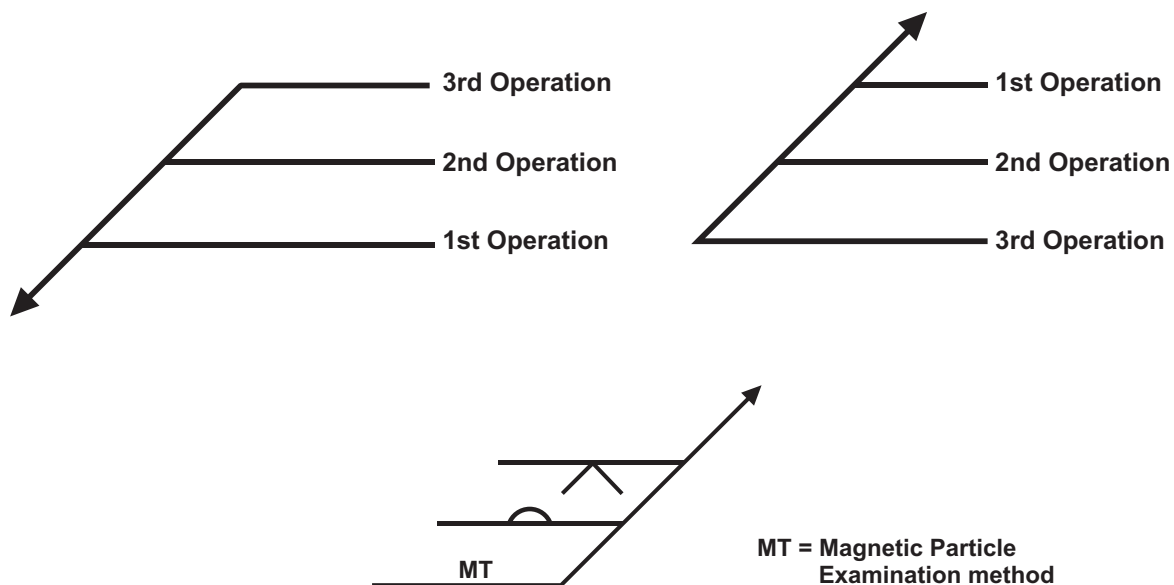
Groove welds are normally continuous for the full length of the joint, in which case no reference to length is needed in the welding symbol.

3.15 Multiple Reference Lines

The very objective of the multiple reference line concept is to give the welding symbol the added capability to specify the sequence of welding operations as well as to provide additional information relative to the examination of welds or other operations.

Two or more reference lines are feasible. They should, however, be used with good judgment.

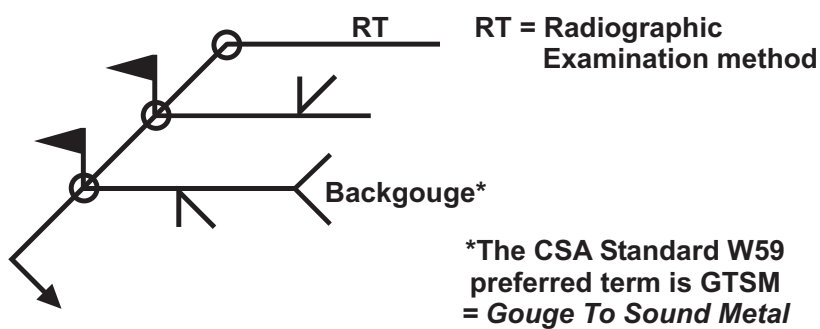
The rule that applies to sequencing is very clear. It states that the operation that is desired first is to be shown on the reference line closest to the arrow. All subsequent operations are to follow the same sequencing order as the pertinent reference lines move away from the arrow. The welding symbol shown in **Figure 3.34** explains this principle:



Sequence: 1) weld single-V on arrow side,
2) weld back-pass on other side,
3) inspect other side, using MT method.

Supplementary symbols may also be used as applicable.

Figure 3.34



Sequence: 1) weld the all-around arrow-side bevel-groove in the field;
2) back-gouge from the other side (in the field, obviously);
3) complete the all-around "other side" bevel-groove weld in the field
4) inspect, in the field, the whole weld using the radiographic examination method.

Figure 3.35

3.16 Complete Penetration

Where complete joint penetration (that is penetration equal to the thickness of material) is to be obtained with no regard to the type of weld and joint preparation, the letters CJP must be shown in the tail of the welding symbol.



Figure 3.36

The definition of complete joint penetration groove welds may vary from one governing design standard to another. Important observations on this subject are offered in the section on groove welds.

When a sequence is to be specified for a joint defined by the following welding symbol...

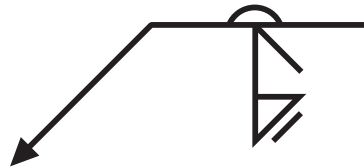


Figure 3.37

then these sequencing alternatives may be considered:

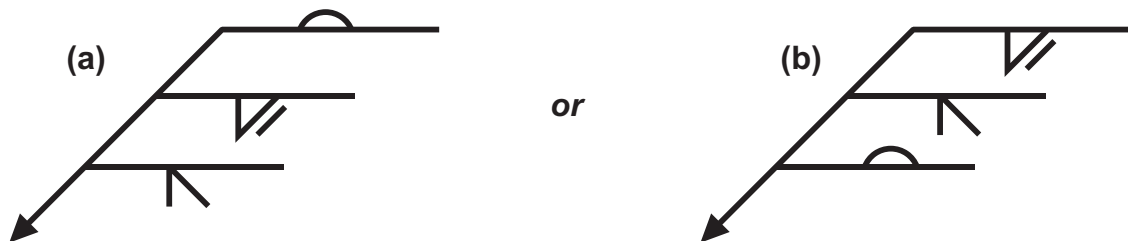


Figure 3.38

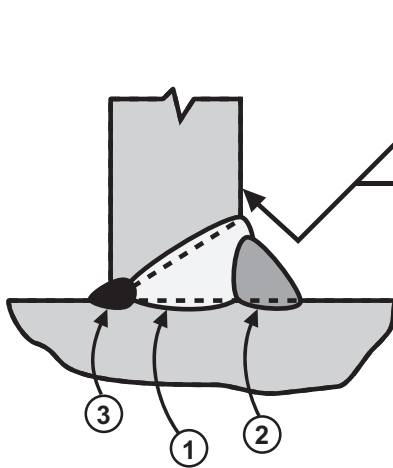
The specified sequence for each case is shown as follows:

Sequence (a)

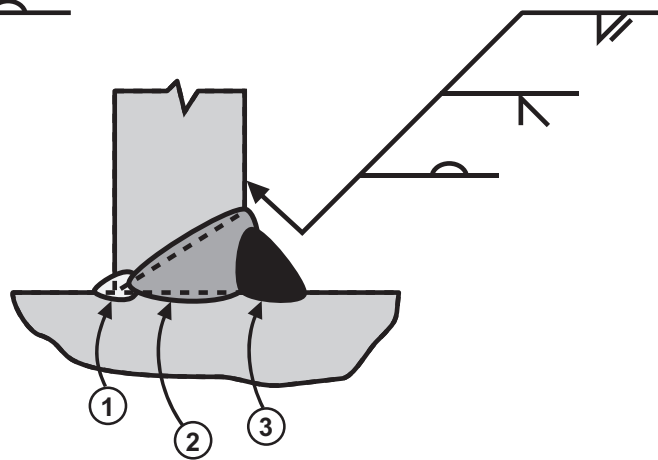
- | | | |
|----|-------------------|------------|
| 1) | weld bevel-groove | arrow side |
| 2) | weld flat filler | arrow side |
| 3) | weld back pass | other side |

Sequence (b)

- | | |
|-------------------|------------|
| weld backing pass | other side |
| weld bevel groove | arrow side |
| weld flat fillet | arrow side |



Desired Weld and Sequence



Desired Weld and Sequence

Figure 3.39

Weld examination requirements may also be placed on the second or third reference line – as, obviously, the first or the first two lines must provide a weld that can then be examined.

3.17 Groove Welds

3.17.1 Location of Dimensions for Single-Groove Welds

Although **Figure 3.27** shows the location of all the standard elements for any type of weld, including a groove weld, it will be of advantage to extract from that figure all those elements that specifically apply to grooves.

Since there are many types of grooves, with each assigned its own weld symbol, as evident from **Figure 3.25**, specific and comprehensive information must be provided in the welding symbol to accurately describe the required preparation and fit-up of the two members in the joint.

Besides the applicable weld symbol for the pertinent type of groove, the additional information will have to define:

- 1) The depth of preparation – also described as the depth of chamfer – from each side of the joint (arrow side and other side), and normally designated by the capital letter “S”.
- 2) The angle at which such preparation should be made, also referred to as angle of chamfer, but officially termed the bevel angle.
- 3) The root opening required for proper fitting of the two members in the joint. Its primary objective is to provide adequate access for welding. It may be used with other related factors in the joint for greater welding economy.

The location of these elements in the welding symbol for single grooves is shown in **Figure 3.40**.

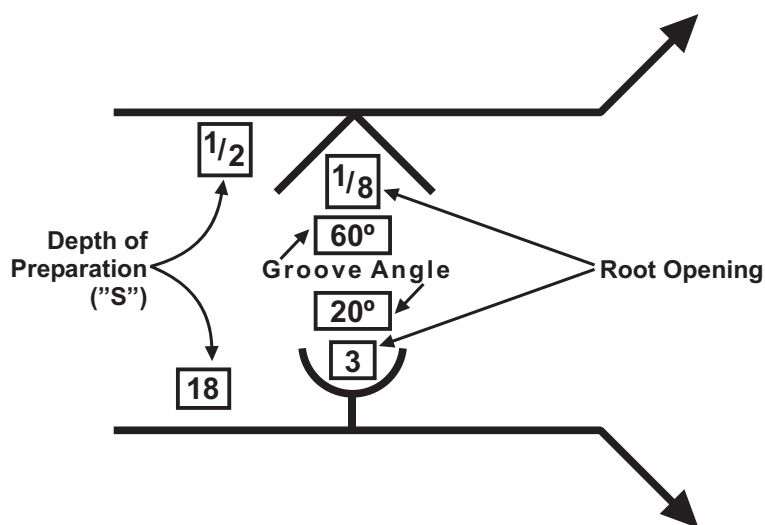


Figure 3.40

3.17.2 Dimensions for Double-Groove Welds

In line with the general principle, and irrespective of its appearance on one or both sides of the reference line, each weld symbol must be accompanied in the welding symbol with all the data necessary for the preparation, fit-up and execution of welding.

The principle applies to all double-groove welds, and it makes no difference whether the data is identical on each side of the reference line or not. However, the size of the root opening, being common to both sides, need only appear once.

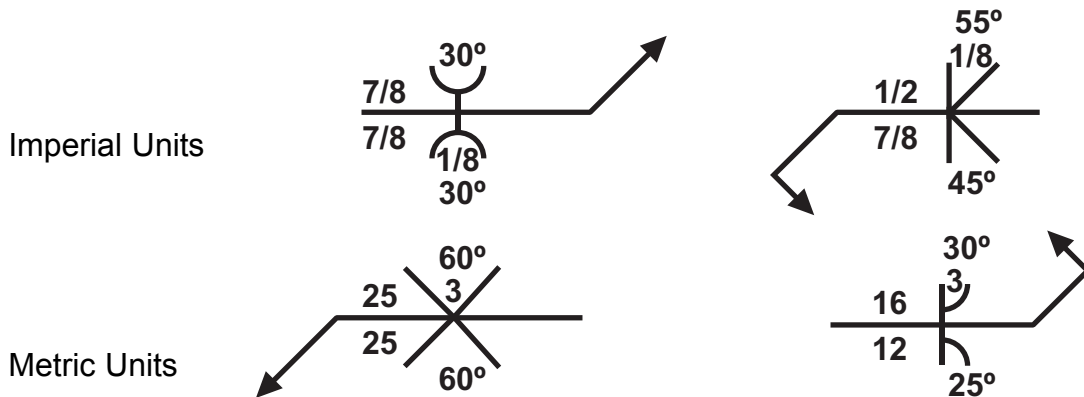


Figure 3.41

The angle with respect to application in the symbol is the groove angle which, for bevel- and J-grooves, will also be the bevel angle. However, it is the groove angle (the angle contained between the fusion faces of the groove) that appears in the welding symbol.

The angle at the root of the joint associated exclusively with J- and U-grooves has strong design implications, as the governing specifications make the applicable effective throat of welds in such grooves a function of this particular angle.

In conjunction with this angle, it should also be noted that the minimum groove radius for the J- and U-grooves is given in CSA W59 and AWS D1.1 for prequalified joints.

Example

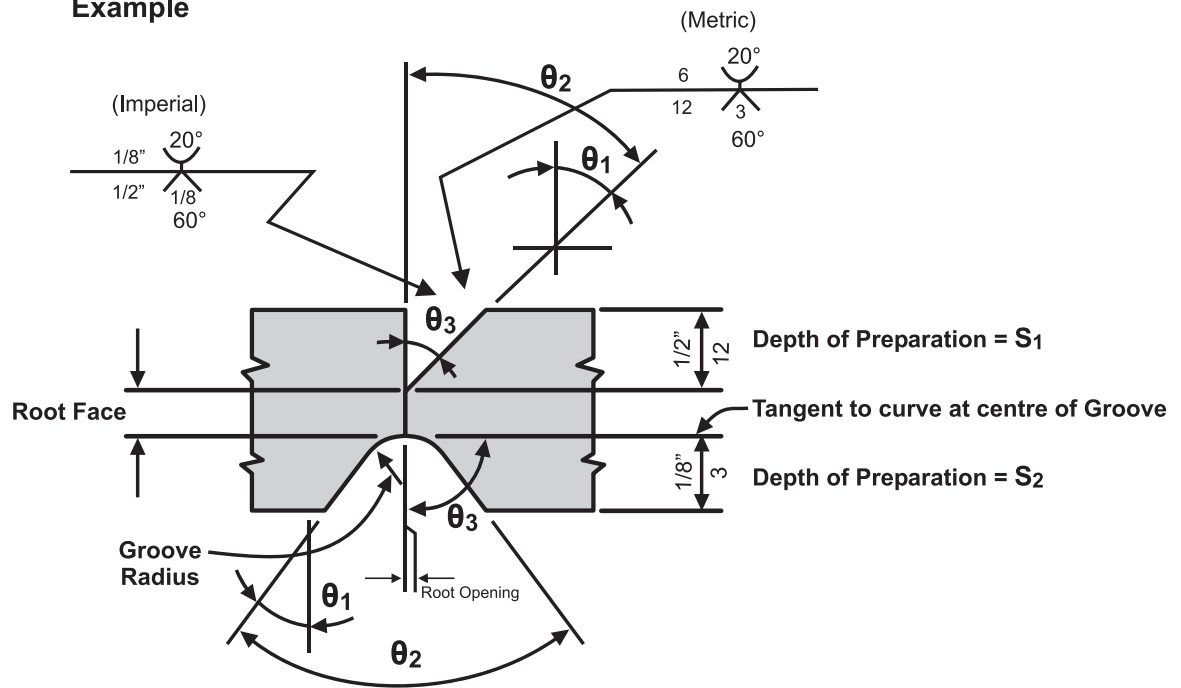


Figure 3.42

There are three basic angles in the joint (**Figure 3.42**), and they are part of every groove except the square groove.

- | | | | |
|----|--|---|--------------|
| 1) | BEVEL ANGLE
(official AWS A3.0 term
or
Angle of Preparation
or
Angle of Chamfer | } | $= \theta_1$ |
| 2) | GROOVE ANGLE | | |
| 3) | ANGLE AT THE
ROOT OF THE GROOVE | } | $= \theta_3$ |

For the U-groove, all three angles have different values with θ_2 being twice that of θ_1 .

For the bevel-groove, however, all the angles have the same value: $\theta_1 = \theta_2 = \theta_3$.

3.17.3 Depth of Preparation and Groove Weld Size

The AWS A2.4 specification has introduced the groove weld size (E) as a quantity to be shown in the welding symbol for groove welds.

The specification ruled at the same time that this new quantity should:

- 1) appear in brackets: (E), and
- 2) be located on the right side of the depth of preparation “S” and so share with it a common location in the welding symbol

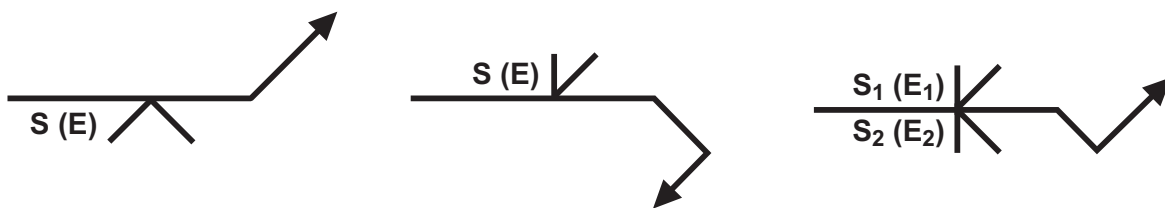


Figure 3.43

The term “throat of a groove weld”, while previously an acceptable term, is now considered a non-standard term for groove welds size.

Unfortunately, the weld size as defined in the AWS A2.4 specification purely from the point of view of logical symbol application, need not necessarily be the same – and in many cases it is not – as the weld size defined in the governing standards for design application.

Therefore, caution must be exercised and appropriate distinction made when referencing weld sizes under the jurisdiction of one specification as compared with another.

While the application of the groove weld size concept is quite straightforward and offers a clear advantage in a number of applications, this advantage is less visible and even confusing in others. A more elaborate discussion on the subject will follow later.

First, let's explore what is meant by groove weld size according to AWS A2.4 specification, and how that size relates to depth of preparation. Both are independent quantities. However, the magnitude of (E) relates strongly to the root geometry of the joint, the welding process and the parameters of the welding procedure (see **Figure 3.44**).

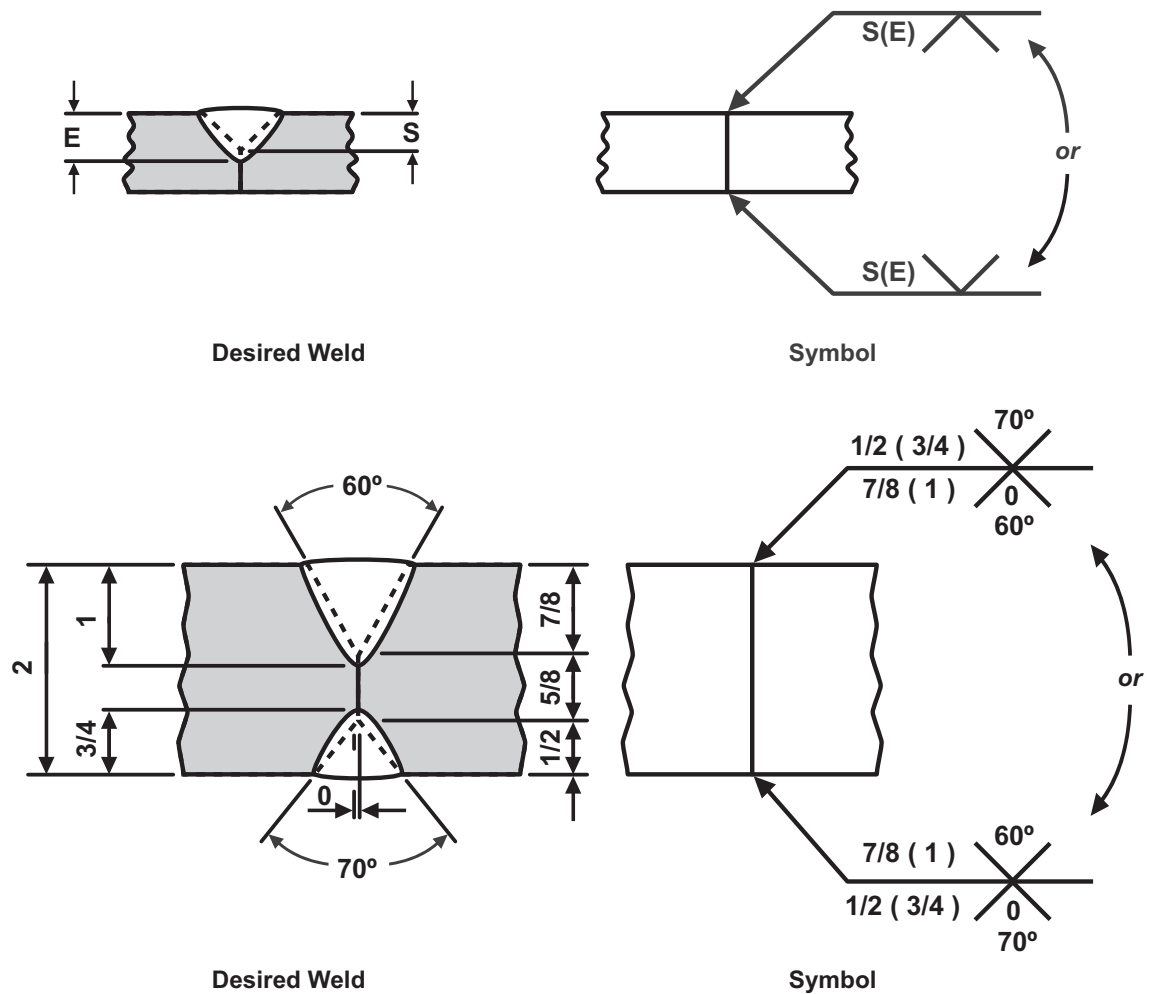


Figure 3.44

The quantity (E) is measured from the top of the plate to the furthest point where the weld penetrates the joint. The AWS A3.0 specification defines this as joint penetration.

The value of (E) may be greater than " S " as shown in **Figure 3.44**. However, it may also be smaller than " S " as shown in **Figure 3.45**.

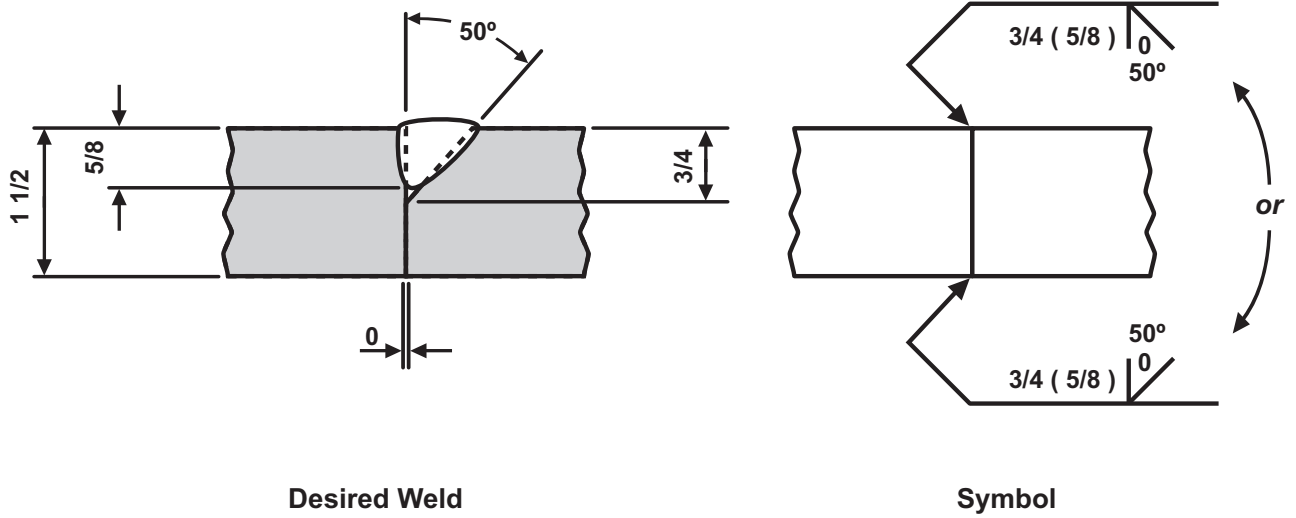


Figure 3.45

3.17.4 Flare-Groove Welds

There are two basic types of flare-groove welds:

As shown in Figure 3.46, the weld symbols for these grooves also reflect the shape of the joint that contains them.

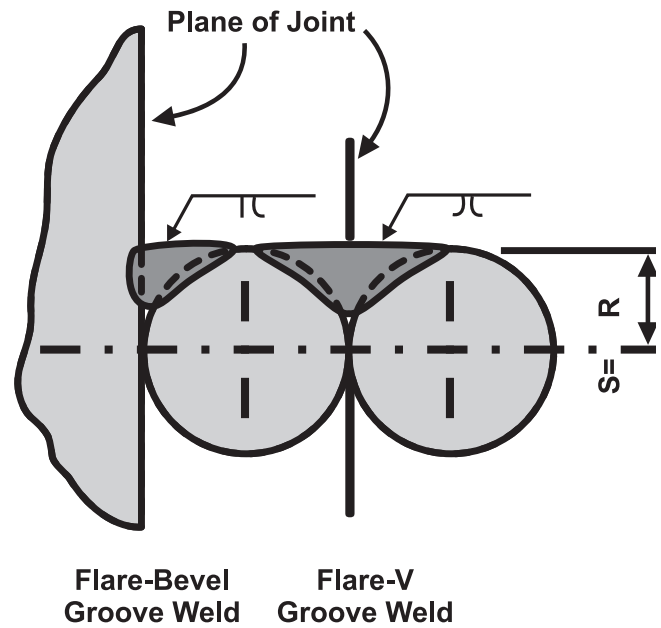
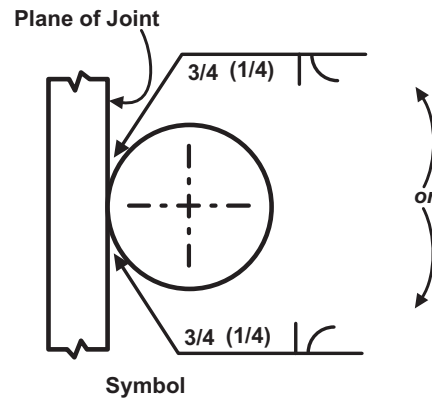
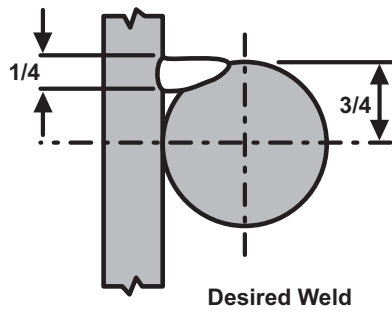


Figure 3.46

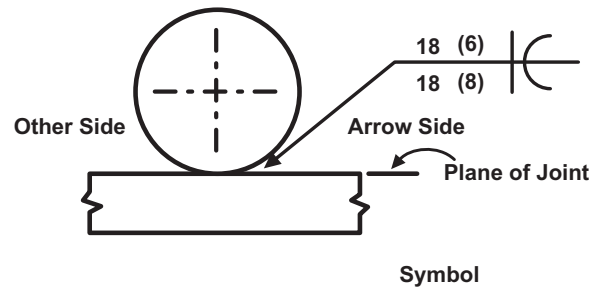
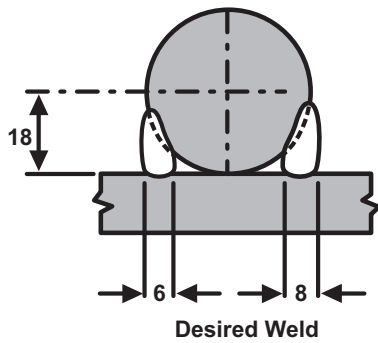
EXAMPLE 14

FLARE-BEVEL-GROOVE WELDS

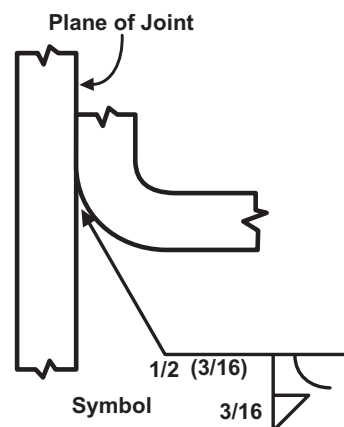
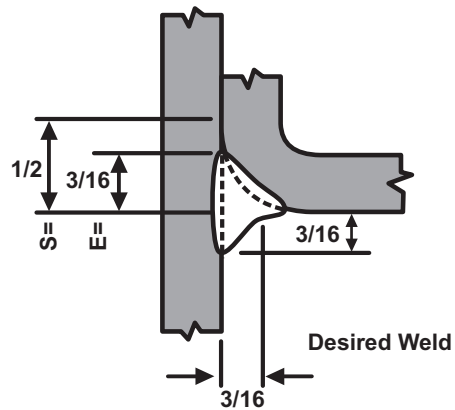
(a) *Single-Flare-Bevel-Groove Weld*



(b) *Double-Flare-Bevel-Groove Weld*

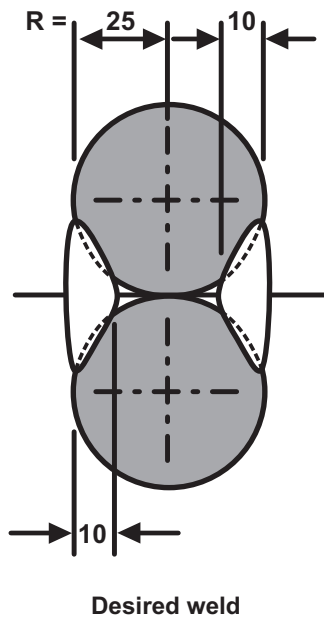


(c) *Single-Flare-Bevel-Groove with a reinforcing Fillet Weld*

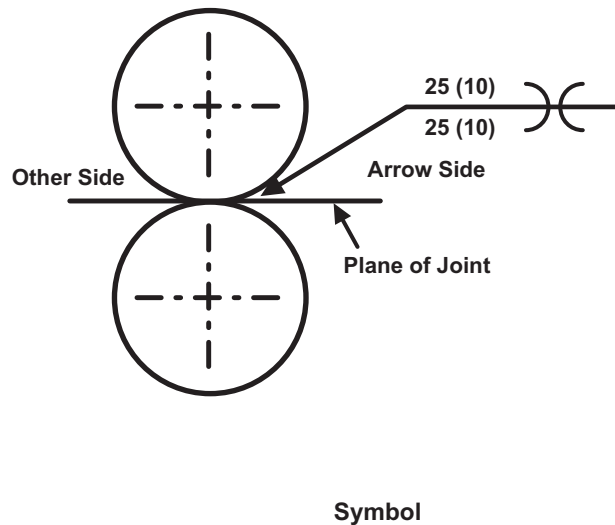


EXAMPLE 15

FLARE-V-GROOVE WELDS



Horizontal Lap Splice of two round Bars of the same size



3.17.5 Surface Finish and Contour of Groove Welds

The desired contour of groove welds may be obtained naturally or with recourse to mechanical means, these being left to the discretion of the user.

The series of welding symbols in **Figure 3.47** shows the correct application of the required supplementary symbols.

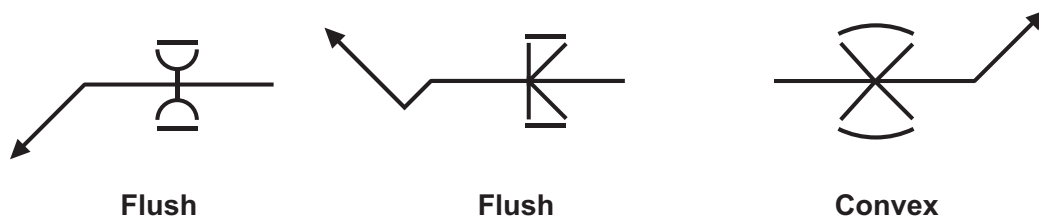


Figure 3.47

The most common contour for groove welds is the flush contour, and this is in view of its expectedly better performance in service. To further improve that performance, a mechanical finish may be considered and indicated in **Figure 3.48**.

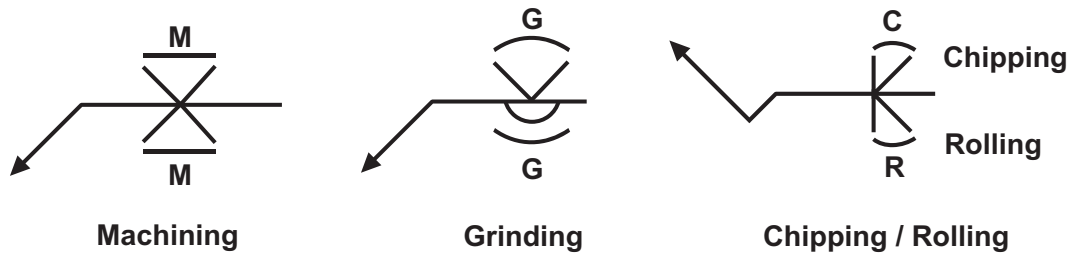


Figure 3.48

3.17.6 Joints with Backing

Joints with backing are joints welded from one side. Such welds must be considered where there is no access for welding from the other side or where, if such access is feasible, the more skill-demanding and less-productive welding in overhead position, or welder discomfort, will dictate their use.

The welding symbol designating a groove with backing shows the groove and the supplementary backing symbols (**Figure 3.49**).

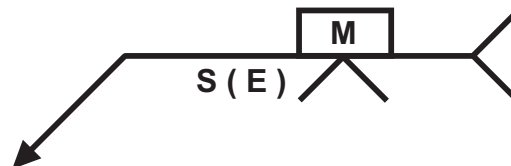


Figure 3.49

It should be noted that the supplementary symbol for backing is a rectangle while that for consumable inserts is square in shape.

1. The type of backing material must be identified, and such identification (by means of an assigned letter) must appear inside the rectangle of the supplementary backing symbol.



Designating a material in general terms

2. The direction to remove the backing, if required, must also be placed in the rectangle, using the letter "R" for removal.

MR

3. The dimensions of the backing must be specified in the tail of the symbol or elsewhere in the drawing.

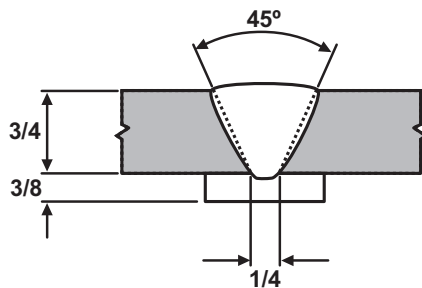
Many materials are successfully used as backing materials. As stated, they must be identified in the symbol. For the purpose of explanatory examples, only steel (S) will be used.

For joints in which there is no fusion into the backing material, the removal of such material need not be specified in the symbol.

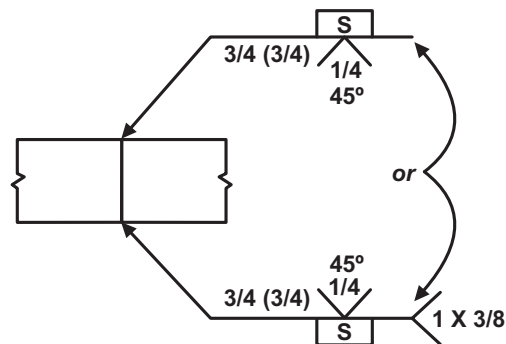
Joints with backing will be joints with complete penetration.

EXAMPLE 16

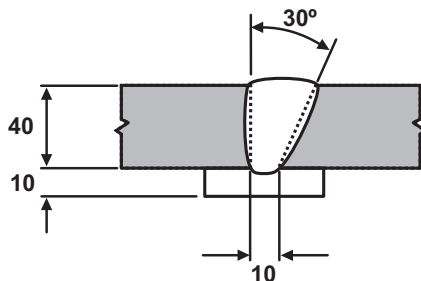
JOINTS WITH BACKING



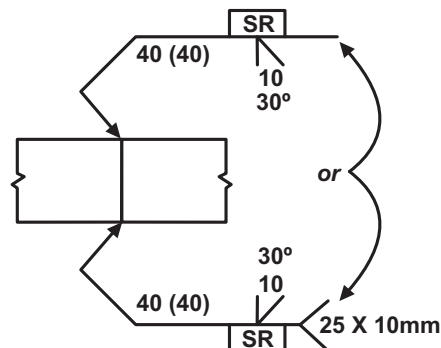
Desired Weld



Symbol



Desired Weld
(Backing to be removed)



Symbol

3.18 Fillet Welds

Fillet welds are the most commonly used type of weld in welding fabrication. It does not require special joint preparation, like bevel cutting. A fillet weld joins two surfaces, usually, but not always, at right angles to each other. Fillet welds are used to make lap joints, T-joints or corner joints. The profiles of fillet welds and the associated terms are shown in **Figures 3.50 and 3.51**. These are equal leg fillet welds.

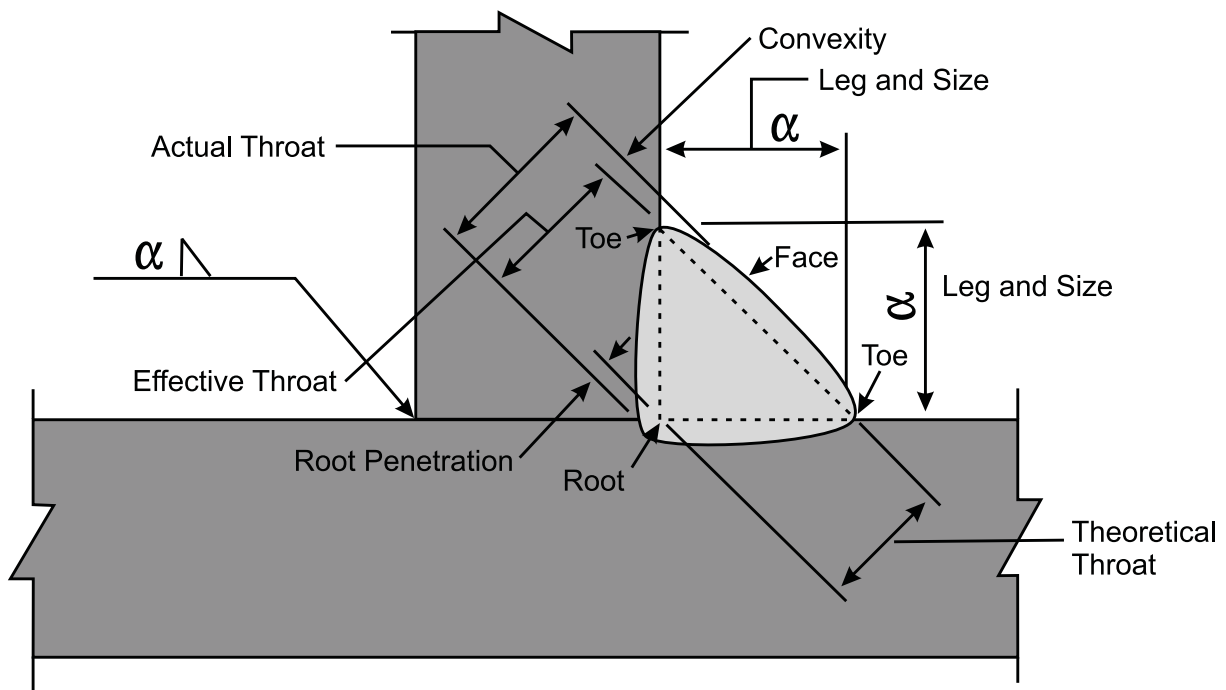


Figure 3.50: Convex Fillet Weld

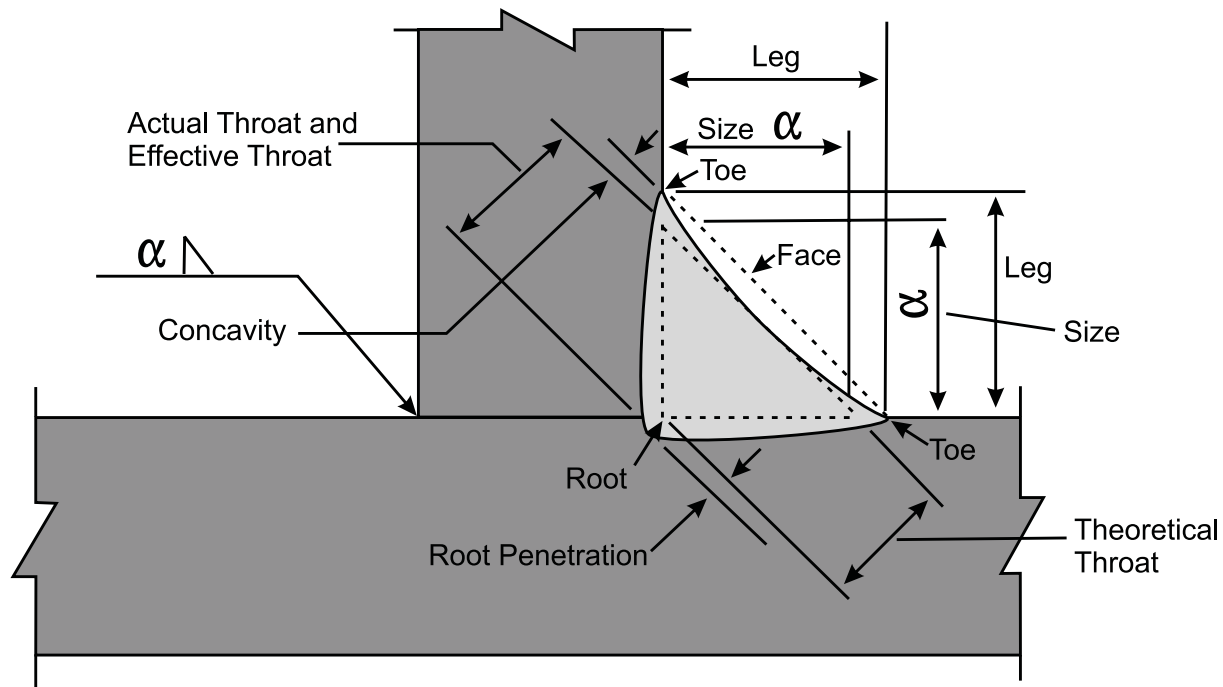


Figure 3.51: Concave Fillet Weld

In **Figures 3.50 and 3.51**, all the terms are self explanatory. The term “Effective Throat” is the shortest distance measured from the root of the weld to its face, less any reinforcement. Also, it should be noted that the root penetration is only considered as part of the effective throat for fillet welds made by the submerged arc welding process. This is stated in the CSA W59 Standard (Clause 4.3.2.4). In some standards or codes, the root penetration is not considered.

3.18.1 Symbols of Fillet Welds

The composition of welding symbols for fillet welds is governed by a number of explicit rules. For proper application of such welds in welded fabrication these rules require that the following information be shown at designated locations in the welding symbol unless specific general notes covering standard dimensions of fillet welds appear elsewhere on the drawing. Also, see **Examples 2 and 3** given on pages 3-28 and 3-29 for the correct ways of placing symbols to a cruciform joint.

1. *The Fillet Weld Symbol*

Rule: The vertical side of the triangle representing the weld symbol must always be on the left side from the reader's viewing position as shown in **Figure 3.52**.

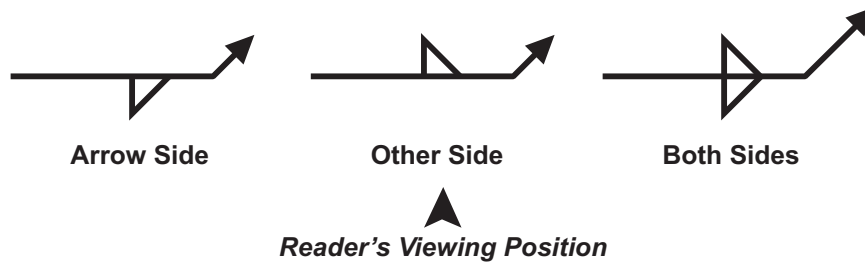


Figure 3.52

2. *Location of Fillet Weld Size*

Rule: The size must be shown for each weld symbol and must always appear to the left of each weld symbol as shown in **Figure 3.53**.

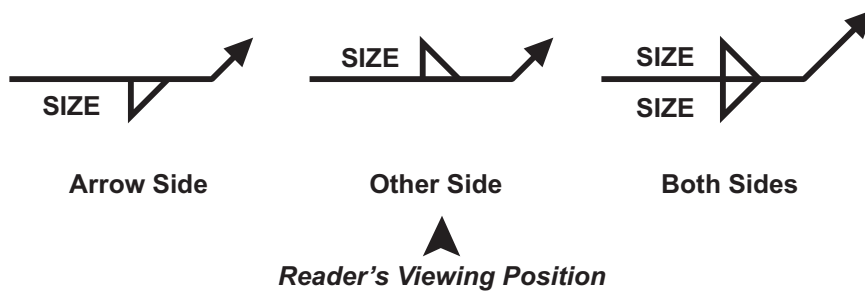


Figure 3.53

3) *The Length of the Fillet Weld*

Rule: The length must be shown for each weld symbol and must always appear on the right side of each weld symbol as shown in **Figure 3.54**. Absence of a specified length designates a length defined by the side of the joint between two points of abrupt change.

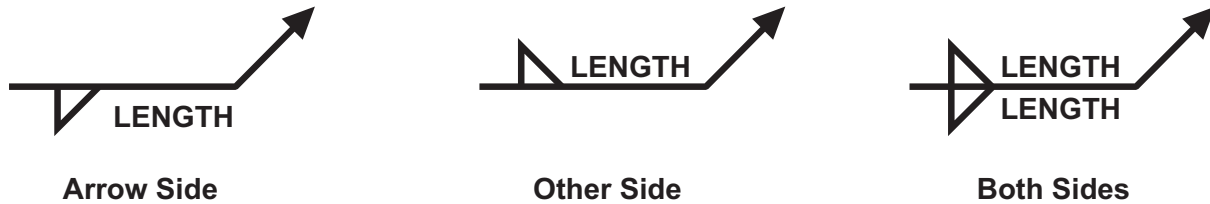


Figure 3.54

Depending on the specific conditions or requirements for a given application, additional use may be made of the following supplementary symbols:

1. *Weld All Around*

Symbol represented by a circle placed at the junction of arrow line and reference line (**Figure 3.55**).

2. *Field Weld*

Symbol represented by a flag with its direction optional but preferably pointing away from the arrow and placed at the junction of arrow line and reference line (**Figure 3.55**).

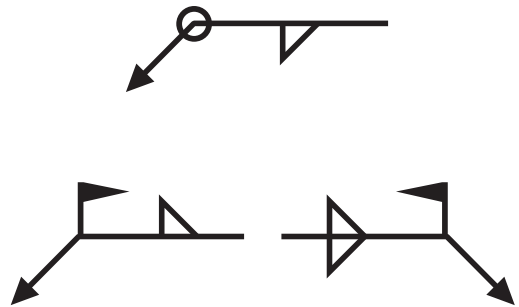


Figure 3.55

3. Contours

Contours may be obtained in either one or two ways:

- a) with no application of mechanical means (**Figure 3.56**)

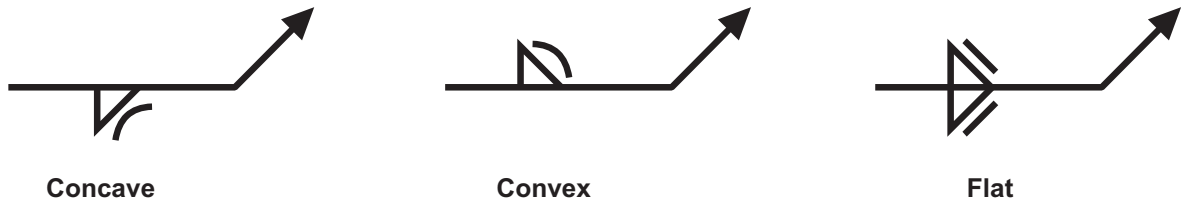


Figure 3.56

- b) with application of mechanical means (**Figure 3.57**)

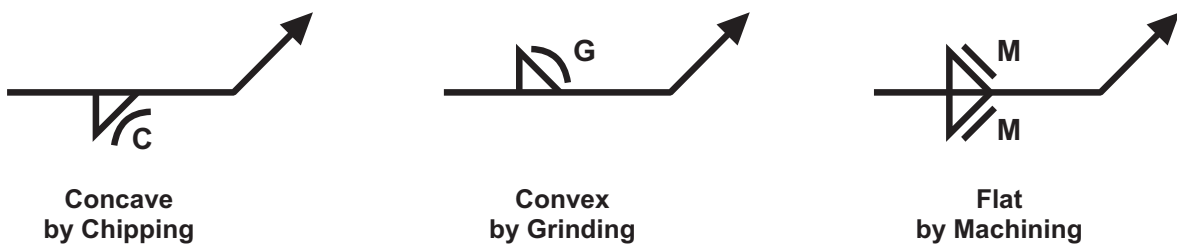


Figure 3.57

4. References

The designated location for reference is the tail of the welding symbol (**Figure 3.58**).



Figure 3.58

3.18.2 Size of Fillet Welds – Equal Leg Fillet Welds

The strength of a fillet weld is governed by both the fillet size and the effective throat thickness. The fillet size is the length of the side of the largest triangle that can be inscribed within the weld cross-section as shown in **Figures 3.50 and 3.51**. For equal leg convex fillet welds, the measured leg size is the fillet size as shown in **Figure 3.50**. For equal leg concave fillet welds, the fillet size is the side of the inscribed triangle, or the theoretical effective throat multiplied by 1.4 as shown in **Figure 3.51**.

- 1) The *Specified Size* is the size as it appears in the welding symbol and is designated by the letter “S”.
- 2) The *Effective Size* is the size that corresponds to the specified size and is designated by the expression “S effective” = “ S_{eff} ”.
- 3) The *Measured Size* is the size established on the basis of measurement and is designated by the term “S measured” = “ S_m ”.

These sizes for the following three types of fillet welds are as shown in **Figure 3.59**.

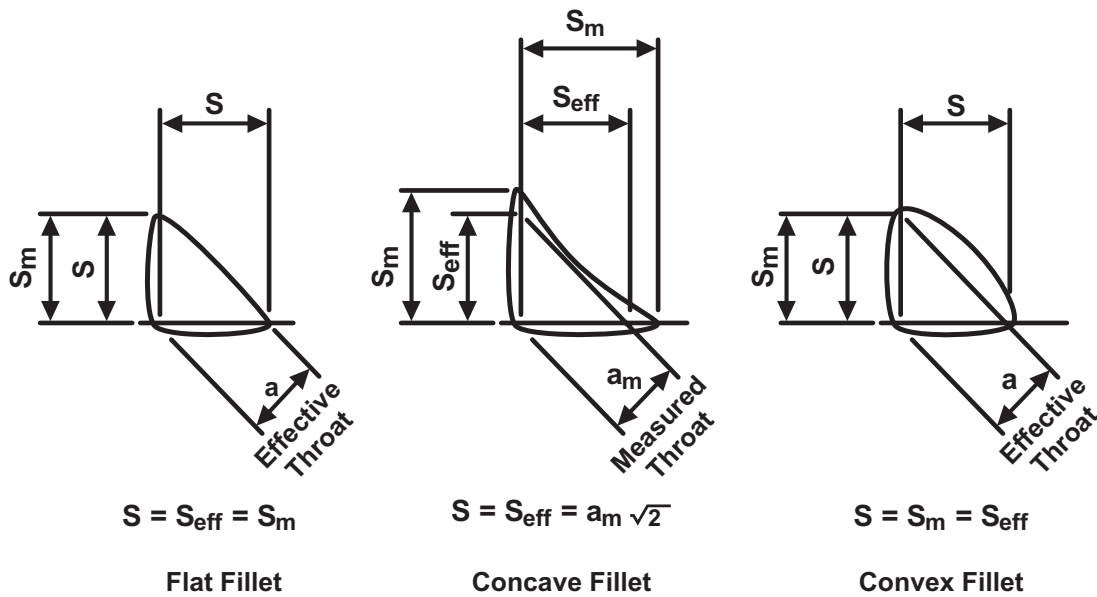


Figure 3.59: Size of fillet welds (equal legs).

Figure 3.60 shows a few examples of fillet weld sizes and symbols. The fillet size specified in the design must be the effective size.

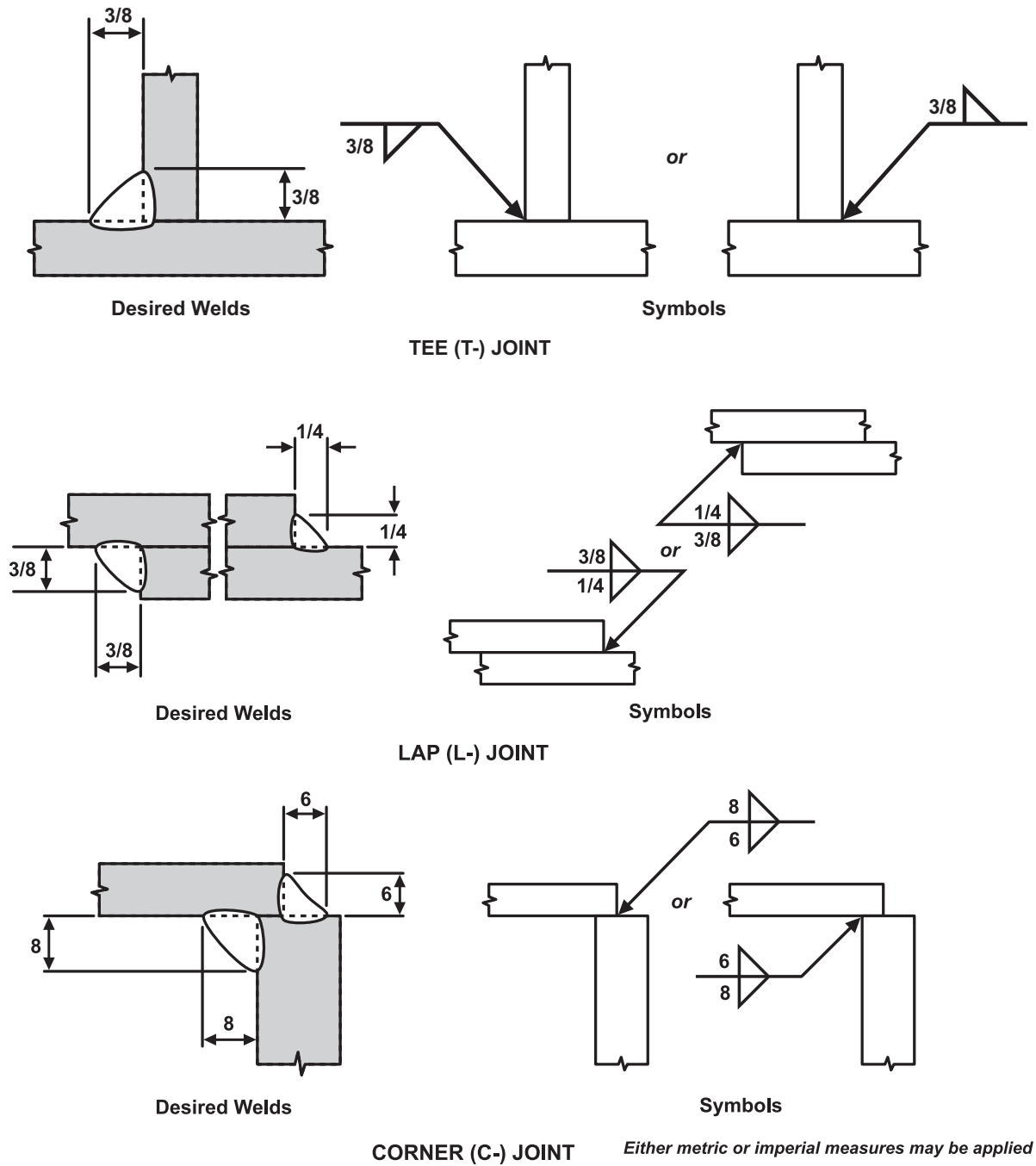


Figure 3.60: Fillet weld sizes and symbols.

It is of interest to note that in some countries the size of the fillet as it appears in the welding symbol may be specifying the size of the throat of the weld rather than the size of the leg (**Figure 3.61**).

The International Standards Organization (ISO) responsible for the formulation of international standards has recently established its own position on this issue. Sub-committee 7 “Graphical Welding Symbols” of its Technical Committee 44 on Welding (ISO/TC44/SC7) has, in recognition of the entrenched practices in using one or the other system, officially accepted both, leaving it at the discretion of each country adopting the ISO Standard to opt for the one system it prefers.

However, as a necessary precondition of such compromise, ISO has made it a mandatory requirement that each system be clearly identified by the following means.

It should be understood that the designations “z” and “a” have no other significance except to identify the system. It is also very important for the student to be aware of the difference in interpretation attached to the definition of sizes of fillet welds between the AWS and the ISO concepts, both of which are used internationally. This awareness will be of specific importance to those who, because of involvement with international contracts, are dealing with foreign drawings. In North America, fillet welds are specified by leg dimensions.

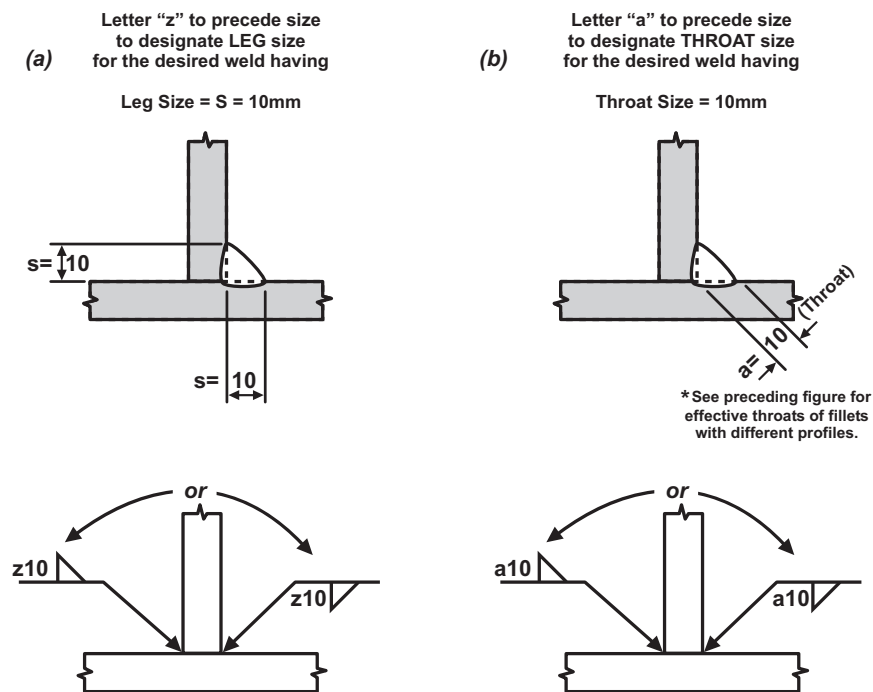


Figure 3.61: ISO fillet size designation.

The interrelation of both sizes is expressed by:

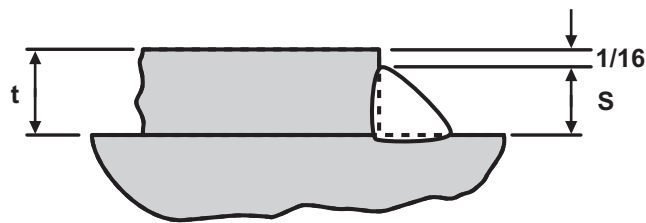
$$z = a\sqrt{2} \quad \text{or} \quad a = \frac{z}{\sqrt{2}}$$

3.18.3 Minimum and Maximum Fillet Size

It is advisable to point out that some governing design applications like CSA W59 (Welded Steel Construction) or AWS D1.1 (Structural Welding Code) stipulate minimum fillet sizes as a function of material thickness.

On the other hand, maximum fillet sizes may be set either by considerations of balanced design, that is, by keeping the capacity of the welds reasonably close to that of the parent metal, or by requirements of good welding practice.

With regard to the latter, specific reference is made to welding against a cut edge where the maximum recommended fillet size for thicknesses over ¼ inch (6mm) is:



where: $S = t - 1/16$ (Imperial)

or: $S = t - 2$ (Metric)

Figure 3.62

3.18.4 Conventional Fillet Sizes

The fillet sizes are usually measured in millimeters (mm) in the metric system or in inches (in) in the imperial system. The smallest dimension is adjusted to the nearest size in mm or in inches, 1/16 of an inch intervals. The common sizes used are shown as follows:

Metric (mm)	3	5	6	8	10	12	14	16	18	20
Imperial (1/16 in)	1/8	3/16	1/4	5/16	3/8	1/2	9/16	5/8	11/16	3/4

3.18.5 Size of Fillet Welds – Unequal Leg Fillet Welds

For unequal leg convex fillet welds, the effective throat (t), as shown in **Figure 3.63**, is the shorter leg (a) multiplied by sin θ.

$$t = a \times \sin \theta = \frac{ab}{\sqrt{a^2 + b^2}}$$

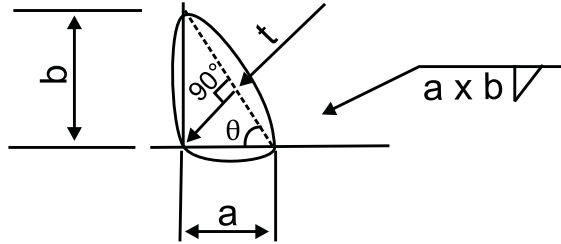


Figure 3.63: Unequal leg fillet (convex).

For unequal leg concave fillet welds, the effective throat thickness must be obtained by direct measurement which is the shortest distance from the root point to the weld surface. Its equivalent leg sizes are the lengths of the sides of the inscribed triangle as shown in **Figure 3.64**.

$$t = a' \times \sin \theta = \frac{a' b'}{\sqrt{(a')^2 + (b')^2}}$$

a' is the shorter side

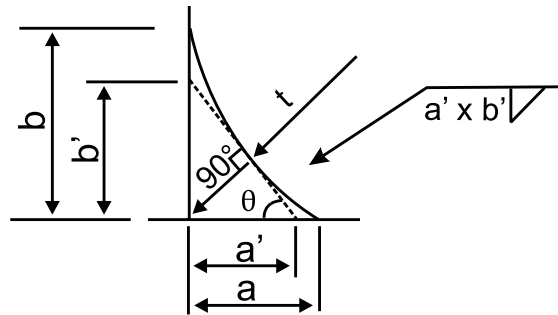
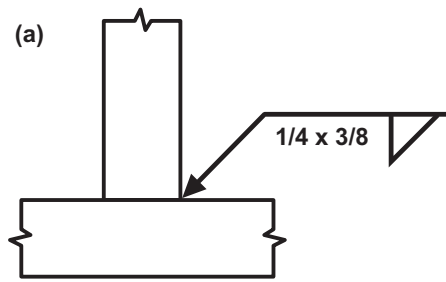


Figure 3.64: Unequal leg fillet (concave).

The AWS Standard A2.4 does not define the convention of which leg size is specified first. Where it is possible to misinterpret the fillet leg sizes, a sketch defining the leg sizes must be shown on the drawing. In recognition of this shortcoming, AWS A2.4 requires that a sketch of the joint complete with the desired orientation of the fillet weld be shown on the drawing whenever necessary. **Figure 3.65** will illustrate this point.

The Fillet Weld specified in T-joint (a):



could be interpreted to mean:

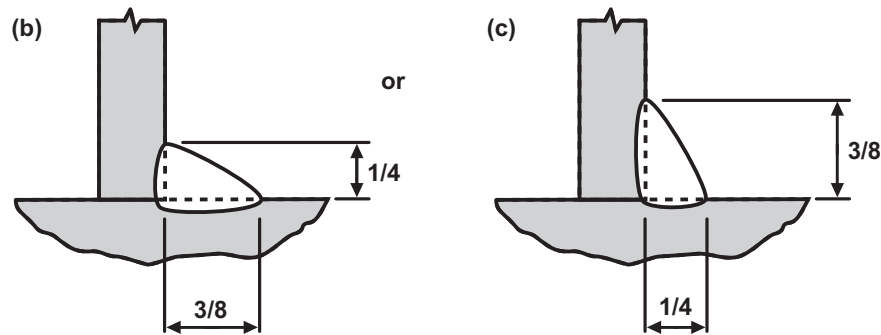


Figure 3.65: Unequal leg fillet size and symbol.

Consequently, in addition to the basic symbol under (a), an additional sketch showing either fillet weld (b) or (c) – as applicable – must be shown on the drawing. Only then will complete information be provided for an error-free interpretation at the time of welding. Such clarifying sketches may not always be necessary, although they may be considered.

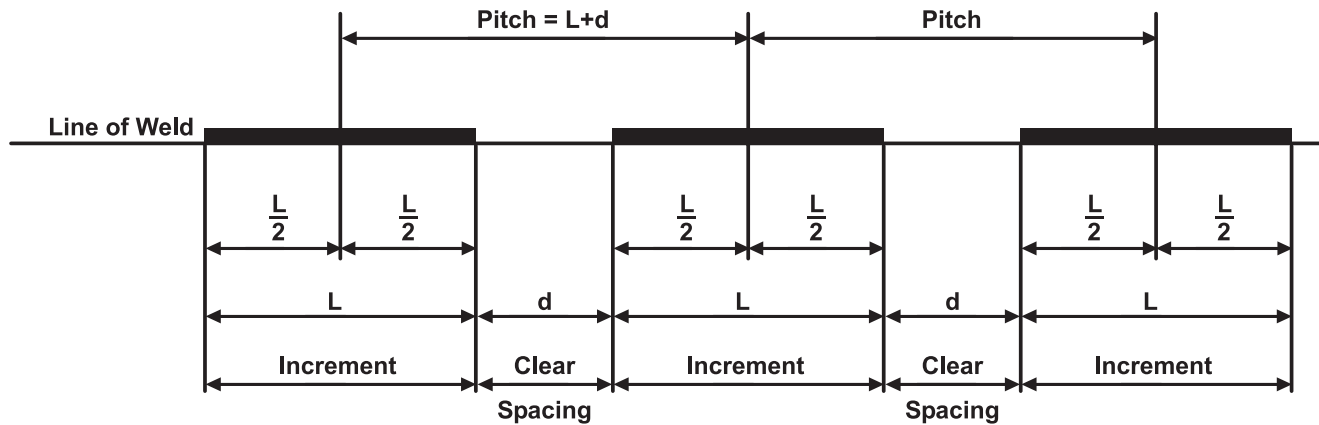
The effective throats of unequal leg fillets are discussed previously.

3.18.6 Intermittent Fillet Welds

There are three types of intermittent fillet welds, although the first one is inherent in the remaining two:

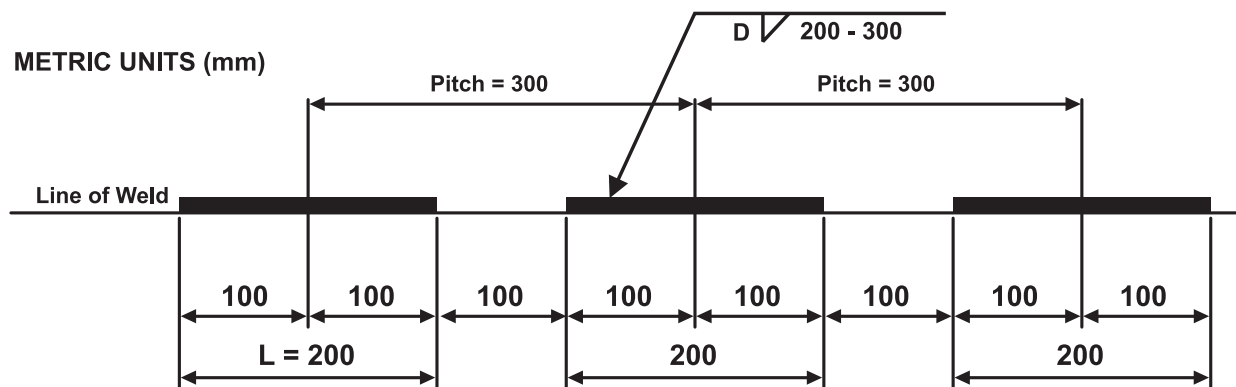
- 1) basic intermittent fillet welds, applicable to a single line of fillet welds (**Example 18**)
- 2) staggered intermittent fillet welds (**Example 19**)
- 3) chain intermittent fillet welds (**Example 20**)

The following sketches will help explain the fundamental concept and the rules governing its application.

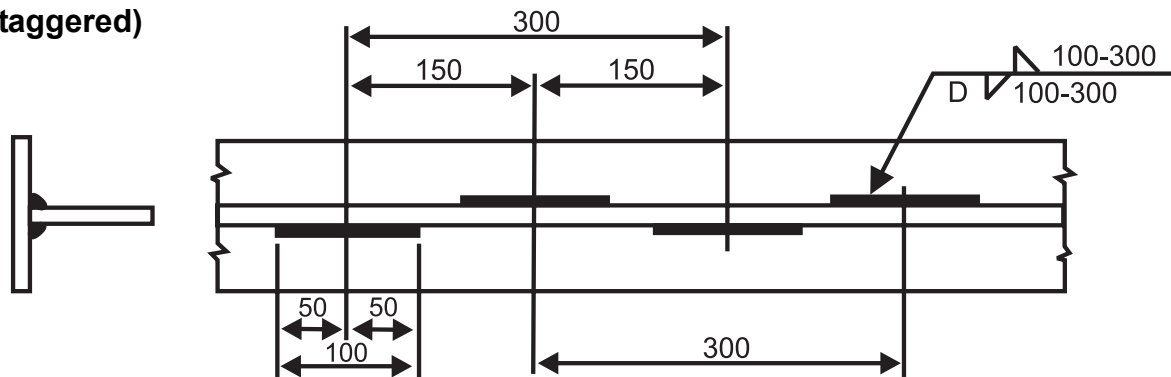


EXAMPLE 17

METRIC UNITS (mm)

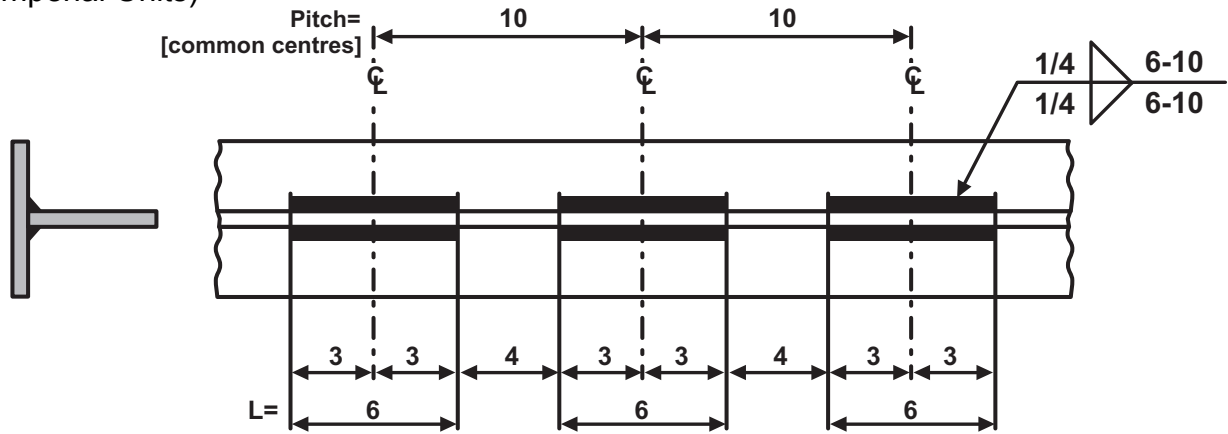


EXAMPLE 18 (Staggered)



EXAMPLE 19 (Chain)

(Imperial Units)



Under normal circumstances the general tendency is to keep the length of the increments and the size of the fillets the same on both sides of the joint, if only to simplify fabrication and avoid errors.

3.19 Plug Welds

Information required for the application of plug welds must include the following:

- 1) Size of hole
- 2) Angle of countersink
- 3) Depth of filling
- 4) Spacing of welds
- 5) Reference to contour and surface finish, if required

3.19.1 Size of Plug Welds

In line with the common principle, the size of the plug weld is expressed by the diameter of the hole and must be placed on the left side of the weld symbol as shown in **Figure 3.66**.

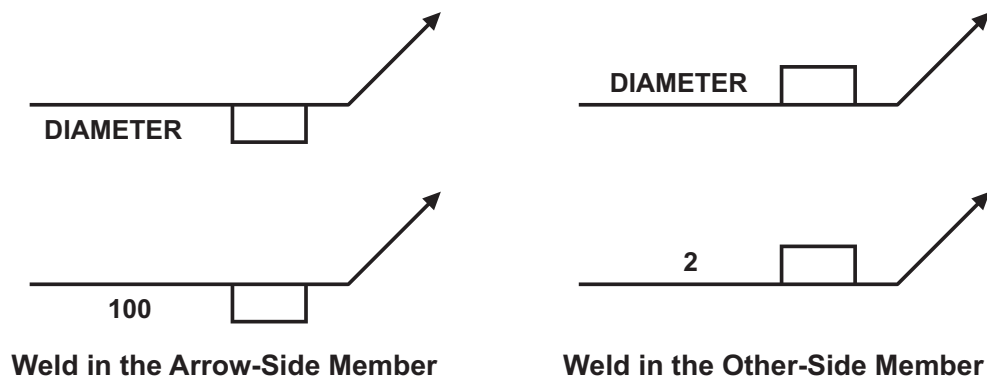


Figure 3.66

It should also be noted that the governing design specification may relate the minimum hole diameter to the thickness of material in which a plug weld has to be made. CSA W59 and AWS D1.1 set this minimum at

$$d_{\min} = t + 8\text{mm} \quad (\text{CSA W59 [metric]})$$

$$= t + 5/16 \text{ in.} \quad (\text{CSA W59 and D1.1 [imperial]})$$

3.19.2 Angle of Countersink

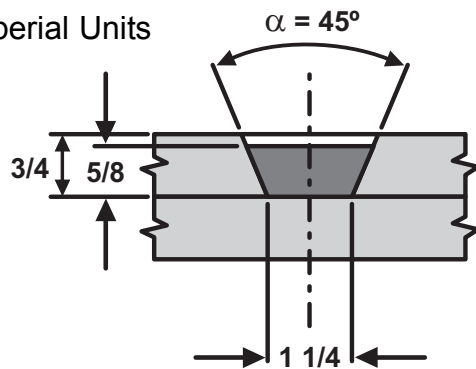
In order to facilitate welding and provide easier access to the root, hence greater assurance of soundness, countersunk holes with circumferentially sloping sides may be considered. When specified in the symbol, the angle of countersink must be placed outside the horizontal side of the weld symbol.

3.19.3 Depth of Filling

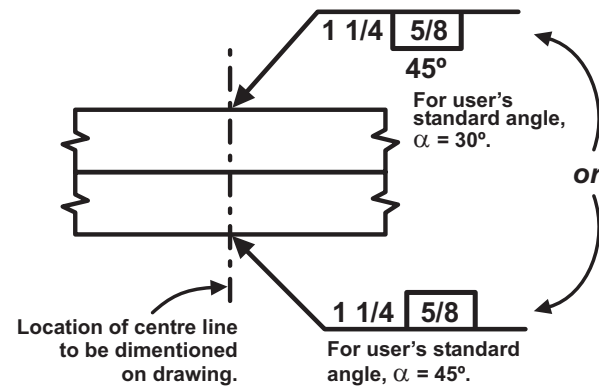
If complete depth of filling is required, it need not be specified in the welding symbol. However, if the depth of filling required is less than complete, it must be specified and shown inside the weld symbol.

EXAMPLE 20

Imperial Units



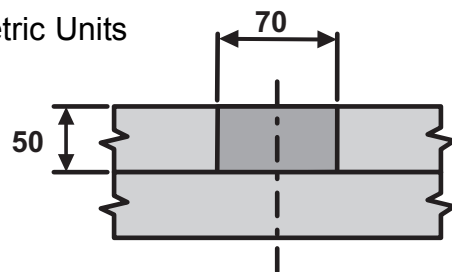
Desired Weld



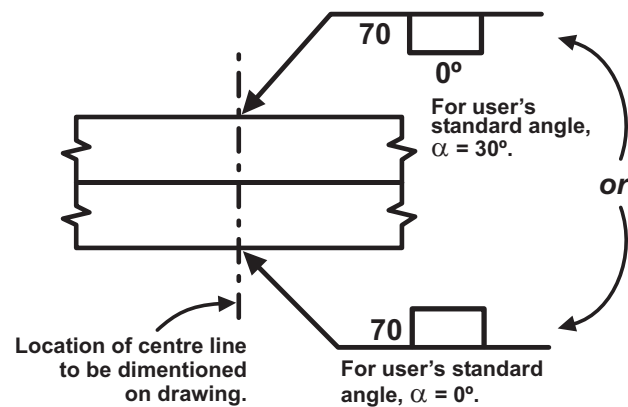
Symbol

EXAMPLE 21

Metric Units



Desired Weld



Symbol

3.19.4 Spacing of Plug Welds

The concept of pitch is used to designate the centre-to-centre spacing of plug welds. As in the case of other welds, the assigned standard location for length is at the right side of the weld symbol as shown in **Figure 3.67**.

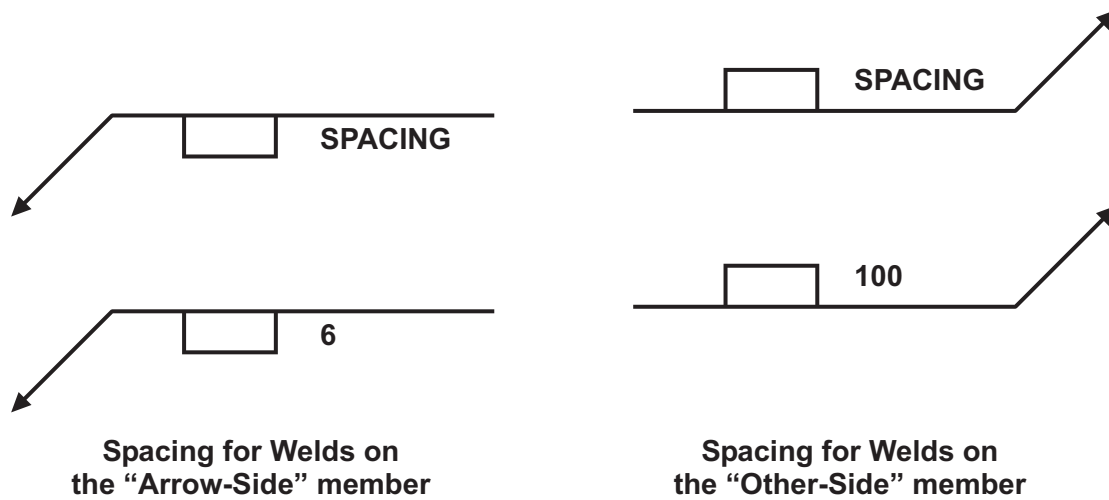


Figure 3.67

Chapter 4

Metal Arc Welding Processes

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4.1 Introduction

There are quite a few arc welding processes. We are concentrating on those processes that are used in structural fabrication shops. There are four commonly used welding processes in the structural fabrication shops, and each has its own intrinsic characteristics. See **Table 4.1**.

Table 4.1

Process	Abbreviation	Electrode Designation (Example)
Shielded Metal Arc Welding	SMAW	E49XX
Gas Metal Arc Welding	GMAW	ER49S-X
Flux Cored Arc Welding	FCAW	E49XT-X
Submerged Arc Welding	SAW	E49AX-EXXX

Each welding process requires its own equipment, power source and filler metal (with or without gas shield or flux). Therefore, the manual skills, set-up and deposition rate are all different. Each process is suitable for certain types of joints and welding positions. This chapter briefly explains each process in more general terms. There are several other welding processes that are not discussed here, but are covered in depth in the following CWB Modules:

Module 4	Welding Processes and Equipment
Module 5	Power Sources for Welding
Module 6	Electrodes and Consumables

The types of welding joints and welding positions mentioned above can be found in Clause 10 of CSA W59 “Welded Steel Construction (Metal Arc Welding)”. The electrode designations and classifications can be found in the CSA W48-01 standard, which covers electrodes for various welding processes:

*CSA W48.1	Mild Steel Covered Arc Welding Electrodes
*CSA W48.2	Stainless Steel Electrodes
*CSA W48.3	Low-Alloy Steel Covered Arc Welding Electrodes
*CSA W48.4	Solid Mild Steel Filler Metals for Gas Shielded Arc Welding
*CSA W48.5	Mild Steel Electrodes for Flux Covered Arc Welding
*CSA W48.6	Base Mild Steel Electrodes and Fluxes for Submerged Arc Welding

(* indicates previous designations given here for cross reference.)

4.2 Shielded Metal Arc Welding (SMAW)

Shielded metal arc welding (SMAW), or manually operated metal arc welding with covered electrodes, is one of the most commonly used welding processes. It allows the greatest amount of flexibility in terms of the range of materials and thicknesses that can be joined in all welding positions.

The SMAW process is the first one developed during the experimental stage of arc welding in the early 1920s. The knowledge of joint design, arc action, heat control and metal reaction gained from shielded metal arc welding has been of great value in developing all other variations of the arc welding process.

4.2.1 Principles of Operation

In shielded metal arc welding, an arc is established between the end of a covered metal electrode and the workpiece to be welded. The heat of the arc melts the surfaces of the joint as well as the metal electrode. The filler metal is carried across the arc into the weld joint and mixes with the molten base metal. As the arc is moved at a suitable travel speed along the joint, the progressive melting of the metal electrode and the base metal provides a moving pool of molten metal, which cools and solidifies behind the arc (**Figure 4.1**).

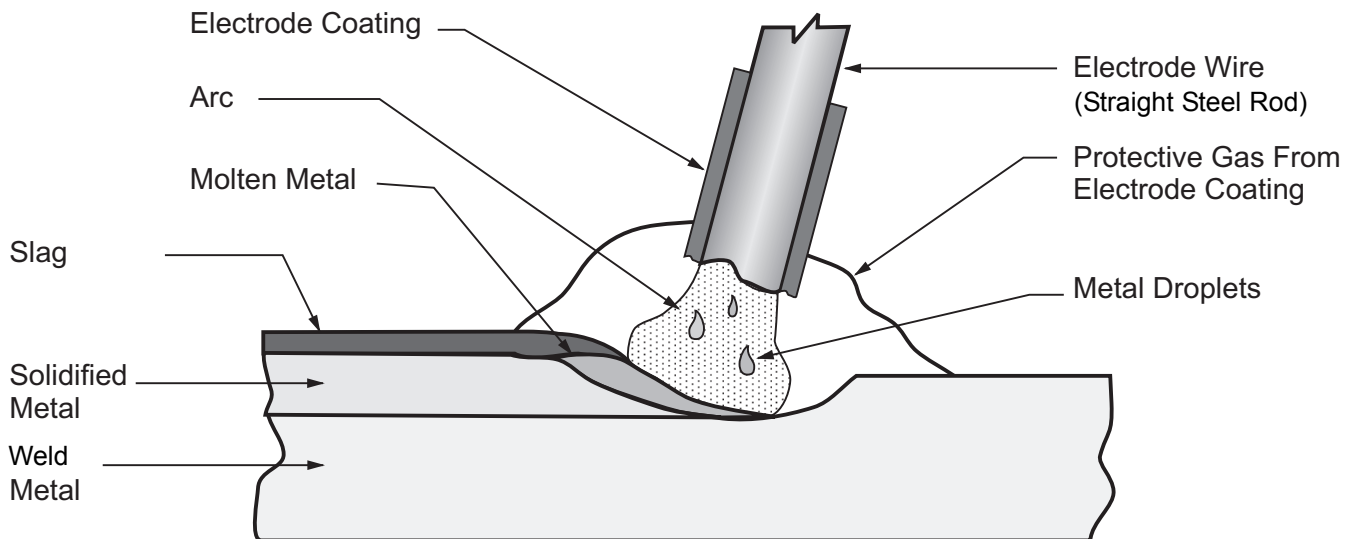


Figure 4.1: Schematic sketch of the shielded metal arc process.

The electrical circuit for shielded metal arc welding is relatively simple and is shown in **Figure 4.2**. It comprises a power source with electrical leads connected to the workpiece and the electrode holder. The arc characteristics, weld bead shape, and weld metal soundness and properties depend on the selection of the type of power source, electrode, joint design, as well as welding parameters and welder skill.

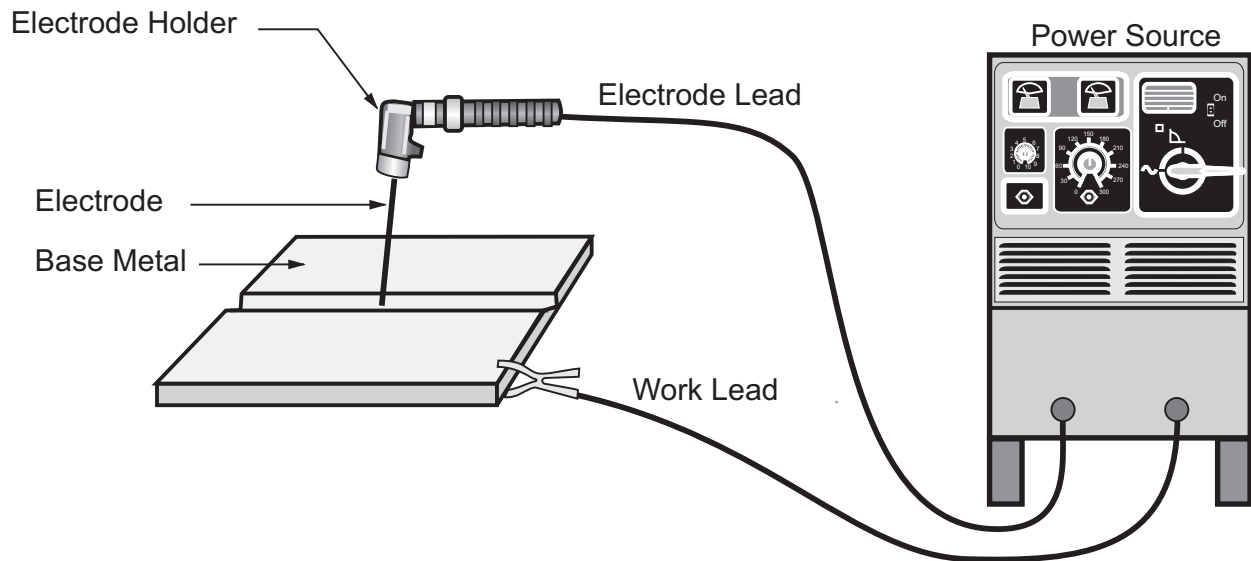


Figure 4.2: Electrical circuit for SMAW.

4.2.2 Power Sources

The power source used for SMAW is a constant current type, i.e., it has a drooping volt-ampere curve (see **Figure 4.4**). With such a power source, the welder sets the required current at the power source and the voltage is controlled by the arc length that the welder maintains during welding. The drooping power source is preferred because there is a small but continual variation in the arc length due to the manual nature of the welding process. This is reflected in a continual change in the arc voltage, but due to the drooping characteristics of the volt-ampere curve the accompanying changes in the arc current, and therefore the electrode melt off and deposition rates, are small. **Figure 4.3** shows typical SMAW power sources.

Different power sources, however, may have different slope (or incline) for the volt/ampere curve, and some machines are designed to enable some adjustment of the slope. **Figure 4.4** shows that when the volt-ampere curve is flatter, there is a greater change in current for a given change in voltage. The adjustment of the slope of the volt/ampere curve enables the welder to maintain better control of the weld pool and penetration in certain situations such as out of position welding (vertical or overhead positions) or depositing a root pass in a pipe over a varying gap. For example, by adjusting the volt/ampere curve to be flatter an intentional increase in the arc length by a welder pulling the electrode away increases the arc voltage and decreases the current sufficiently to reduce penetration or risk of burn-through.

Conversely, electrode sticking is also prevented when the rod is in near contact with the base metal and the arc length, and therefore voltage is reduced, causing the current to increase sufficiently to increase the burn off rate to prevent sticking. With a pure drooping (or vertical) volt/ampere curve, there would be no change in the current due to change in voltage or arc length. The welder would have no control over the electrode burn-off rate in this case.



Figure 4.3: Typical SMAW power sources.

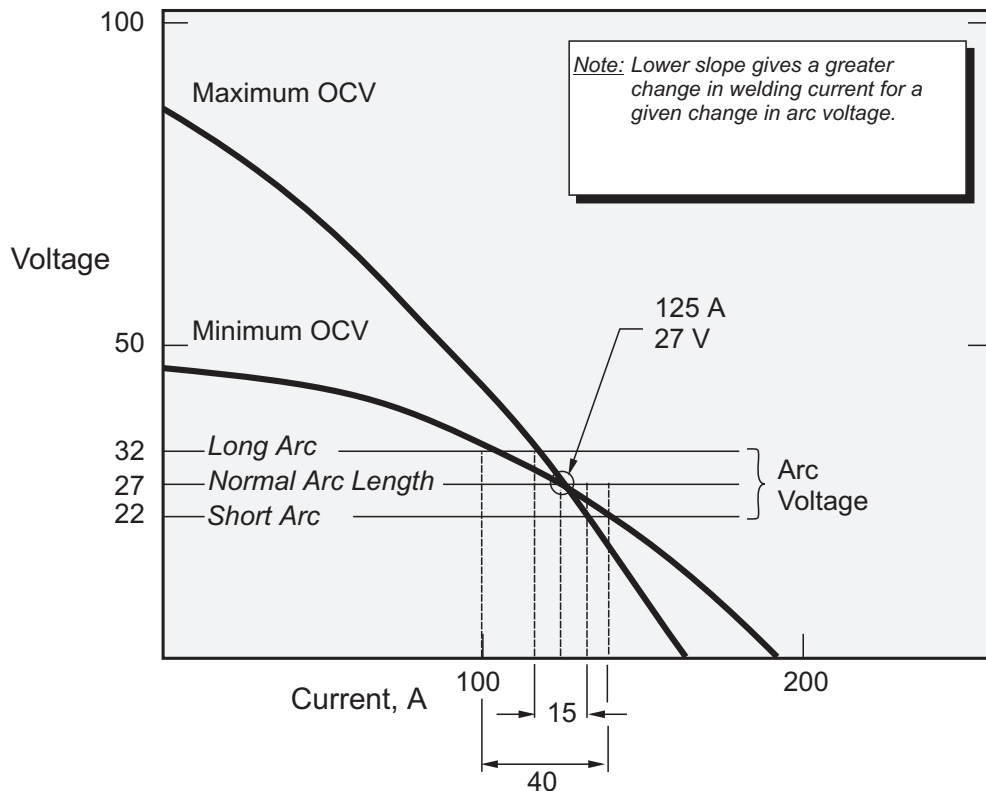


Figure 4.4: Change in current due to change in voltage in a constant current power source.

Power sources are available to provide direct current (DC), alternating current (AC), or both. A transformer or an alternator type of source is used for AC welding, and transformer/rectifier or motor generator type for DC welding. Some power sources (single phase transformer/rectifier or alternator rectifier type) can be used for AC and DC welding. Inverters are becoming popular due to their portability and smooth operating characteristics. **Figure 4.5** shows a typical inverter power source.



Figure 4.5: Portable inverter type constant current power source.

4.2.3 Types of Electrodes

Electrodes for shielded metal arc welding generally comprise a coated, solid electrode wire (core) of limited length (300 to 400 mm or 12 to 16 in long). Occasionally, the solid electrode can be replaced by a metallic sheath containing metal powders with the objective of adding specific alloying elements to the weld metal.

The covering on the electrodes can be applied either by an extrusion process or by dipping, though extrusion is far more common. The covering itself contains several ingredients depending on the type of electrode. The function of these ingredients is generally one of the following:

- ◆ provide a gas shield to prevent contamination of the weld metal by atmospheric gases
- ◆ provide a slag cover to protect the hot weld metal from atmospheric contamination and control the bead shape
- ◆ scavenge some of the impurities in the weld metal
- ◆ stabilize the arc by promoting electrical conduction across the arc; this is especially important for AC welding where the arc effectively goes out and needs to be re-established after each current reversal
- ◆ provide a means to add alloying elements to enhance mechanical/corrosion properties, and iron powder to increase deposition rate

Each electrode classification produces different amounts of gases and slag to shield the weld metal. Electrodes that rely on slag to protect the metal can carry higher current and provide a higher deposition rate. Conversely, electrodes producing a smaller amount of slag and relying on the gas shield are stable to operate at lower currents and therefore are more suitable for out of position welding.

All electrodes can be used with direct current, although some are designed for use with AC also. Use of AC reduces arc blow and voltage drop in welding cables.

Direct current (DC) power has certain advantages:

- ◆ easier arc initiation
- ◆ better arc stability
- ◆ good wetting action
- ◆ ability to maintain a short arc

Direct current is especially useful for applications requiring small diameter electrodes and low currents, e.g., out of position welding, welding of thin materials, etc. When direct current is used for SMAW, DCEP (electrode positive) polarity provides deeper penetration and DCEN (electrode negative) polarity provides a higher electrode melting rate.

4.2.4 Classification of Electrodes

Shielded metal arc welding electrodes are available for welding of carbon and low alloy steels, stainless steels, cast irons, aluminum, and copper and nickel and their alloys. However, electrodes for welding carbon and low alloy steels and for stainless steels are of greatest commercial significance, and systems for their classification as described in CSA Standard W48-01 are summarized here. For more details, see Module 6 - Electrodes and Consumables of the CWB Modular Learning System (MLS).

1) Carbon and low alloy steel electrodes

The electrode designation comprises the letter E (for electrode) followed by digits, e.g., E4918 for metric designation (E7018 for imperial). For metric designation, the first two digits indicate the minimum tensile strength (in MPa) of the weld metal. For imperial designation, the first two digits indicate the tensile strength in ksi.

The third digit (imperial designation or metric designation) indicates the welding position for which the electrode is designated with 1 meaning suitable for all welding positions (flat, horizontal, vertical and overhead), 2 suitable for horizontal fillet and flat positions only and 4 meaning suitable for vertical, downwards progression only.

The fourth digit (imperial or metric) indicates the usability characteristics of the electrodes (type of coating, welding current type, etc.). For example, 0 and 1 indicate cellulosic covering, 2 and 3 indicate covering containing rutile, 8 indicates low hydrogen, iron powder containing covering, etc. These digits may be followed by additional letters and digits, which are usually indicators of weld metal toughness or alloy content. Further details about digits, indicating suitable current type and polarity, etc., can be found in CSA Standard W48-01 or from electrode manufacturers.

The usability characteristics of some of the more commonly used electrode types can be summarized as follows in metric designation.

- EXX10: high cellulose, sodium compounds for arc stability, DC electrode positive polarity; deeply penetrating arc; suitable for all welding positions; may be used for welding from one side with adequate back bead profile; 5 mm or smaller diameter electrodes used for all position welding;
- EXX11: high cellulose, potassium compounds for arc stability, AC or DC electrode positive polarity; otherwise similar to EXX10 electrodes;
- EXX12: high titania with sodium compounds, AC or DC electrode negative polarity; medium penetrating, quiet arc; most often used for single pass, high speed, high current, horizontal fillet welds;
- EXX13: high titania with potassium compounds, similar to EXX12 type; used for sheet metal work for vertical down welding; provides better radiographic quality in multipass welds than EXX12 electrodes;
- EXX14: high titania and iron powder covering; AC or DC either polarity; similar to EXX12 or 13 but with iron powder providing a higher deposition rate;
- EXX15 : basic covering with sodium compounds; DC electrode positive polarity; limestone and other basic ingredients in the covering provide weld metal with good toughness and low hydrogen content; also suitable for welding high sulfur steels; usually 4 mm or smaller diameters are used for all position welding;
- EXX16: basic covering with potassium compounds; AC or DC electrode positive polarity; otherwise similar to EXX15;
- EXX18: basic, iron powder covering; similar to EXX15 or 16 but with iron powder in the covering thus providing higher deposition rates; most structural steels are welded with EXX18 type of electrodes;

- EXX22: iron oxide covering; AC or DC either polarity; used for single pass, high speed, high current flat and horizontal lap and fillet welds in sheet metal;
- EXX24: titania, high iron powder covering; AC or DC either polarity; similar to EXX14 electrodes but restricted to welding in flat and horizontal positions; used mostly for fillet welds;
- EXX28: basic, high iron powder covering; AC or DC electrode positive polarity; similar to EXX18 but with higher iron powder content; suitable for welding horizontal fillets and flat position welds only;
- EXX48: basic, iron powder covering; AC or DC either polarity; also similar to EXX18 but designed for welding in the vertical position with downward progression.

2) Stainless Steel Electrodes

Requirements for covered electrodes for welding stainless steels are included in CSA Standard W48-01. These electrodes are classified based on the chemical composition of the undiluted weld metal, the welding position and the type of welding current for which the electrode is designed. A typical designation can be represented as EXXXxx-XX where E represents electrode, and the next three digits and any letters immediately thereafter (e.g., 309L, E310M) indicate the weld metal composition. The last two digits are usually 15, 16, 17 or 26, where digit 1 indicates suitability for all position welding for electrode diameters up to 4 mm. Conversely, digit 2 indicates suitability for flat and horizontal positions only. The number 5 indicates that the covering contains calcium carbonate (limestone) and sodium silicate, and that the electrode is suitable for welding using DC electrode positive polarity. The letter 6 indicates the presence of titania and potassium silicate in addition to the calcium carbonate. The presence of potassium compounds makes the electrode suitable for AC welding. The 7 signifies an acid flux with a significant amount of silica, which makes the slag more fluid.

The EXXXxx-15 electrodes provide a more penetrating arc, and a convex and coarsely rippled bead. These electrodes are preferred for out-of-position welding since the slag solidifies quickly. The EXXXxx-16 electrodes provide a smoother arc, less spatter, and a finely rippled bead. These electrodes are less popular for out-of-position work because the slag is quite fluid. For more details, see Module 6 - Electrodes and Consumables of the MLS series.

3) Handling and Storage of Electrodes

The electrodes should be handled with care to ensure that the electrode covering is not chipped off. Unopened boxes should be stored at $30^{\circ}\text{C} \pm 10^{\circ}\text{C}$ with relative humidity less than 50%. Cellulosic electrodes (EXX10 or 11), however, are supposed to have a certain amount of moisture in the covering and therefore should be stored in relative humidity of 20 to 70%.

Electrodes with basic (low hydrogen) coatings (containing calcium carbonate) are prone to moisture absorption from the atmosphere and therefore should be packaged in hermetically sealed containers. Once the container is opened, the electrodes should be removed from their packaging and stored in a holding oven at a temperature of about 120°C. Also, if the basic electrodes for welding carbon and low alloy steel have been exposed at ambient temperature for 4 hours or more, or if their packaging has been damaged, they should be rebaked at a temperature (370°C to 430°C) and for a time (1 to 2 hours) recommended by the electrode manufacturer. Cellulosic electrodes, however, should not be placed in holding ovens or rebaked.

4) Selection of Electrode Diameter and Current

The classification and size of electrode, and the welding current for a given application are chosen in light of the thickness of the material to be welded, groove geometry and welding position. Generally, larger diameter electrodes are used for welding thick materials and in the flat position so that higher deposition rates can be achieved. Smaller diameter electrodes are generally needed for welding the root passes in V grooves and for out-of-position welds so that the welder can have better control of the weld pool and the bead shape.

For prequalified joints, CSA Standard W 59 “Welded Steel Construction” limits the maximum electrode size to 4 mm for welding in the vertical position (fillet and groove welds), and to 5 mm for groove welds in horizontal and overhead positions, and fillet welds in the overhead positions. Larger diameter electrodes are used for welding in the horizontal and flat positions only.

Table 4.1 shows typical current ranges for satisfactory electrode burn off and stable arc conditions using steel electrodes of various diameters. However, the complete range of current may not be suitable for all situations. When welding on thinner material, the lower end of the range might be applicable. This would also apply when welding in the vertical or overhead positions. For example, 3.2 mm diameter E4310 electrode, according to **Table 4.1** has a usable current range of 75 to 125 A. For joining heavy material in the flat position, it would be logical to use the upper part of the range, 100 to 125 A. But if welding is to be done in the vertical up position, the range might be 90 to 110 A.

**Table 4.1: Typical Current Ranges (in Amperes) for Electrodes of Different Diameters
(from CSA Standard W48-01)**

Electrode Diameter, mm	E4 X 00 E4 X 10 E4 X 11	E4 X 12	E4X 13	E4 X 22	E4 X 27	E4914
1.6	–	20 – 40	20 – 40	-	-	-
2.0	–	25 – 60	25 – 60	-	-	-
2.5	45 – 85	40 – 90	50 – 90	-	-	90 – 135
3.2	75 – 125	80 – 140	80 – 130	110 – 160	125 – 185	110 – 160
4.0	110 – 170	110 – 190	105 – 180	140 – 190	160 – 240	150 – 210
5.0	155 – 235	155 – 265	165 – 250	200 – 410	230 – 330	220 – 300
6.0	190 – 290	225 – 360	225 – 315	380 – 520	270 – 380	295 – 375
8.0	275 – 425	300 – 500	320 – 430	-	375 – 475	390 – 500
Electrode diameter, mm	E4915 E4916	E4918	E4924 E4928	E4948		
2.5	70 – 120	80 – 110	110 – 160*	-		
3.2	110 – 150	115 – 165	140 – 190	80 – 140		
4.0	140 – 220	150 – 220	180 – 250	150 – 220		
5.0	200 – 280	220 – 350	250 – 335	210 – 270		
6.0	270 – 350	285 – 360	300 – 390	-		
8.0	375 – 475	375 – 470	400 – 525*	-		

* These values do not apply to the E4928 classification.

4.2.5 Applications and Limitations of the SMAW Process

The shielded metal arc welding process can be used to weld most metals and alloys of engineering significance. It has been extensively used to weld all types of steels (carbon and low alloy steels, stainless steels, etc.) in the fabrication of pressure vessels, oil and natural gas pipelines, field storage tanks, bridges, buildings, ships and offshore structures, railway cars, trucks and automobiles, nuclear power stations and numerous other miscellaneous products including those made from cast iron. Among the non-ferrous alloys, the shielded metal arc welding process is used for welding nickel and nickel-based alloys, and to some extent copper alloys, such as bronzes. Though electrodes are available, it is not popular for welding aluminum alloys. The process is also used for hardsurfacing various components exposed to wear, impact, corrosion and heat resistant alloys.

The shielded metal arc welding process is usually the most appropriate for repair and maintenance welding since each job is usually a one-time-only situation, the amount of welding required is relatively small and in-situ locations are most suitable for the shielded metal arc process only. The process is also frequently the only one in shops where welding constitutes only a small portion of the complete manufacturing process. The shielded metal arc welding process is also generally the easiest to use in the field due to the simplicity of the equipment and its tolerance to the normal outdoor environment. Nonetheless, it is advisable to install protective enclosures when welding in the field to get protection from rain, wind, etc.

The advantages of the shielded metal arc welding process thus include its applications to a variety of materials, and the ability to weld in all positions (vertical and overhead as well as flat and horizontal) and at most locations. As well the equipment required is easily portable and relatively inexpensive. The main limitation of the SMAW process is the necessity of frequent breaks as each electrode is consumed to about 50 mm of its original length and a new one used to re-initiate the welding operation. This frequent change of electrode along with the need to chip off the slag means that duty cycle (percentage of time that an arc is maintained for the purposes of welding) is less than 20% and the deposition rate is low. Also, the unusable electrode stubs add to waste and cost of the filler material.

4.2.6 Shielded Metal Arc Welding of Carbon and Low Alloy Steels

Joint Design

For base metal thickness up to about 6 mm, a square groove with suitable root opening may be employed for a complete penetration groove weld, provided that welding is performed from both sides and in the flat position. At low current, a skilled welder can weld base metal as thin as 1.6 mm. For larger thicknesses, the base metal edges must be beveled, and in very thick sections, J- and U-grooves become more economical by reducing the weld metal volume required. The root gap for groove welds is typically equal to the electrode diameter to achieve complete penetration, and the groove angle should be large enough to achieve side wall fusion and minimize slag entrapment. In assembling a joint for welding, the fit-up should be good enough to maintain the groove geometry within acceptable tolerances. Thus, too small a root gap or misalignment between the two members to be joined can locally lead to incomplete joint penetration. Fit-up tolerances and workmanship and some prequalified joint geometries given in CSA Standard W 59 “Welded Steel Construction” are shown in **Table 4.3** and **Figure 4.6**, respectively. For complete prequalified joint design, see Clause 10.2 of CSA Standard W59.

Table 4.3 : Fit-up and Workmanship Tolerances for SMAW Groove Welds

	Root Not Gouged	Root Gouged
1. Root Face of Joint	+ 2 mm	Not limited
2. Root Opening of Joints: Without Steel Backing	+ 2 mm	+ 2 mm - 3 mm
With Steel Backing	+ 6 mm, - 2 mm	Not applicable
3. Groove Angle of Joint	+ 10°, -5°	+ 10°, - 5°

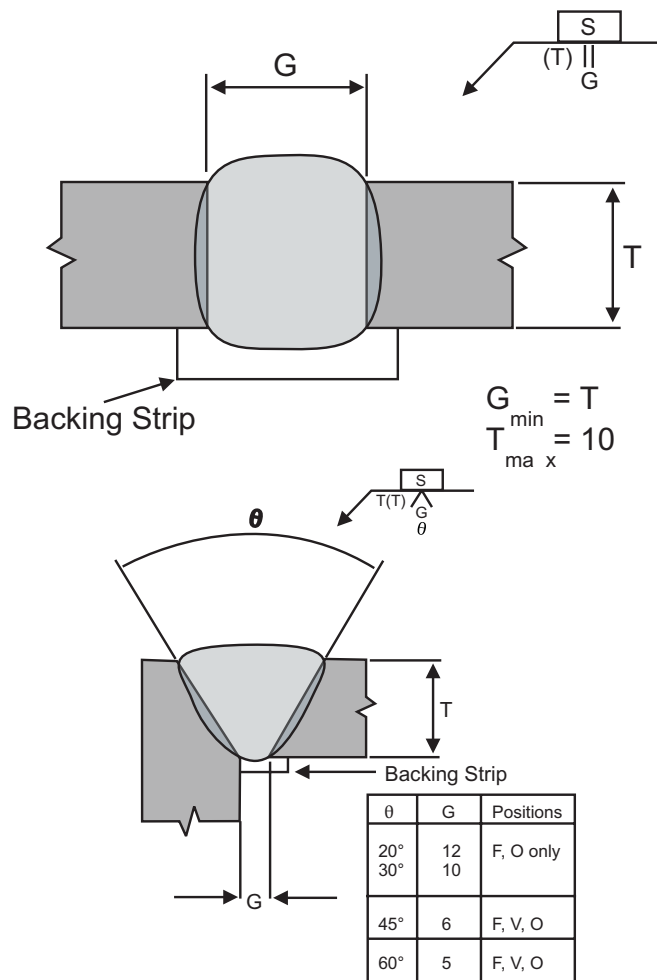


Figure 4.6: Typical prequalified complete joint penetration groove welds for the shielded metal arc welding process (SMAW).

4.3 Gas Metal Arc Welding (GMAW)

4.3.1 Principles of Operation

The gas metal arc welding process is shown schematically in **Figure 4.7**. Compared to the shielded metal arc welding process, the metal electrode is bare (without any covering). The coiled wire electrode is fed continuously through the welding gun. The continuous wire feed improves the productivity of the process by allowing longer welds to be made without stopping. In contrast, in SMAW the length of weld that can be deposited is limited by the length of the electrode. The protection of the weld zone from atmospheric contamination is provided by a continuous stream of shielding gas or gas mixture.

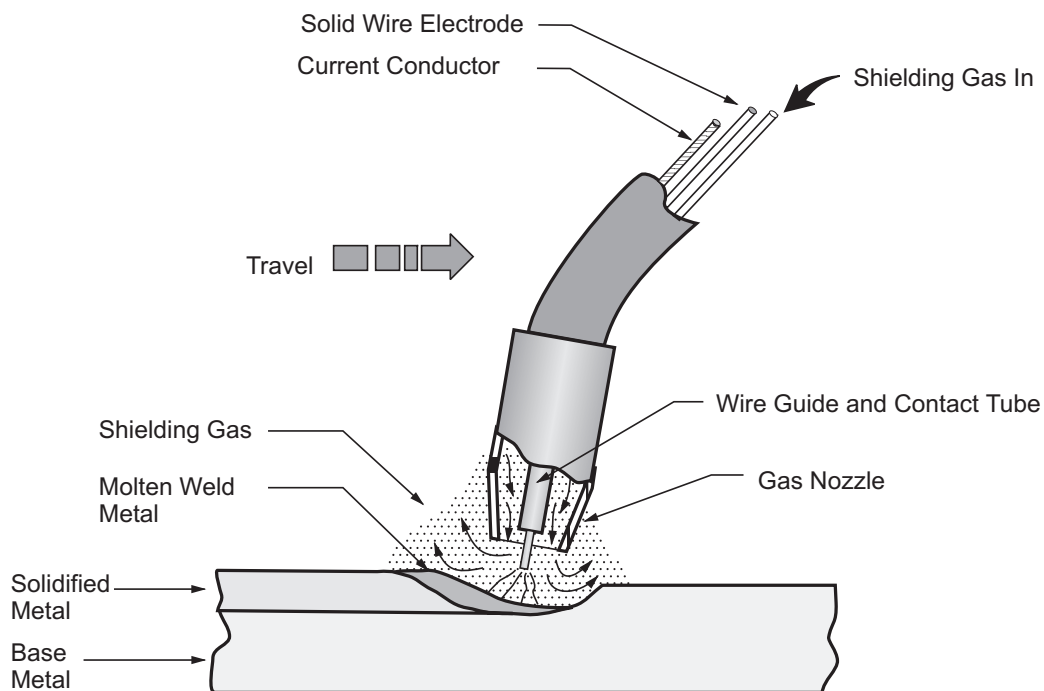


Figure 4.7: Schematic representation of the GMAW process.

An arc is struck between a continuously fed bare consumable wire electrode and the workpiece. The heat generated by the arc melts the end of the electrode and part of the base metal in the weld area. The arc transfers the molten metal from the tip of the melting electrode to the workpiece where it combines with the melted base metal to form the weld deposit.

The process was first applied to the welding of aluminum using inert gases for shielding the arc and the weld pool. The term MIG (Metal Inert Gas) welding has been a popular name for the process. However, for joining of steels, it is common to have carbon dioxide and/or oxygen present in the shielding gas mix. These two gases are not inert. Changing the proportions of carbon dioxide and oxygen in the shielding medium can influence the chemical composition and therefore the properties of the weld metal. The process therefore is sometimes referred to as Metal Active Gas (MAG) welding in Europe. In North America, a more generic description “Gas Metal Arc Welding (GMAW) has been adopted.

The equipment arrangement for the GMAW process is shown schematically in **Figure 4.8**. It comprises a power source, electrode wire feeder and control system, the welding gun and a supply of shielding gas.

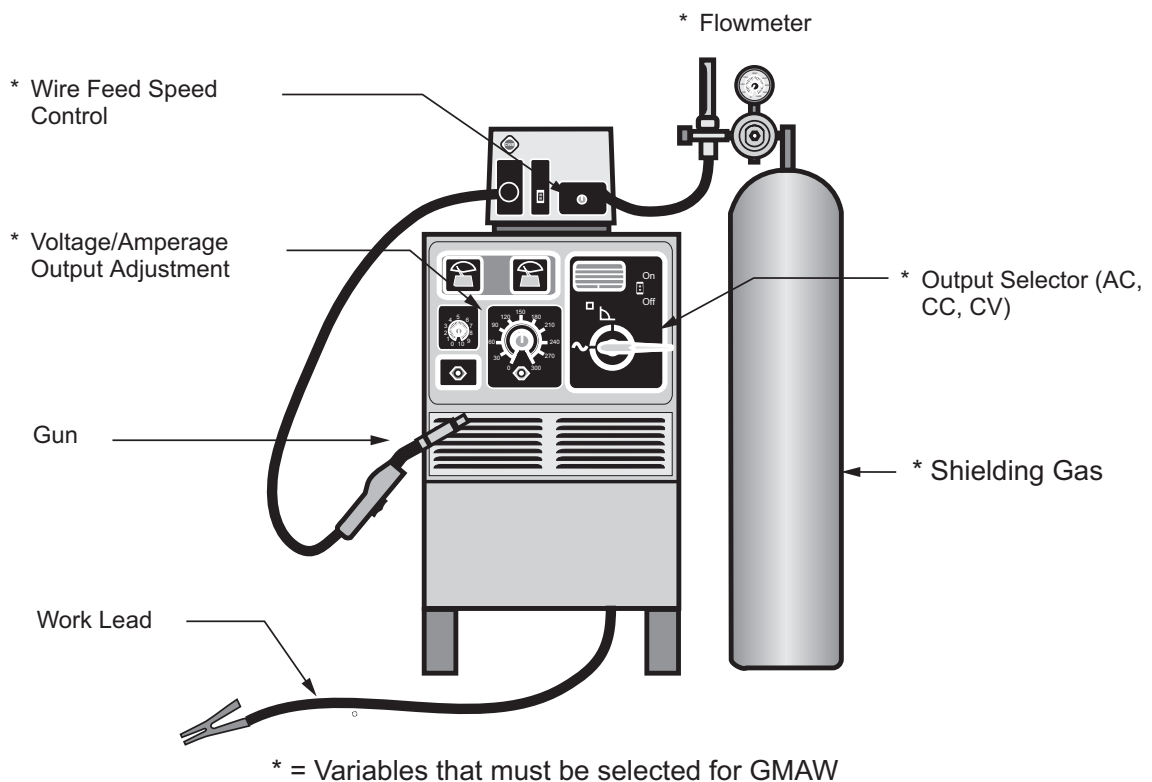


Figure 4.8 Equipment arrangement for GMAW.

A constant potential (i.e., a constant voltage) power source and a constant speed wire feeder are generally used for GMAW welding, and current type is almost exclusively direct current with electrode positive (DCEP). In such an arrangement, the amperage controls the electrode melting rate (wire feed speed) and the power source tries to maintain a constant voltage by adjusting current output. Voltage is closely related to arc length. Should there be a change in the arc length (for example, due to welding over a tack weld or moving the gun toward or away from the workpiece), the power source responds by changing current output. Since current affects wire melt-off rate, controlling current to keep the wire burning off at the same distance from the puddle will maintain an essentially constant arc length - constant arc voltage. The power source is constantly responding to the changing demands of the arc, and to fluctuating input power. For the process to operate in a stable manner the power source must be capable of responding correctly. The following describes a typical power source response.

In **Figure 4.9(a)**, the preset welding parameters are 400 A and 34 V, and let us assume that the corresponding wire feed speed is 400 inches per minute (one inch per minute per ampere welding current). When arc length increases, the power source responds by reducing current output and thereby slowing wire melt-off rate. **Figure 4.9(a)** shows that if arc voltage increases to 37 V, the operating current and wire melt-off rate would be 325 inches per minute. However, the wire feeder will still keep on feeding wire at 400 inches per minute. Since the wire feed rate is greater than the wire melt-off rate, the electrode extension will increase and the arc length will progressively decrease, and the operating point will again move towards the initial setting. If the arc length were to shorten inadvertently, then the adjustment would be just reversed (see **Figure 4.9(b)**).

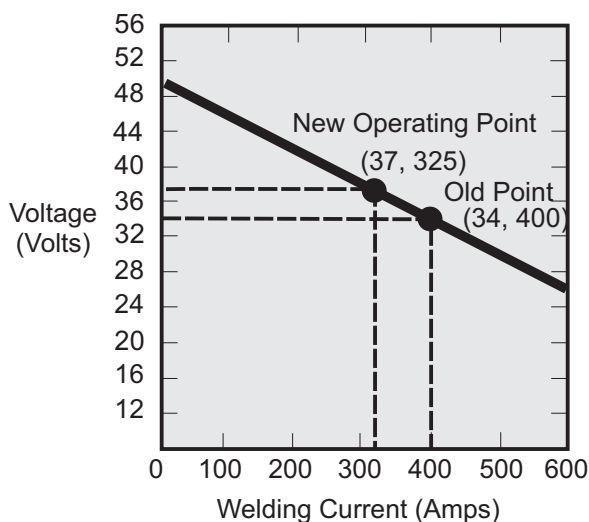


Figure 4.9(a): Shift in operating point due to an increase in arc length.

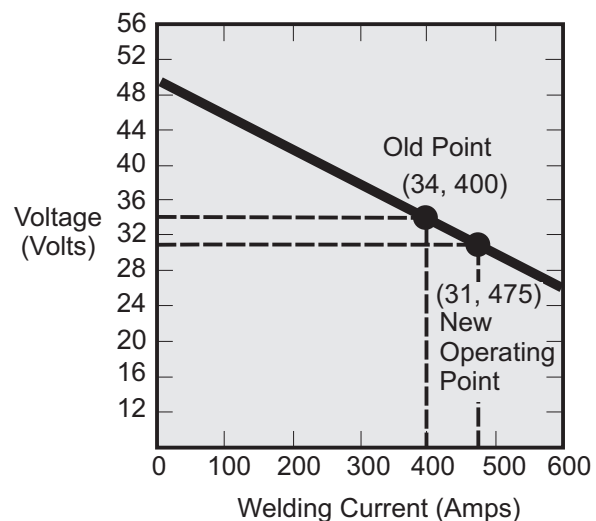


Figure 4.9(b): Shift in operating point due to a decrease in arc length.

4.3.2 Equipment

The GMAW process is most often used in the semi-automatic mode, that is, a welder holding the gun moves and guides it along the weld seam while depositing the weld metal. This also gives him the flexibility to manipulate the gun to maintain appropriate weld pool shape and wetting and fusion along the side walls. A typical gun is 250 to 375 mm in length and provides the means to supply current, continuously feed the wire and provide the shielding gas to protect the arc and the molten weld pool (see **Figure 4.10**). Some guns rated for higher currents or higher duty cycles may also have provision for water cooling.

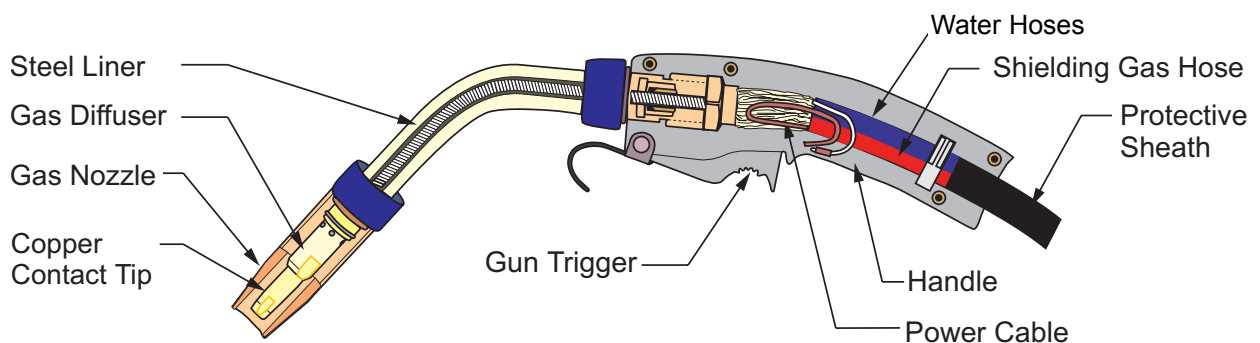


Figure 4.10: Schematic sketch of GMAW gun.

The direct current constant potential power sources used for gas metal arc welding can be engine driven generators, transformer rectifiers or inverters. The latter two types are more common since the generator type power source responds slowly to changing arc conditions.

It should be noted that though the power source recommended is a constant voltage type, the volt-ampere curve does have some slope instead of being a flat horizontal line. Also, the electric circuit in the power source has some inductance, a characteristic that controls the rate at which the current increases in the case of a short circuit. Slope and inductance together determine the dynamic characteristics of the power source and are key factors affecting the performance of a GMAW power source for semi-automatic applications. As a result of different slopes and inductance values, one power source may operate more smoothly for a given set of welding conditions than another. Some power sources are available with adjustable slope and inductance, allowing them to provide smooth operation for a range of wire types and diameters. More information about these features can be found in Module 5 - Power Sources for Welding.

In a conventional semi-automatic equipment set up, an analog constant speed wire feeder is used in conjunction with the constant voltage power source. The wire feeder's main components are drive rolls, guide tubes, a gear box, a variable speed motor, wire support and controls and meters. **Figure 4.11** shows a four-drive-roll system, which is more dependable than a two-roll system. A grooved roll is usually combined with a flat roll for feeding solid wires. The groove is usually V-shaped for carbon and stainless steel, and U-shaped for softer aluminum wires.

With the basic analog wire feeder and standard power source set up, the wire feed is adjusted by using an incremental dial on the feeder and checking the wire feed speed with a hand held meter. Alternatively, the dial may be adjusted to obtain a desired current reading. Although connected, the wire feeder and power source do not communicate with each other in this set up; the power source simply supplies the necessary power to burn off the wire as fast as it is fed into the arc. As a result, for the same dial setting, the actual wire feed speed can vary depending on the actual line voltage, slippage, etc. Therefore, unless the wire feed speed is verified on a regular basis, there will be variations in welding current and arc characteristics for no apparent reason.

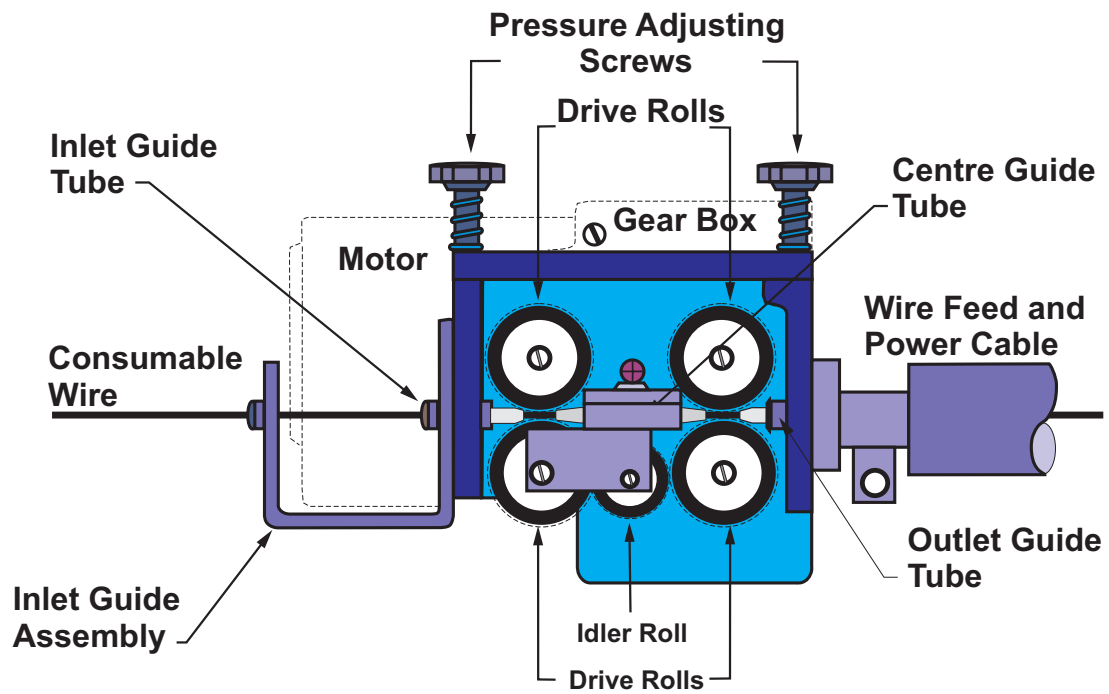
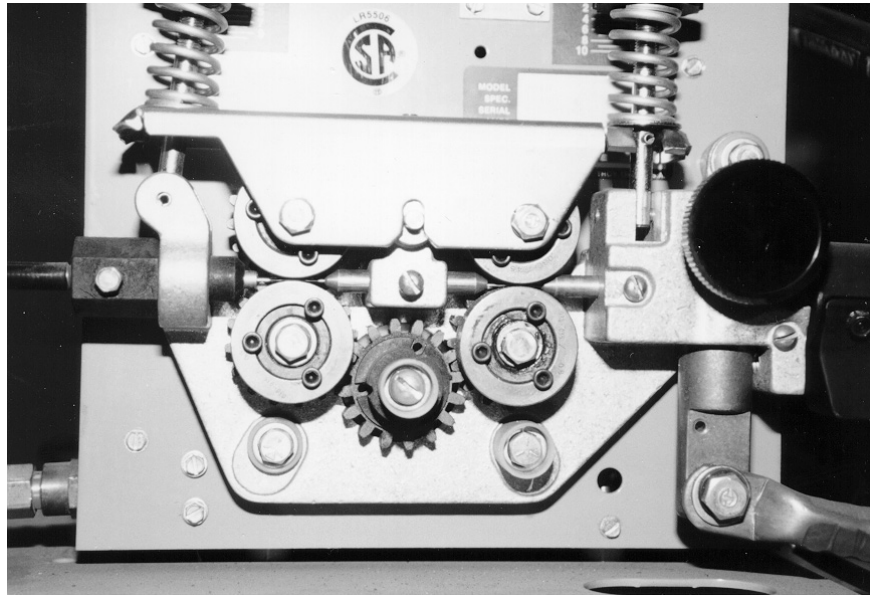


Figure 4.11: Four-drive-roll wire feed system.

On digital wire feeders with wire feed speed modulation capabilities, the target wire feed speed can be set directly. The feeder provides an accurate set-to-actual speed relationship through the use of better speed control on the feed motors, feedback of actual speed from tachogenerators, etc. Otherwise, there is no special communication between the feeder and power source. Digital wire feeders, compared to analog ones, result in better repeatability of procedures, which positively affects the quality and economy of welding operations.

4.3.3 Metal Transfer Across the Arc in GMAW

The GMAW process is identified with a number of different modes of metal transfer depending on the following welding parameters: current, electrode size, shielding gas composition, electrode chemistry and the type of power source.

Once the tip of the electrode melts into a globule of molten metal from the heat of the arc, one of the forces acting to detach it and propel it across the arc to the weld pool is the electromagnetic pinch effect. The strength of the magnetic field, and therefore the pinch effect, depends most strongly on the current density (welding current divided by the cross sectional area of the electrode). Consequently, the rate and mode of droplet detachment also depends on the current density. The principal droplet transfer modes of interest in GMAW are: short circuiting, globular, spray and pulsed (where pulsed transfer is a form of spray transfer).

1) *Short Circuiting Transfer*

In the **short circuiting** mode (**Figure 4.12**), the current density, i.e., the amperage used in relation to the wire size, is relatively low. The wire therefore melts at the electrode tip but the pinch force is not enough to detach it. However, the wire feeder keeps on feeding the wire and therefore the molten electrode tip comes into contact with the weld pool. When this happens, the constant voltage power source increases the amperage which in turn increases electrode heating and the magnetic pinch effect acting at the electrode tip. The magnetic forces pinch off the droplet, which is then drawn into the weld pool by surface tension forces. The gap between the electrode and the weld pool is then recreated and the arc is re-established. This process repeats itself very quickly, typically more than 100 times per second, so that the human eye does not notice the short circuits and the arc seems continuous.

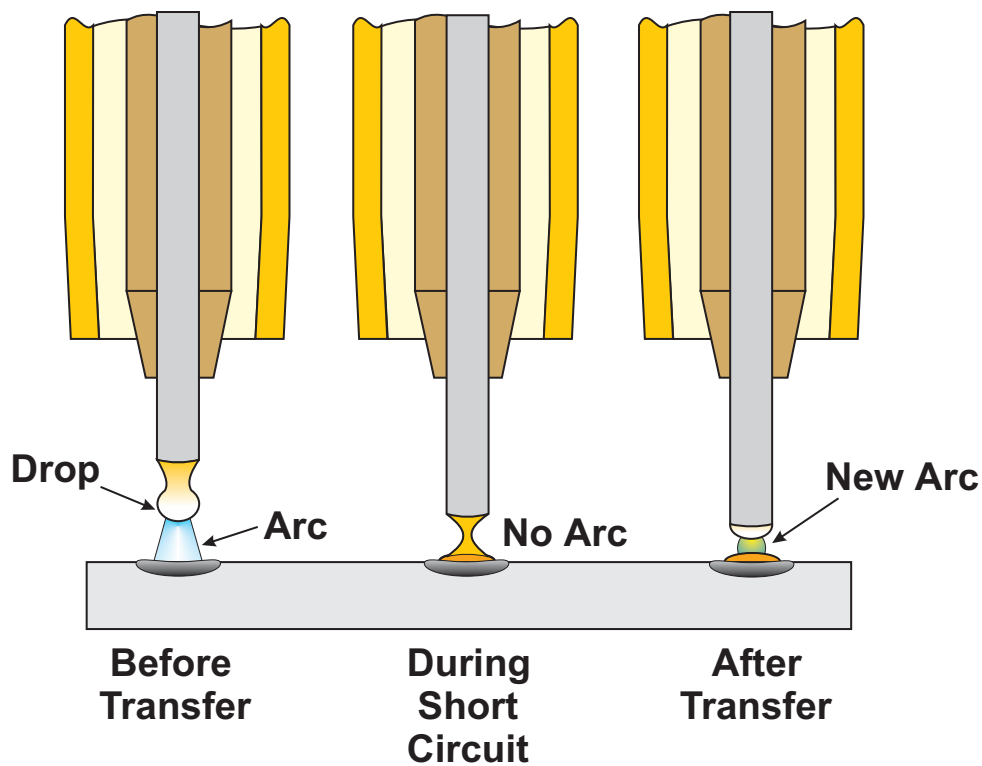


Figure 4.12: Short circuit transfer.

The welding current and voltage for short circuit welding, also called short arc or dip transfer welding, are relatively low and therefore it is best suited for welding of thin ferrous materials in all welding positions, and root passes of thicker steels. The short circuiting mode of metal transfer can be difficult to apply successfully to thicker materials because of the smaller diameters wires (1.2 mm or smaller) and low currents (less than 200 A for 0.9 mm diameter wire), and the resulting low heat input which can cause fusion problems (cold welding). Consequently, welding specifications for critical structural applications such as pressure vessels, bridges, naval vessels, etc, prohibit short circuit transfer mode if GMAW process is to be used. The shielding gases used for carbon-manganese steels are normally carbon dioxide (CO_2) or 75% argon - 25% CO_2 .

The short circuiting mode of metal transfer can not be applied to non-ferrous metals and alloys. Cast irons are mostly welded in the short circuiting mode.

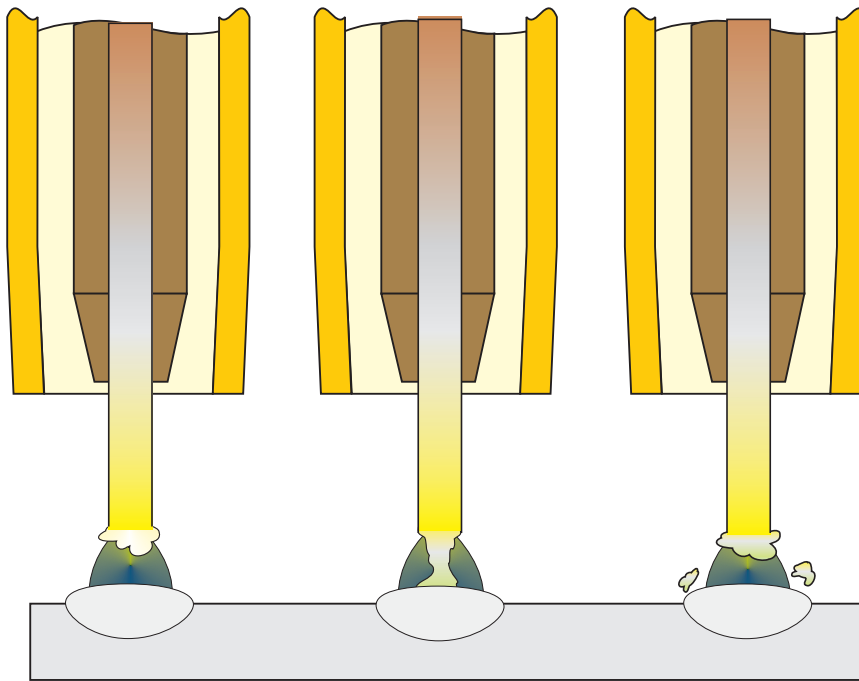


Figure 4.13: Globular transfer.

2) Globular Transfer

Globular transfer occurs as the current and voltage increase beyond those for short circuiting transfer. In this transfer mode (**Figure 4.13**), the molten drop of metal at the electrode tip can reach a diameter 1.5 to 3 times the wire diameter. This large drop of metal detaches from the electrode tip due to the force of gravity. It has an irregular shape, may have a rotational motion and takes an irregular path across the arc. The glob of molten metal splashes into the weld pool causing expulsion of some liquid metal (spatter). Globular transfer in GMAW tends to splatter and is usually avoided.

Carbon dioxide as well as argon rich gas mixtures containing CO_2 or oxygen can provide globular transfer. Very good penetration characteristics can be produced at higher current levels. The main drawbacks of globular transfer are spatter formation, irregular bead shapes and formation of numerous slag islands.

3) *Spray Transfer*

Spray transfer (**Figure 4.14**), also called axial spray, occurs at current and voltage levels above those for globular transfer, and when an argon rich (85% minimum) shielding gas mixture is used. The molten metal is transferred across the arc in a continuous stream of fine droplets, and the droplet diameter is typically less than the wire diameter. The arc is quite stiff so that the drops travel directly along the centerline of the electrode and into the weld pool, and therefore can be easily directed without affecting the arc behaviour.

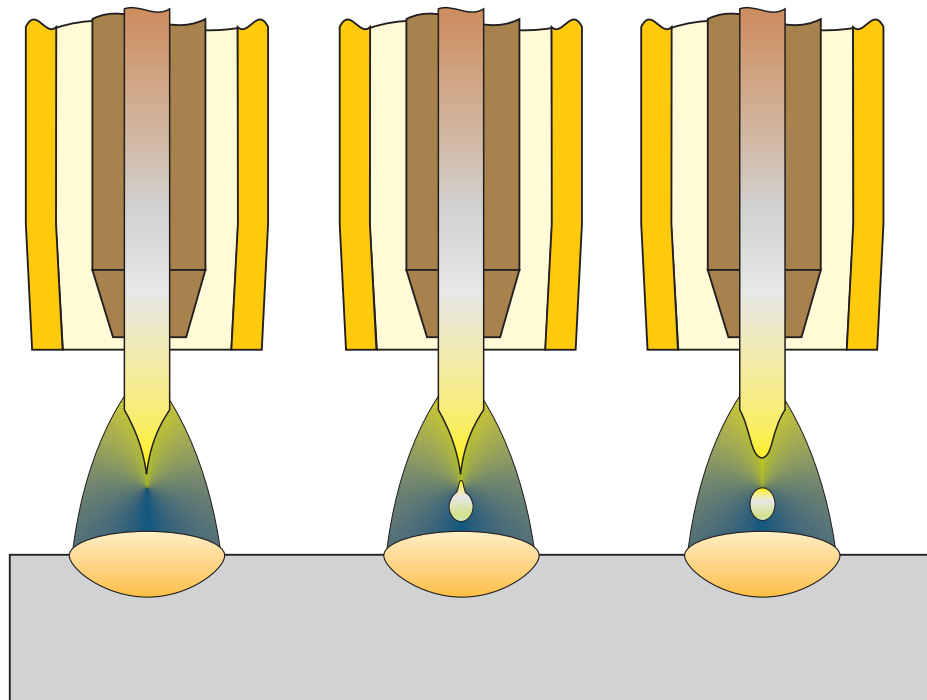


Figure 4.14: Spray transfer.

The **transition current** (the current at which the mode of transfer changes) for the change from globular to spray transfer (**Figure 4.15**) depends on the wire diameter, shielding gas composition, electrode composition and the electrical extension (the length of wire stick out at the contact tube). At very high currents, above the range for axial spray, the line of metal drops begins to rotate about the electrode axis, and there is an increase in spatter.

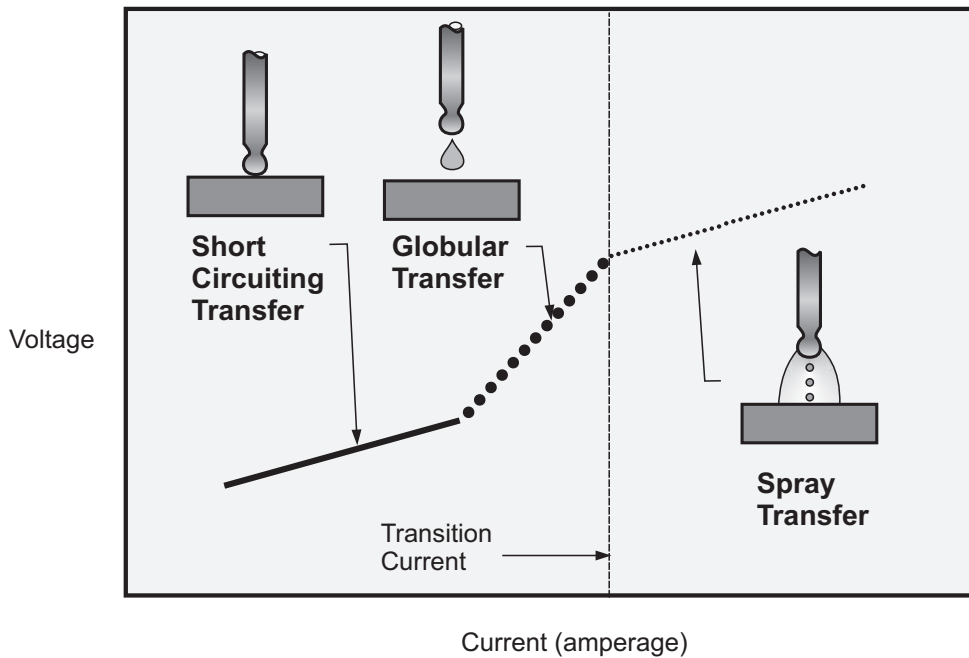


Figure 4.15: Transition current for globular to spray transfer.

Spray transfer is characterized by:

- ◆ minimal spatter;
- ◆ a relatively quiet and smooth arc;
- ◆ weld beads with good penetration and nice appearance.

However, because of the high current and voltage levels, the weld pool is rather large and difficult to control for out-of-position welds. Spray transfer is therefore suitable for welding in the flat and horizontal positions, and welding thick materials.

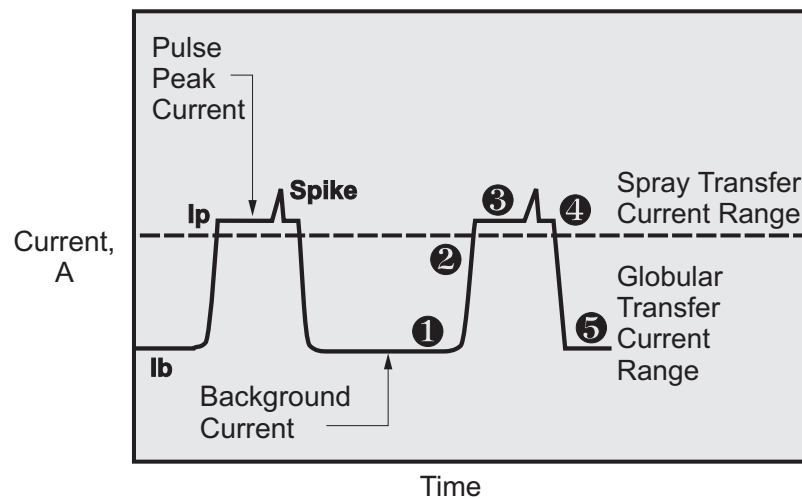
Pulsed Transfer (GMAW-P)

Pulsed transfer is a form of spray transfer. Its primary benefits are:

- ◆ all-position capability for ferrous and non-ferrous metals
- ◆ more productive for thin material than GTAW
- ◆ no spatter even for difficult filler metals
- ◆ able to use larger diameter electrodes

Pulsed spray transfer involves the use of a specially designed power source whose current output changes or "pulses" between a peak value and a background value at a rapid but controllable rate (**Figure 4.16(a)**). Peak current surges to above the transition value for spray transfer then drops to a background level so that in each pulse a drop of metal is detached and transferred across the arc. Background current is sufficient to maintain the arc and keep the electrode tip hot and ready to detach the next droplet during the next pulse.

The average current is generally in the range for globular transfer, well below the spray transition value, but the bead appearance resembles that obtained with spray transfer. Also, the lower average current implies a smaller weld pool and lower heat input, thus enabling out-of-position welding and welding of thin materials.



Pulsed-Spray Welding Current Characteristics

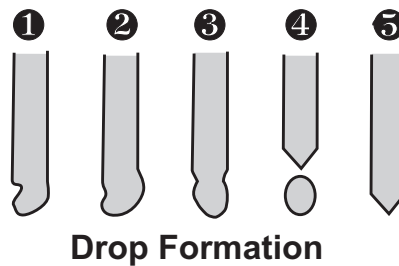


Figure 4.16(a): Pulsed spray transfer.

Aluminum and other reactive metals are welded with pulsed spray transfer. Larger diameter electrodes improve feeding and reduce weld pool contamination to significantly reduce the wire surface incorporated into the deposit. The length of electrode per kilogram(pound) greatly reduces as the electrode diameter increases. (eg., 1 kg of 0.9 mm diameter aluminum wire is 592 m long. By comparison, the same wire at 1.1 mm diameter is only 358 m long, a reduction of about 40%.)

An electronically controlled wire feeder with real-time wire feed regulation is used to ensure wire feed speed always remains close to the set speed.

a) *Effects of Pulse Parameters*

Electronically controlled pulsed power supplies allow adjustment of a number of pulsing parameters (**Figure 4.16(b)**):

- ◆ pulse rate
- ◆ pulse width
- ◆ peak amperage
- ◆ background amperage

b) *Pulse Rate*

Changes in wire feed speed are accompanied by changes in pulse frequency. As wire speed increases, the pulse frequency and therefore average current must also increase so that wire feed speed and burn-off rate are continuously matched. The increase in average current causes an increase in heat input. Pulse frequency can readily be used to control arc length.

c) *Pulse Width*

Pulse width is the time at peak amperage. Average amperage and heat input are directly effected by pulse width- both increase with increasing pulse width. Increasing pulse width also has some effect on increasing droplet size and widens the arc cone (bead width increases).

d) *Peak Amperage*

Peak current must be high enough to be above the spray transfer transition. Peak current detaches droplets and propels them across the arc. Peak current directly affects arc length - arc length increases with increasing peak current. Some power sources produce a spike to promote droplet detachment from the electrode tip.

e) *Background Amperage*

Control of current rise and fall during the pulse cycle is used to control droplet shape and to shape the electrode end in anticipation of the next droplet detachment.

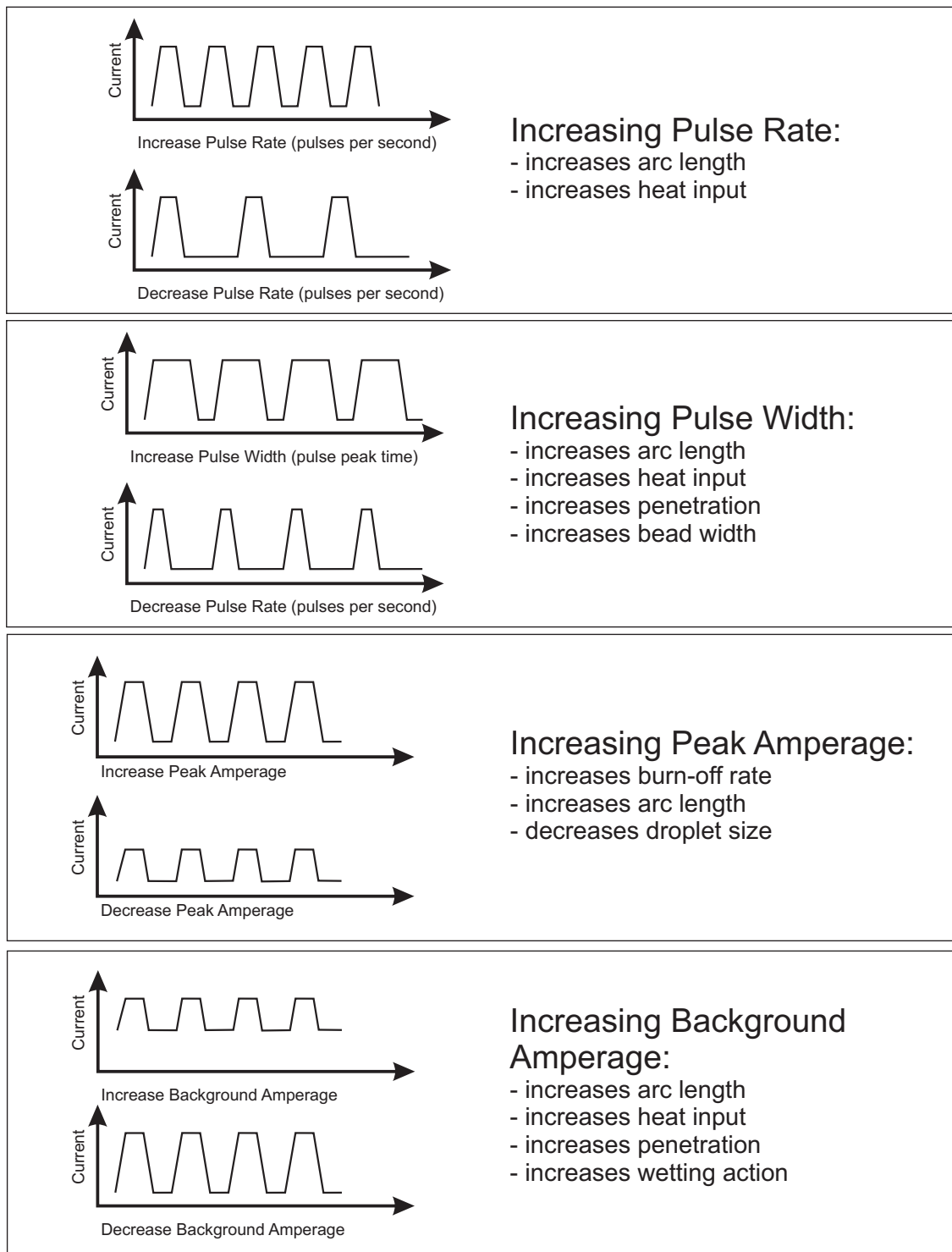


Figure 4.16(b): Summary of effects of pulse parameters.

Modern power sources allow peak current (I_p), background current (I_b) and the pulse width (duration or frequency) to be pre-programmed for a given application (i.e., shielding gas, wire type and diameter) and changes in wire feed speed are accompanied by changes in pulse frequency. As wire speed increases, the frequency and thus the average current increases so that wire feed speed and burn-off rate are continually matched. Some power sources produce a spike to facilitate the droplet detachment from the electrode tip.

With modern GMAW-P equipment there is a wide variation from one manufacturer to another in arc control methods and pulse programming. As a result, care must be taken in selecting appropriate equipment. Procedures that were successful with one equipment package may not be duplicated successfully on a different package and a certain amount of procedure development may be required for each case.

Synergic power sources are electronically controlled power sources that can provide a variable pulse frequency that is proportional to the wire feed speed. Synergic control is a "one knob" system that changes a number of interrelated variables at one time, simplifying operator control. Synergic power sources are commonly pre-programmed for 0.9, 1.2 and 1.6 mm diameter mild steel, stainless steel and aluminum wires. The systems are designed to allow re-programming or "fine tuning" of the pre-packaged programs.

The pulsed spray mode of metal transfer can be substituted for any of the three transfer modes discussed in the preceding paragraphs. When developed and applied correctly, the pulsed spray transfer mode enables welding in all positions, and helps reduce heat input, distortion and spatter.

The effect of metal transfer mode on weld bead shapes is shown in **Figure 4.17(a)** and **4.17(b)** which present cross sections of six bead-on-plate welds.

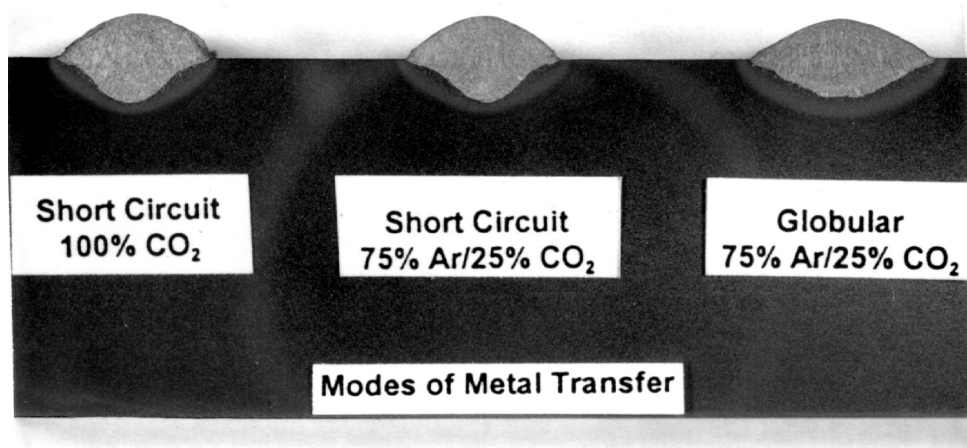


Figure 4.17(a): Short circuit and globular transfer.

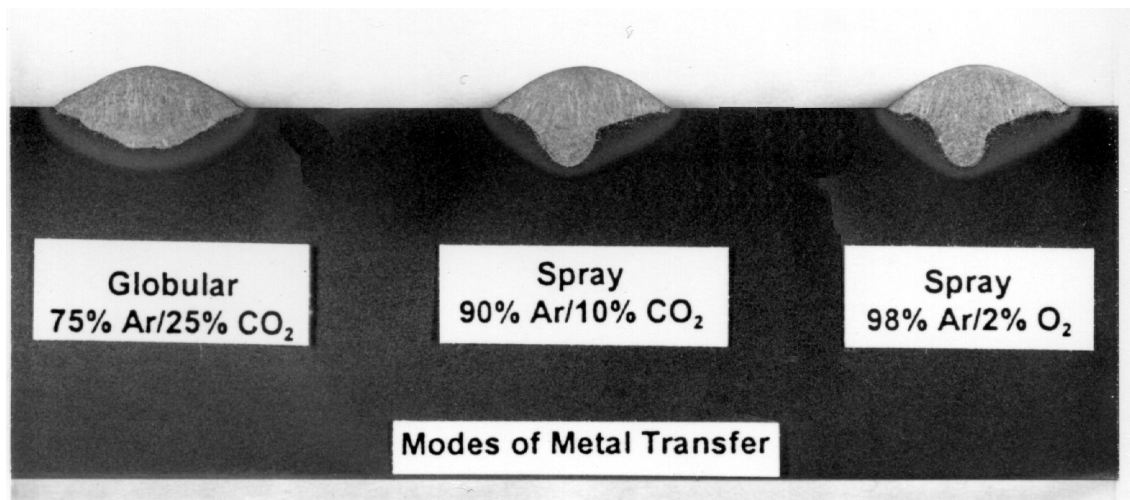


Figure 4.17(b): Globular and spray transfer.

4.3.4 Shielding Gas

The following shielding gas or gas mixtures are normally used for welding of carbon and alloy steels:

- ◆ carbon dioxide
- ◆ argon-carbon dioxide
- ◆ argon-oxygen

Carbon dioxide is the least expensive of the shielding gases used for gas metal arc welding. Once ionized, carbon dioxide has a high thermal conductivity, which helps to keep the arc plasma as a small, dense column under the electrode, and the metal is transferred in either the short circuiting or globular mode. The arc is less stable and spatters. The deposited weld bead has a rough surface but deep and round penetration as carbon dioxide transfers the greatest amount of heat to the weld pool (**Figure 4.18**).

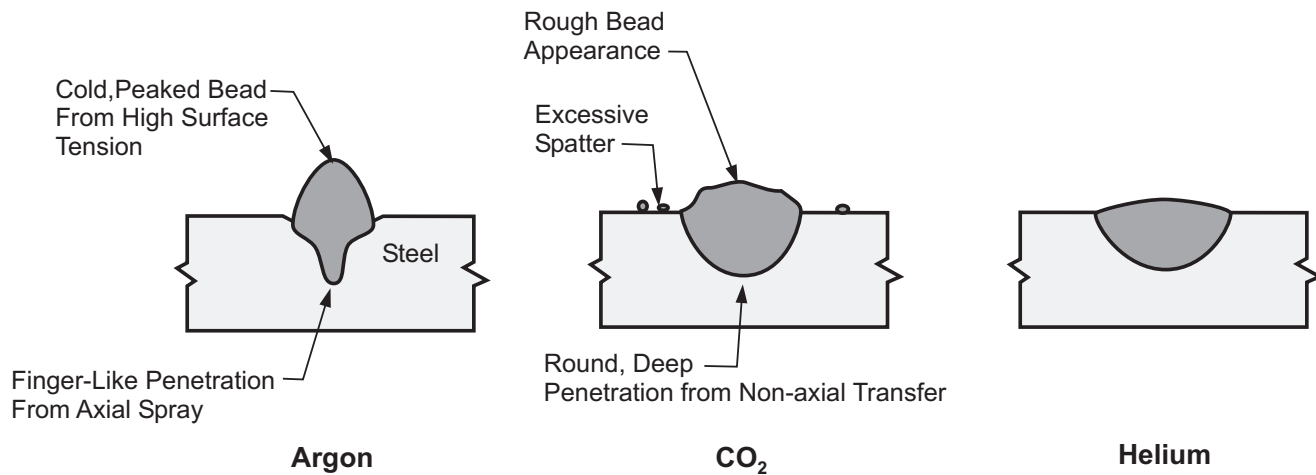


Figure 4.18: Effect of shielding gas on weld bead shape.

Carbon dioxide is an active gas in the sense that at the arc temperature it dissociates to produce carbon and oxygen, and the latter can oxidize the weld metal to form slag. The GMAW wires for use with carbon dioxide shielding gas therefore have sufficient level of deoxidizers like silicon, manganese, etc. to tie up the oxygen. As a result, the manganese and silicon contents of the weld metal tend to be lower than those in the wire. Conversely, in the case of stainless steels, the weld metal can pick up some carbon, which can make stainless welds more prone to corrosion.

Argon has a low ionization potential, which means that arc voltage and therefore the arc length can be smaller. Also, in the ionized form, argon has a low thermal conductivity. This causes the arc column to expand and extend upwards above the end of the electrode as the welding current is increased. The electrons hitting the electrode above the tip cause local heating and tapering of the electrode. This increases the local current density and the pinch force, causing small droplets to be easily detached and propelled at a high velocity to the weld pool in the form of a spray. However, the arc tends to be cold and unstable, and the weld bead formed is peaky with undercut and finger shape penetration (**Figure 4.18**). As a result, pure argon is not used for welding of steels. With higher conductivity gases such as carbon dioxide, the plasma column does not expand as much and therefore the electrons are restricted to striking the end of the electrode only. Therefore, no preheating of the wire end occurs and globular or short circuit transfer is promoted.

Small additions of active gases like carbon dioxide or oxygen to argon lead to the formation of a small amount of iron oxide on the surface of the weld pool. The oxide is able to increase arc stability as it is a better electron emitter, and it also reduces the weld pool surface tension. Lower surface tension promotes weld pool fluid motion and helps to reduce the tendency toward lack of fusion-type flaws. Carbon dioxide also transfers more heat to the base material and promotes rounded rather than finger penetration. **Argon-carbon dioxide** mixtures contain 75% argon and 25% carbon dioxide, commonly referred to as C-25 gas. This mixture provides better bead appearance and less spatter than straight CO₂ (**Figure 4.19**). It is generally used on mild and low alloy steels with short-circuiting or globular transfer.

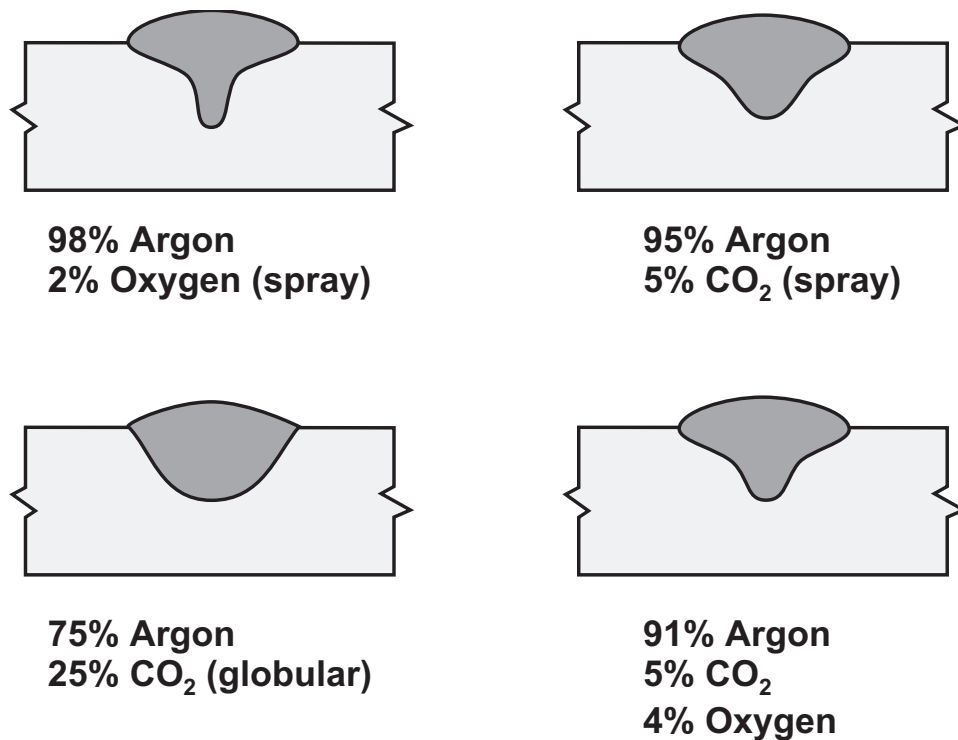


Figure 4.19: Effect of argon rich shielding gas mixture on weld bead shape.

Reducing the carbon dioxide content decreases the transition current for spray transfer, and therefore mixtures containing 15% or less carbon dioxide are more conveniently used for spray transfer. When the argon content is 85% to 92%, good penetration and smooth bead appearance are obtained. The current required for spray transfer is still reasonably high and the resulting higher arc energy and good penetration makes this gas composition range suitable for welding thicker materials.

With further increase in the argon content of the gas mixture to 95%, stable spray transfer can be maintained at a lower voltage. As a result, the arc energy is somewhat lower and therefore these higher argon containing gases are more suitable for welding thinner material in the flat and horizontal positions, though they can be used for thicker materials as well.

Since argon is an inert gas, it does not influence the weld metal composition. Therefore, as the amount of carbon dioxide, an active gas, is reduced in the argon-carbon dioxide mixture, a greater proportion of manganese and silicon present in the wire will be retained in the weld metal. As well, the weld metal will have a lower oxygen content and this can help to improve the notch toughness of the weld metal. Thus, argon-5% carbon dioxide is a commonly used gas mixture for welding high performance naval steels, where high notch toughness is very desirable.

There are some other gas mixtures that are used for stainless steel, aluminum and other alloys. Information regarding these gas mixtures can be found in CWB Module 4, Chapter 4, Gas Metal Arc Welding.

Safety with Gas Cylinders

The shielding gases and gas mixtures are normally supplied as compressed gases in cylinders. Whether in use or in storage, the cylinders must be secured and handled carefully since knocks or falls could damage the cylinder or the valve, and could cause a leak or an accident. The following precautions should be taken in the use of gas cylinders:

- ◆ always properly secure the cylinders
- ◆ while standing to one side, momentarily open the valve to clear any dirt present before connecting a regulator
- ◆ after connecting the regulator, release the pressure-adjusting screw and then slowly open the cylinder valve to prevent a high-pressure gas surge in the regulator
- ◆ always shut off the cylinder valve and back off the adjusting screw when the cylinder is not in use

The cautions given above apply to all shielding gases, whether for use with the GMAW process or other gas shielded processes (FCAW, MCAW, GTAW) discussed later. For more details on Welding Safety, reference CSA Standard W117.2 “Code for Safety in Welding and Cutting (Requirements for Welding Operators)” or Module 1, Welding Health and Safety, of the MLS series.

4.3.5 Advantages and Limitations of the GMAW Process

The main advantages of the GMAW process are its application to a wide variety of materials, higher deposition rate and productivity compared to the shielded metal arc welding process (**Figure 4.20**) and the better quality of the deposited weld metal. As well, with the recently developed advanced welding power sources and the availability of smaller diameter wires (0.9 and 1.1mm diameter), welding procedures can be developed to apply the process in all welding positions, both in semi-automatic and automatic modes.

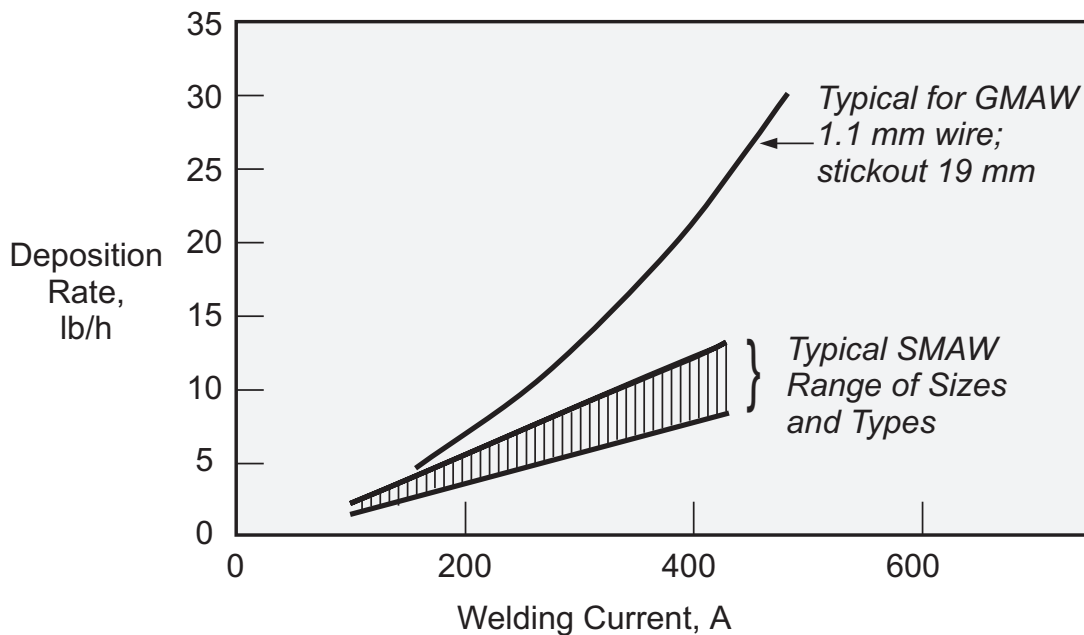


Figure 4.20: Comparative deposition rates of GMAW and SMAW.

The higher deposition rate results from the absence of electrode covering and higher current density (same current but smaller diameter wire). The higher productivity of this process results from:

- ◆ a higher duty cycle
- ◆ the time saved in not having to clean slag or flux from the deposited metal
- ◆ higher utilization of the filler metal

The weld metal deposited using the GMAW process is generally cleaner (fewer non-metallic inclusions) and in the case of high strength structural steels, weld metal with superior toughness can be obtained with proper selection of shielding gas (Ar-5% to 15% CO₂). Such applications include girth welding of large diameter natural gas and oil pipelines, submarine hulls, etc. The “low hydrogen” nature of the process is an additional important characteristic, especially for welding of high strength steels.

One of the main limitations of the gas metal arc welding process is its sensitivity to the welding parameters. Seemingly small changes in voltage, electrode extension, etc. can have a significant influence on the bead shape and penetration, and thus on the incidence of weld flaws such as incomplete fusion. Faithful reproduction of qualified welding procedures is therefore critical to obtain sound production welds. In this regard, matching wire feed speed between the qualification procedure and production situation is a good indicator that the correct procedure has been implemented. One must also be aware that air drafts can reduce the effectiveness of the shielding medium causing porosity in the weld metal.

4.3.6 Application of Gas Metal Arc Welding Process

Virtually all weldable materials can be joined with the GMAW process. Nonferrous alloys (aluminum, magnesium, copper, nickel, titanium and their alloys) are welded using spray or pulsed spray mode, and successful procedure development depends mainly on selection of the shielding gas and welding parameters. The filler metal is often designed to somewhat match the base material in composition. Due to the inert shielding gas, no significant changes in chemistry of the deposited weld metal should occur. There are exceptions of course; aluminum filler metals are formulated to prevent hot cracking and do not normally match the base metal chemistry.

Gas metal arc welding of structural steels on the other hand can be more complex. Considerations include filler metal composition, shielding gas and metal transfer mode, as well as the metal thickness, joint design and welding position.

Similar joint designs can be employed for gas metal arc welding as for shielded metal arc welding except that groove angles can be reduced due to the smaller diameter of GMAW wires. GMAW can be less forgiving than SMAW or FCAW, particularly when using smaller wire diameters. Good penetration and fusion is easily obtained directly beneath the arc however, in many cases increased oscillation is required to properly fuse into the sides of the joint, whereas for the same joint FCAW or SMAW can produce satisfactory results without oscillation. High argon-content shielding gases create a directional penetration shape (finger penetration), which is prone to incomplete fusion.

Steels in thickness from about 1 to 3 mm can generally be butt welded with square edges in one pass, provided the gap is less than 3 mm. For steel thickness ranging from 3 to 6 mm, a complete penetration groove joint can be obtained with square edge preparation by welding from both sides, provided that there is adequate root gap (1 to 4 mm). Above 6 mm, it is customary to prepare the joint edges. Thicknesses greater than 6 mm usually require multiple passes.

4.3.7 Electrode Wires for Gas Metal Arc Welding

The requirements for filler metals for **carbon steels** are covered in CSA Standard W48-01, and those for **higher strength steels** (ultimate tensile strength greater than 490 MPa) in AWS Specification A5.28. Gas metal arc welding wires are classified based on their composition and the expected weld metal tensile strength. A typical gas metal arc welding electrode designation can be written as:

ER XX S-xxx

where	E	designates an electrode
	R	designates a rod or wire suitable for processes such as GMAW, GTAW, etc.
	XX	represent the minimum weld metal tensile strength (in increments of MPa) in the as-welded condition when deposited in accordance with a specified procedure (W48-01). In AWS specifications, only two digits indicate the tensile strength in ksi
	S	indicates a solid electrode
	xxx	are a one to three digit/alphabet-digit combination indicating the composition of the wire

For example, a wire designation ER49S-2 means that the as-welded deposit will have a minimum tensile strength of 490 MPa and that the wire contains nominal amounts of zirconium, titanium and aluminum for deoxidation purposes in addition to silicon and manganese. Such wires are capable of producing sound welds in semi-killed and rimmed steels, especially using the short-circuiting mode of metal transfer. Moreover, these wires can be used to produce acceptable welds even when there is some rust present at the steel surface. Further guidance on the optimum use of various carbon steel wires is given in the appendix to CSA Standard W48-01. It should be noted that CSA Standard W48-01 certifies GMAW wires based on tests with 100% CO₂ shielding gas only. Certified wires are permitted to be used with argon-rich gas mixtures, but with certain restrictions on the CO₂ and O₂ contents. Argon rich gas mixtures cause an increase in weld metal manganese and silicon content while decreasing oxygen content. This occurs because of a lack of “active gas” in the arc atmosphere. Electrodes certified with CO₂ are purposely over-alloyed with manganese and silicon to compensate for losses in a CO₂ arc environment. Retaining these alloys in the weld will increase the yield and tensile strength properties before deciding to use shielding gas mixtures containing only small amounts of oxygen and/or carbon dioxide.

Electrode diameters are commercially available in the range of 0.9 to 1.6 mm. The largest diameter electrode that can be used depends partly on the steel thickness to be welded. It is usually 0.9 mm diameter for workpiece thickness up to 10 mm, and 1.2 mm for workpiece thickness up to 20 mm.

Gas metal arc welding is treated as a controlled hydrogen welding process as long as due care is taken to ensure that the electrode and the joint surfaces are clean. The shielding gas used must have a low moisture content. Moisture content is evaluated by the temperature at which condensation occurs. Welding grade gases usually have a dew point of -40°C.

4.4 Flux Cored Arc Welding (FCAW)

4.4.1 Principles of Operation

The gas shielded flux cored arc welding process combines specific features from both the shielded metal arc and gas metal arc welding processes. A continuous filler metal electrode is used but it has a hollow core. The core is filled with flux and other ingredients that perform the same functions as the covering on the shielded metal arc welding electrodes, to stabilize the arc, generate gases and provide a slag cover to shield the arc and weld metal from atmospheric contamination, purify the weld metal, add alloying elements, shape the weld bead, etc. Further protection is provided by an externally supplied shielding gas.

In operation, an arc is struck between the continuously fed tubular wire containing the fluxing and other ingredients (flux cored wire) and the workpiece (see **Figure 4.21**). As in the GMAW process, the heat generated by the arc melts the end of the electrode (the metal sheath and the ingredients inside) and part of the base metal at the weld seam. The arc transfers the molten metal from the tip of the melting electrode to the workpiece where it becomes the deposited metal. The arc travel along the weld seam can be mechanized (automatic welding) or manual (semi-automatic welding).

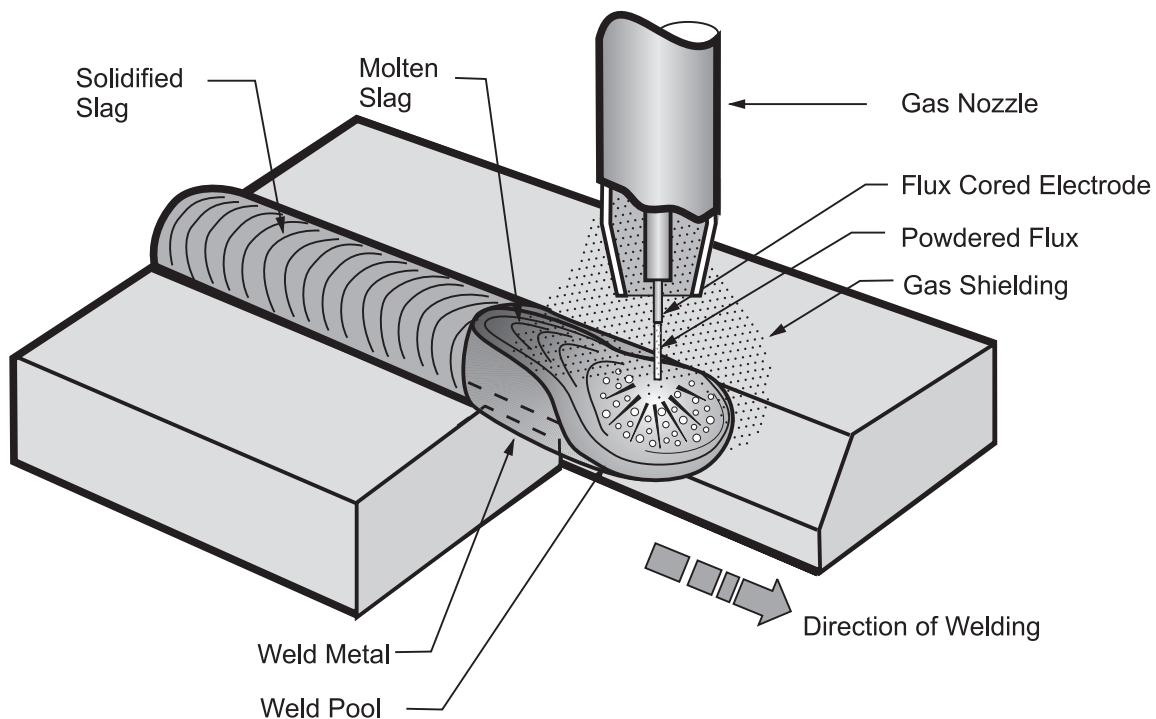


Figure 4.21: Schematic representation of the gas shielded flux cored arc welding process.

There are three groups of tubular electrodes are available for common use:

- ◆ The first group of wires are called gas shielded flux cored wires and these are meant to be used with an external gas shield following the original developments in the 1950s.
- ◆ The first major variation of the gas shielded flux cored wire was the self-shielded flux cored wire. With these wires, as the name implies, no external gas shield is used (**Figure 4.22**) and instead all the required shielding of the arc and the weld pool is provided by the gases formed by the break down of flux ingredients in the core and the slag cover on the weld metal. A certain amount of nitrogen pick-up from the atmosphere is unavoidable and therefore denitrifiers or nitrogen fixers such as aluminum are added to the core ingredients.

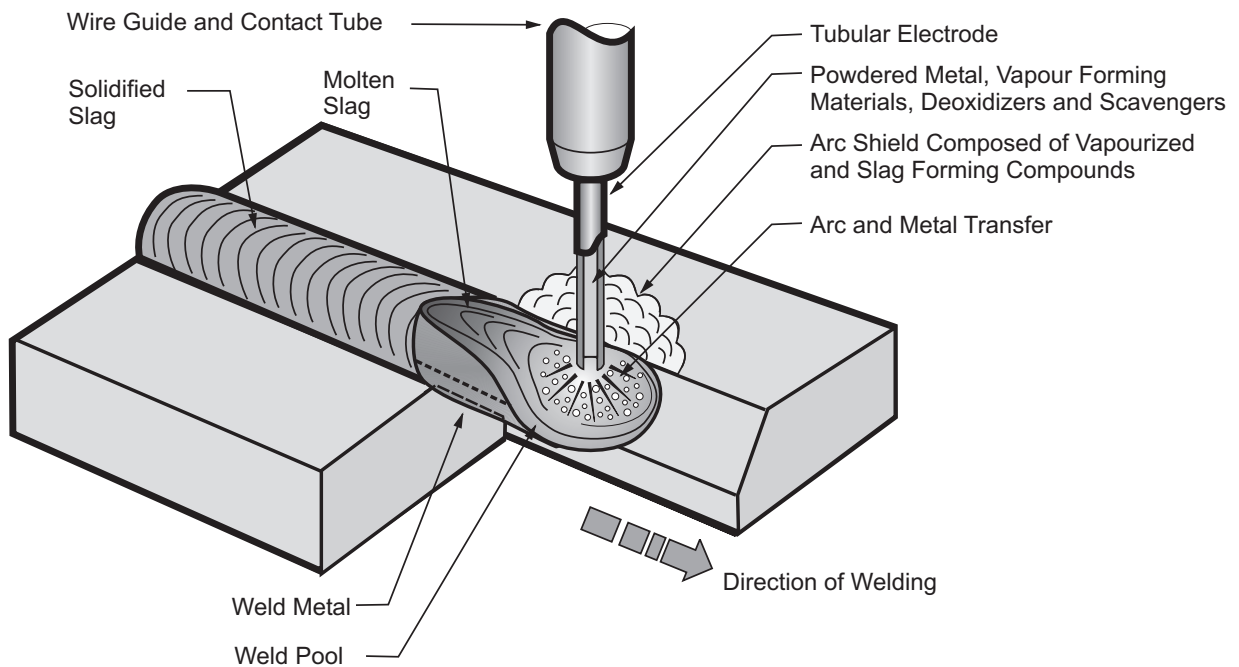


Figure 4.22: Schematic representation of the self-shielded flux cored arc welding process.

- ◆ Another group of tubular wires are called metal cored electrodes. These wires combine features of flux cored and gas metal arc welding wires. The continuously fed wire is cored but does not contain fluxing ingredients. Instead the core contains only arc stabilizing compounds, deoxidizers and metal powders. The shielding is therefore provided only by the externally supplied shielding gas as in GMAW. Metal cored arc welding electrodes are grouped with flux cored arc welding wires in Canadian Standard CSA W 48-01, but in the United States, these wires are considered as a variation of gas metal arc welding process.

4.4.2 Equipment

The equipment arrangement for gas shielded FCAW and MCAW is essentially the same as for GMAW and is described previously (**Figure 4.23**). It comprises a constant voltage power source, a constant speed wire feeder and control system, the welding gun and a supply of shielding gas. The power source and the gun must be rated for the current levels that are likely to be used with the selected electrode. Since the flux cored arc welding process may involve higher welding currents, guns for semi-automatic welding can be provided with an attached protective hand shield. Most electrodes are designed for welding with direct current electrode positive polarity. As in GMAW, the constant voltage power source and constant speed wire feeder enable a constant arc voltage/arc length to be maintained.

In the case of self-shielded flux cored arc welding, the guns used are slightly different since there is no need for an external gas supply. Most self-shielded flux cored arc welding wires are designed for welding with direct current, electrode negative polarity and with longer electrode extensions. Due to the latter, an insulated extension guide is attached to the contact tube to ensure that the wire and the arc are directed at the intended location.

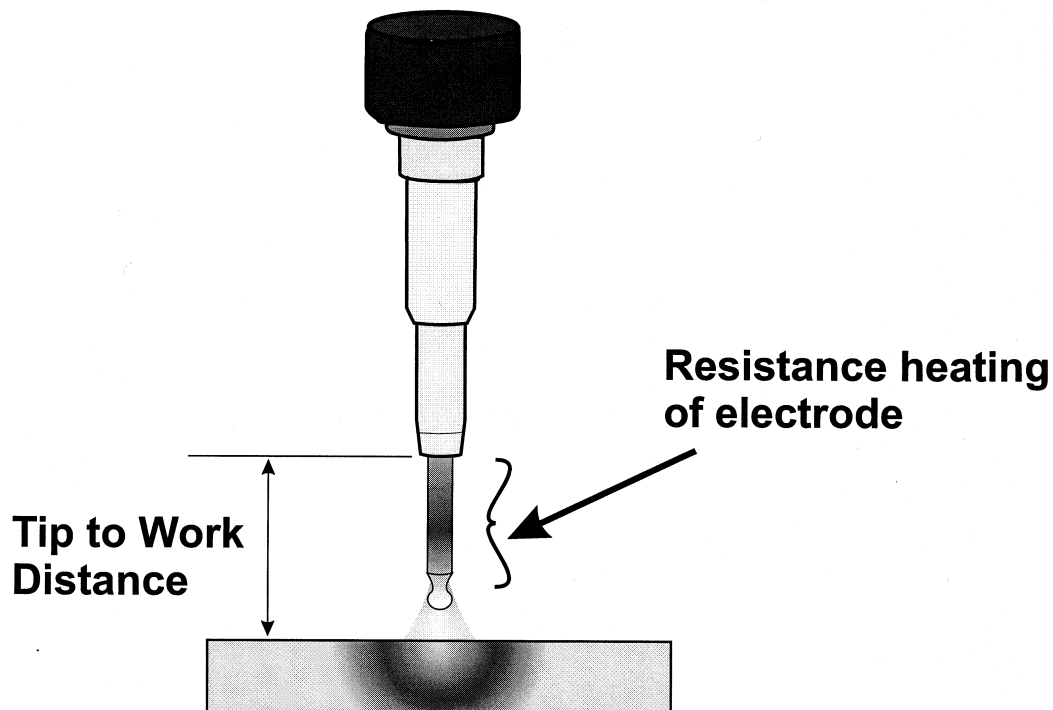


Figure 4.23

4.4.3 Advantages and Applications of the Cored Wire Processes

The cored wire processes offer a high quality weld deposit with higher deposition rate and productivity than the SMAW process. Higher productivity is a result of a high duty cycle, high deposition efficiency and high travel speeds. Compared to GMAW, the cored wire processes are more tolerant of small deviations in welding current, voltage, tip to work distance, etc., and therefore are more likely to provide weld deposits free from incomplete fusion flaws.

Among the three cored wire variations covered here, the self shielded flux cored wires are better able to tolerate air currents than the others and therefore are a more suitable candidate for field work. In automatic applications, very high travel speeds are possible with self shielded wires, leading to high productivity. However, these wires should be properly selected since some formulations are not designed for multipass welds. Metal cored electrodes produce little if any slag or oxide, similar to the GMAW process. However, the metal cored wires provide a higher deposition rate than does GMAW, and also a wider, more rounded bead shape when argon rich gas shielding is used (**Figure 4.24**).

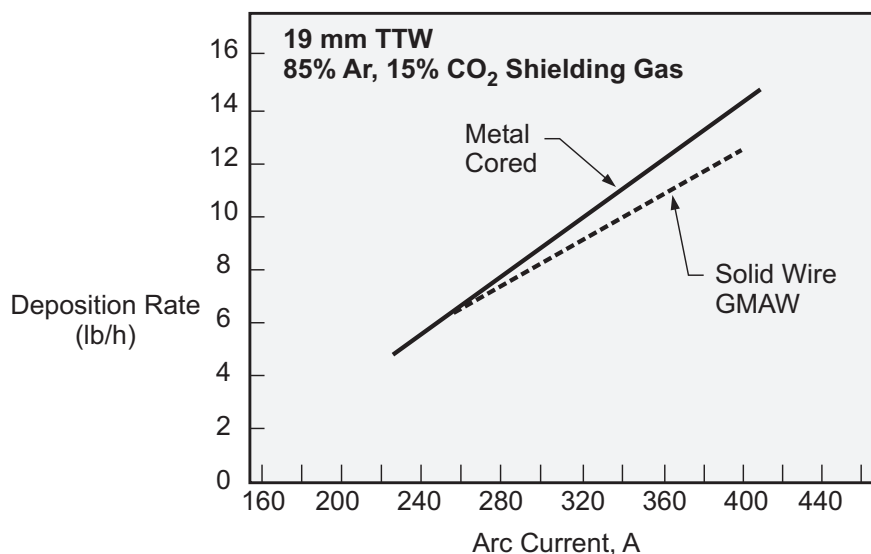


Figure 4.24: Comparative deposition rates for GMA and metal cored wire welding with 1.6 mm diameter wires. (TTW - tip to work distance)

Compared to GMAW, the main disadvantage of the cored wire processes is the amount of fume generation. Self shielded tubular electrodes produce the greatest amount of particulate fumes, which in some cases may be more than covered electrodes. Gas shielded flux cored and metal cored electrodes normally produce less fume than covered electrodes but more than GMAW, though the rates can vary significantly from wire to wire. Secondly, there is a need for interpass slag removal with the flux cored wires. Finally, as for GMAW, the weld quality of gas shielded FCAW and MCAW welds can be impaired by the presence of air drafts.

Tubular electrodes are available for welding several of the commercially significant metals and alloys such as carbon and low alloy steels, stainless steels, nickel alloys, as well as for hardfacing and surfacing applications. Depending on the wire size and the type of ingredients in the core, cored wire processes can be applied for welding in all positions.

The flux cored arc welding process is a more productive substitute for shielded metal arc welding in most applications. It is commonly used for medium thickness workpieces, which may be considered as relatively thin for optimum application of the submerged arc welding process and relatively thick for optimum application of small diameter wire, gas metal arc welding with CO₂ gas shield. Such applications are quite common in the fabrication of construction equipment. General structural steel and industrial equipment fabrication (e.g., machine tool bases, ladles for the steel industry, etc.) are also a major user of the process.

More recently, the flux cored arc welding process is being used for pipe welds. Applications in the pressure vessel industry are also increasing gradually as newer wires provide lower weld metal hydrogen content, better toughness and better control over excessive strength (**Figure 4.25**). Still, the weld metal toughness can be adversely affected by thermal stress relief, and therefore weld tests should be performed to confirm that weld metal toughness is still adequate after stress relieving.

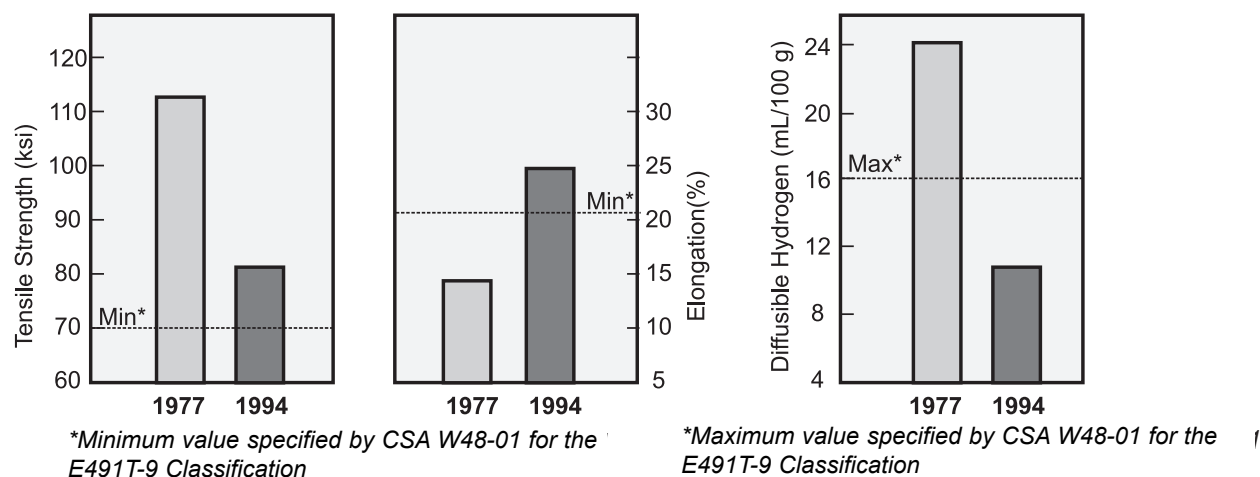


Figure 4.25: Improved control of weld metal mechanical properties and hydrogen content in recently developed E491T-9 wires.

4.4.4 Classification of Cored Wires

The requirements for carbon steel flux cored arc welding wires (both self-shielded and gas shielded) are described in CSA Standard W48-01 and with some differences, in AWS Specification A5.20. Those for low alloy steels, stainless steels, and for surfacing are included in AWS Specifications A5.29, A5.22, and A5.21, respectively.

Gas shielded carbon steel and low alloy steel flux cored wires are usually classified as rutile or basic, depending on the flux chemistry. Metal transfer using rutile wires is in the spray mode over a large operating current range, and for all practical purposes there is no globular-to-spray transition current (**Figure 4.26**). The deposited bead is generally smooth with excellent penetration, and out of position welding capability is achieved by controlling the slag fluidity by suitably designing the core ingredient mix. Recent improvements in the design of rutile wires include lower weld metal hydrogen content and better notch toughness by microalloying the weld metal with titanium and boron.

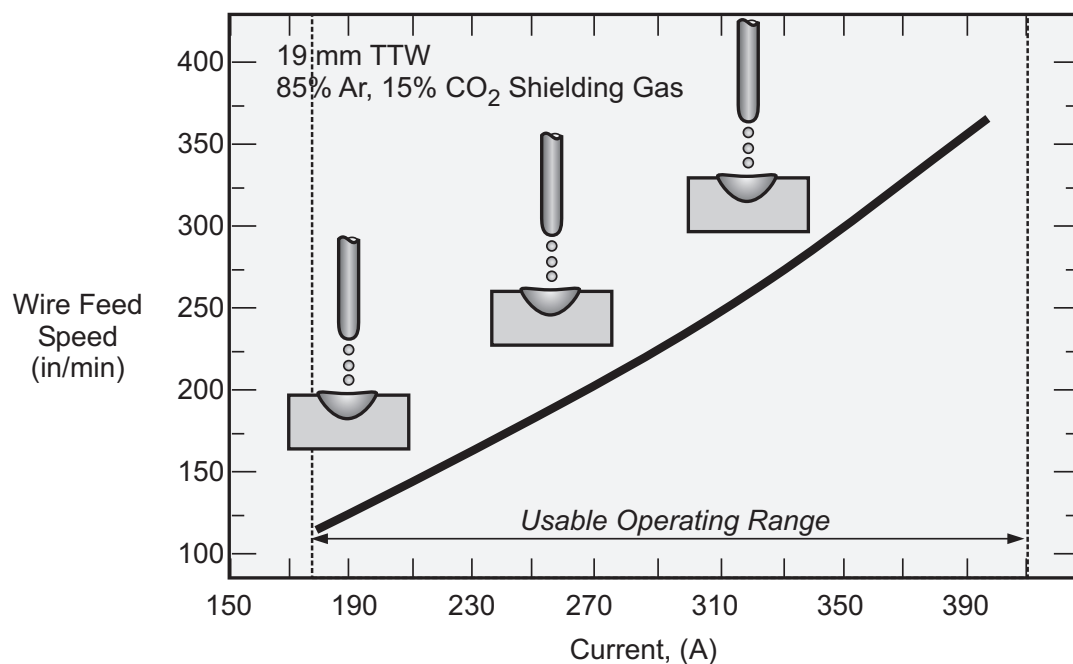


Figure 4.26: Wire feed speed and spray transfer mode with 1.6 mm diameter rutile FCAW wire.

Basic flux cored electrodes have core ingredients rich in limestone and fluorspar, similar to the covering on basic (E4918) electrodes. These electrodes do not readily operate in the spray mode. Metal transfer occurs in the short circuiting mode at low currents and in globular mode at high currents (**Figure 4.27**). While the penetration characteristics are comparable to that of rutile wires, the arc is less stable, with considerable spatter. More important, the slag is very fluid making it difficult to use basic wires for out-of-position welding. Due to the basic nature of flux ingredients, the weld deposit has relatively low hydrogen content and superior notch toughness compared to rutile wires (**Figure 4.28**).

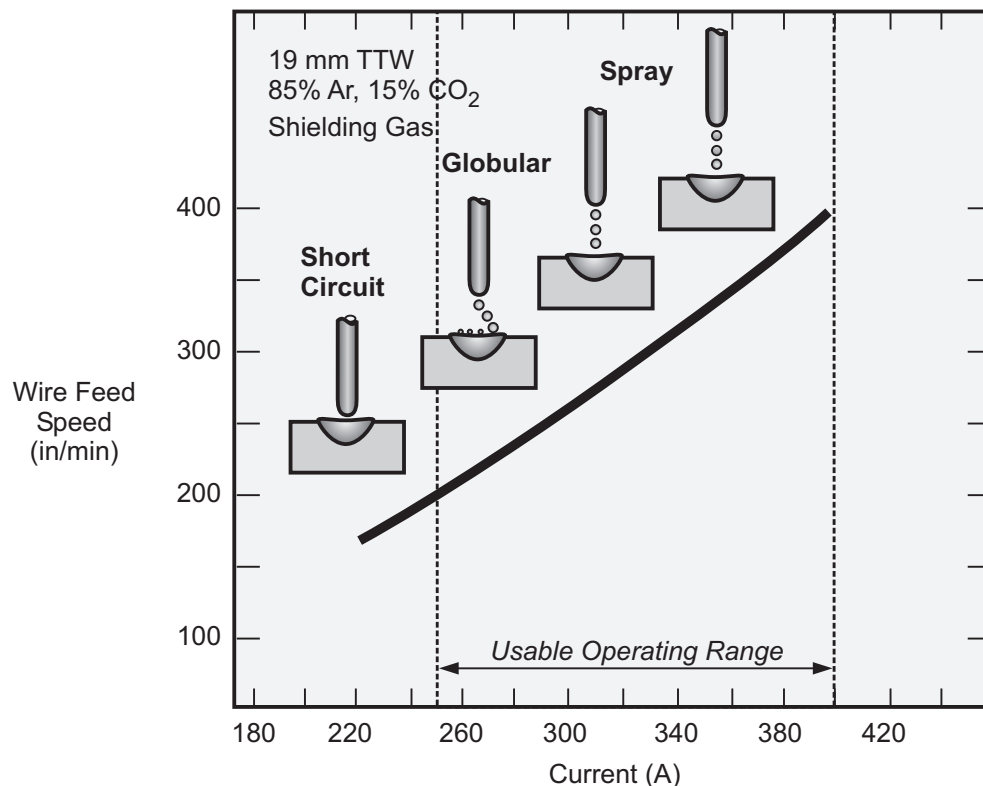


Figure 4.27: Wire feed speed and metal transfer mode in 1.6 mm diameter basic FCAW wire.

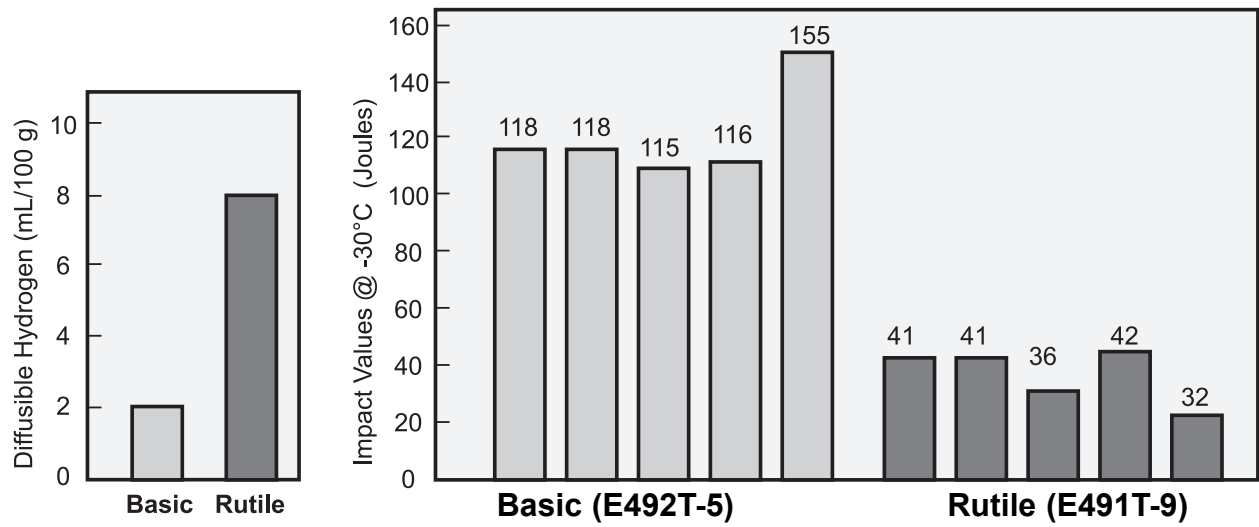


Figure 4.28: Comparative weld metal notch toughness and diffusable hydrogen levels in weld metals deposited by basic and rutile wires.

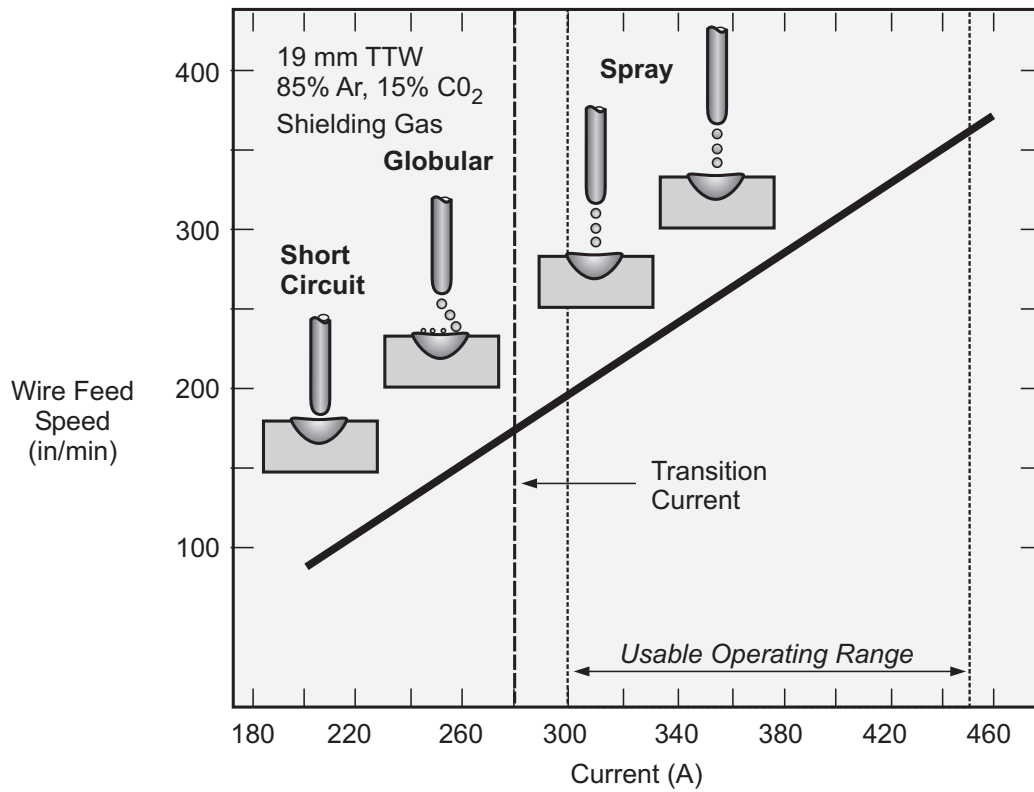


Figure 4.29: Wire feed speed and metal transfer mode in 1.6 mm diameter metal cored wire.

Metal transfer in metal cored wires can be in any of the three modes — short circuiting, globular or spray, depending on the welding parameters and shielding gas (**Figure 4.29**). In practice, spray mode is used most often. For out of position applications pulsed spray transfer can be used.

The cored wire designation schemes followed in CSA Standard W48-01 and in AWS Specification A5.20 for classification purposes are shown in **Figures 4.30(a)** and **4.30(b)**, respectively.

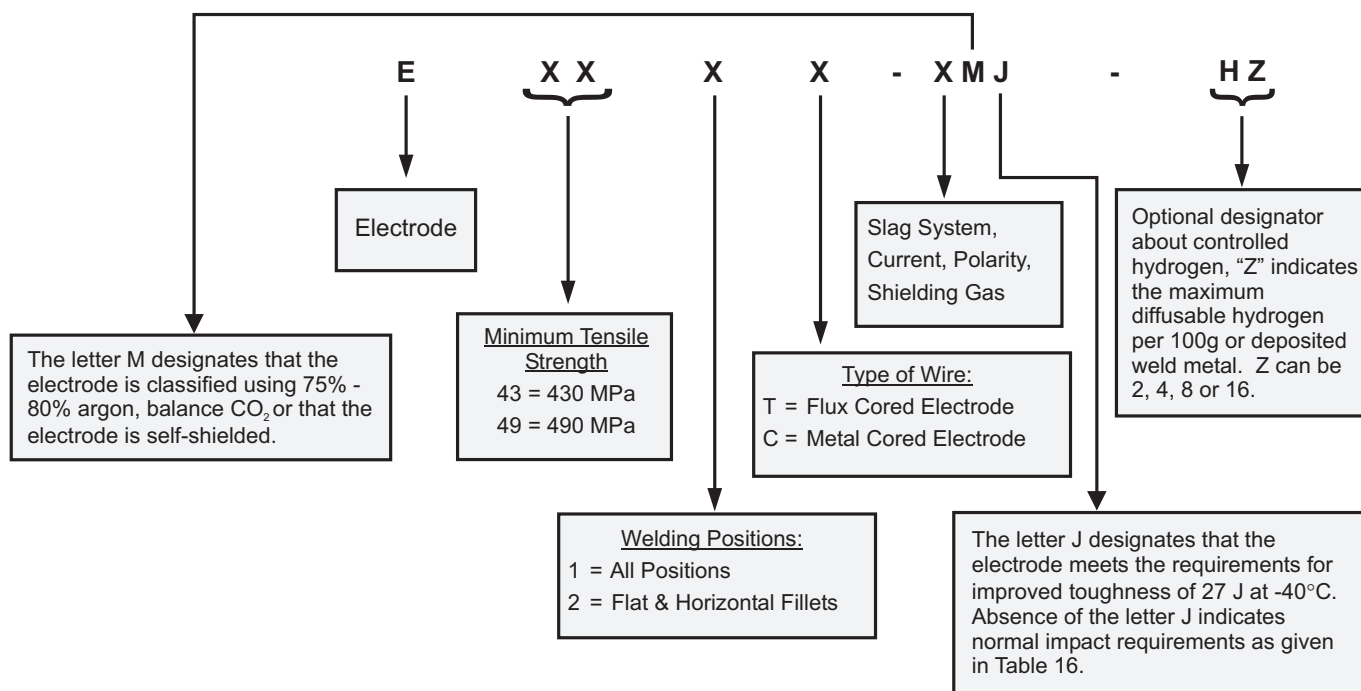


Figure 4.30(a): Classification scheme for flux cored wires in CSA Standard 48-01.

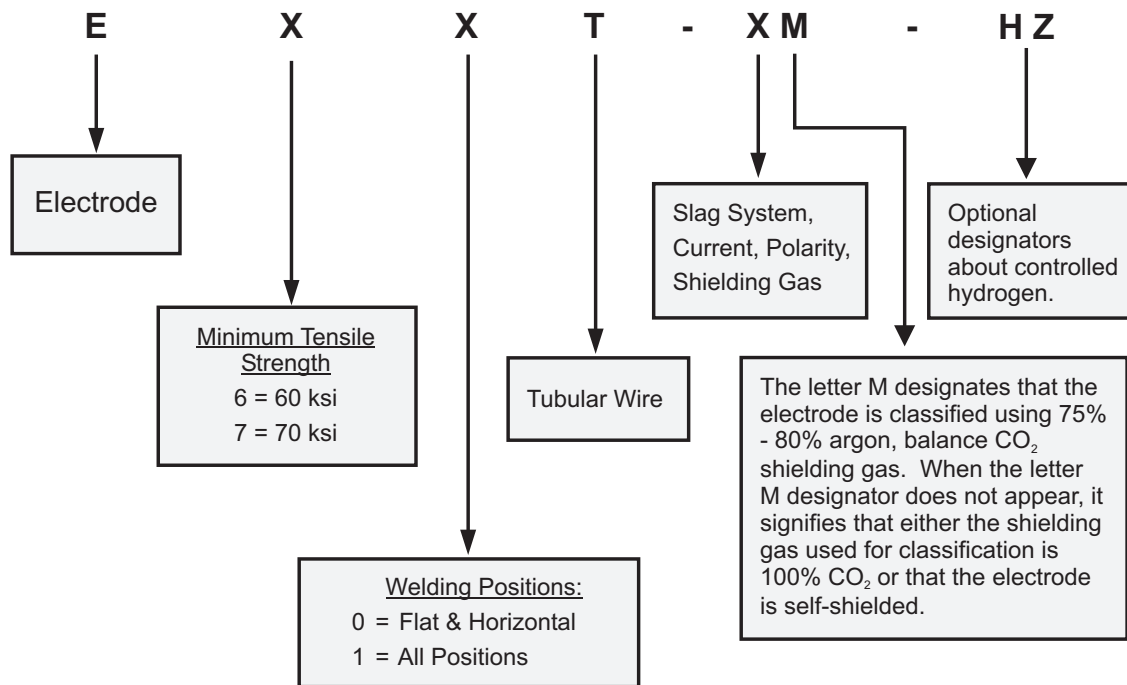


Figure 4.30(b): Classification scheme for flux cored wires in AWS specification A5.20.

The main differences between the two schemes are:

- ◆ Two digits are used in the CSA scheme to denote the minimum weld metal tensile strength (in increments of 10 MPa) as opposed to a single digit (equal to ksi/10) used in the AWS scheme;
- ◆ For the welding position indicator, CSA Standard uses the digit 2 to indicate suitability for flat and horizontal positions whereas the AWS system uses 0 for the same purpose;
- ◆ Metal cored wires are included in CSA Standard tables of CSA W48-01 dealing with flux cored wires whereas in AWS, metal cored wires are included in tables CSA W48-01 dealing with solid wires for gas metal arc welding;

The last digit in the cored wire designation in the classification scheme denotes the slag system, current polarity and shielding gas are shown in **Table 4.4**.

Table 4.4 : Shielding gas, current, polarity and slag system for electrodes of different classification.

CSA W48-01 Classification	Application	Slag System	Shielding Gas	Current and Polarity
T-1*	Multiple Pass	Rutile	CO ₂ *	dc, electrode positive
T-2*	Single Pass	Rutile	CO ₂ *	dc, electrode positive
T-3	Single Pass	Fluoride, rutile	None	dc, electrode positive
T-4	Multiple Pass	Fluoride	None	dc, electrode positive
T-5*	Multiple Pass	Lime, fluoride	CO ₂ *	dc, electrode positive
T-6	Multiple Pass	Basic oxide	None	dc, electrode positive
T-7	Multiple Pass	Fluoride	None	dc, electrode negative
T-8	Multiple Pass	Fluoride	None	dc, electrode negative
T-9*	Multiple Pass	Rutile	CO ₂ *	dc, electrode positive
T-10	Single Pass	Fluoride	None	dc, electrode negative
T-11	Single Pass	Fluoride	None	dc, electrode negative
T-12*	Multiple Pass	Rutile	CO ₂ *	dc, electrode positive
T-13	Single Pass	c)	None	dc, electrode negative
T-14	Single Pass	d)	None	dc, electrode negative
T-G	Multiple Pass	b)	a)	a)
T-GS	Single Pass	b)	a)	a)
C-3*	Multiple Pass	Not applicable	CO ₂ *	Dc, electrode positive
C-6*	Multiple Pass	Not applicable	CO ₂ *	Dc, electrode positive
C-G	Multiple Pass	Not applicable	a)	a)
C-GS	Single Pass	Not applicable	a)	a)

*The classification T-1M, T-2M, T-5M, T-9M, T-12M, C-3 and C-6 are possible if the qualification tests are made with gas mixtures of 75% - 80% argon, balance CO₂.

- (a) As agreed upon between supplier and user.
- (b) Slag system developed by the manufacturer for specific applications.
- (c) Designed for root pass in pipeline girth welds.
- (d) Designed for welding of galvanized and aluminized sheet steels.

The classification scheme for low alloy flux cored arc welding wires in AWS 5.29 Specification is similar to that for carbon steel wires, the main difference being the higher weld metal tensile strength and additional letters and numbers at the end used to indicate alloying elements present in the weld metal. Similarly, metal cored wires for low alloy steels have the same classification scheme as low alloy steel solid wires in AWS A5.28 except that S (denoting solid wire) is replaced by C (indicating composite or metal cored wire). In comparison, stainless steel flux cored arc welding wires are classified based primarily on the weld metal composition and the shielding medium used during welding.

4.4.5 Shielding Gases for Flux Cored Electrodes

When required, carbon dioxide is used as the shielding gas for classification purposes. However, Argon-Carbon Dioxide (Ar-CO₂) mixtures are increasingly becoming popular as their use with rutile wires provides less spatter, smoother beads and better wetting action and puddle control for out-of-position welding. Similarly, with basic wires, less spatter and smoother beads are obtained. Fewer fumes are generated when compared with 100% CO₂ shielding gas. However, weld penetration is reduced to some extent. For the reasons just mentioned, the last revision of the Standard CSA W48-01 allows for a M9 ("Mixed gas") designator in the classification, which allows classification of wires with gas mixtures having 75% - 80% argon, balance CO₂. Metal cored wires are used mostly with Ar-CO₂ mixtures, as welding with 100%CO₂ shielding gas is rare.

Since Argon (Ar) is an inert gas, it does not react with elements in the arc. Use of Ar-CO₂ mixtures as a shielding gas causes less oxidation of Manganese (Mn) and Silicon (Si) present in the wire, leading to higher Mn and Si content in the weld metal. This increases the weld metal tensile strength, and may also reduce the elongation values (**Figure 4.31**). Similarly, the amount of hydrogen retained in the weld metal can be larger compared with the use of CO₂ gas. The wires can be designed to avoid excessive increase in weld metal strength and impairment in elongation, and therefore the manufacturer should be consulted and/or procedure qualification performed before embarking on the use of Ar-CO₂ mixture with flux cored wires in fabrication. The shielding gas selected does not affect the deposition rate to any significant extent.

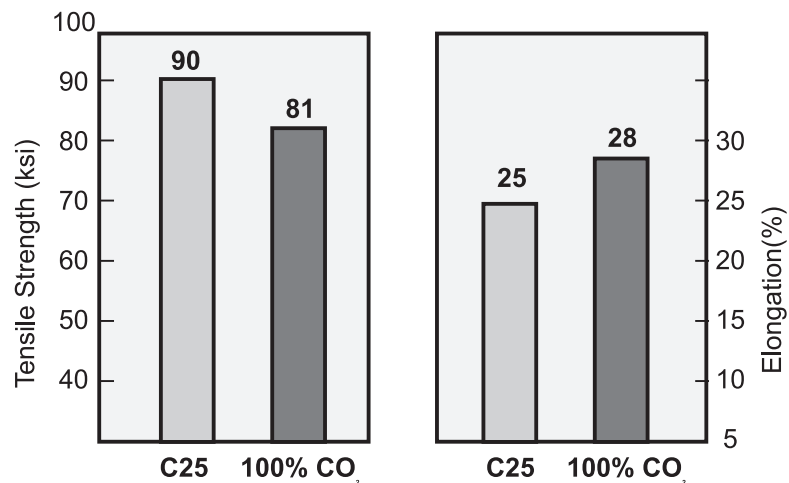


Figure 4.31: Effect of shielding gas on weld metal strength and elongation.

4.5 Submerged Arc Welding (SAW)

4.5.1 Principles of Operation

The submerged arc welding process is shown schematically in **Figure 4.32**. Compared to the shielded metal arc welding process, the flux to provide shielding is laid in granular form on the unwelded seam ahead of the bare metal electrode. The electrode is fed continuously from a coil, thus avoiding the interruptions inherent in the SMAW process to change electrodes. The flux is quite effective in preventing the atmosphere from contaminating the molten weld metal and no external shielding gas is required.

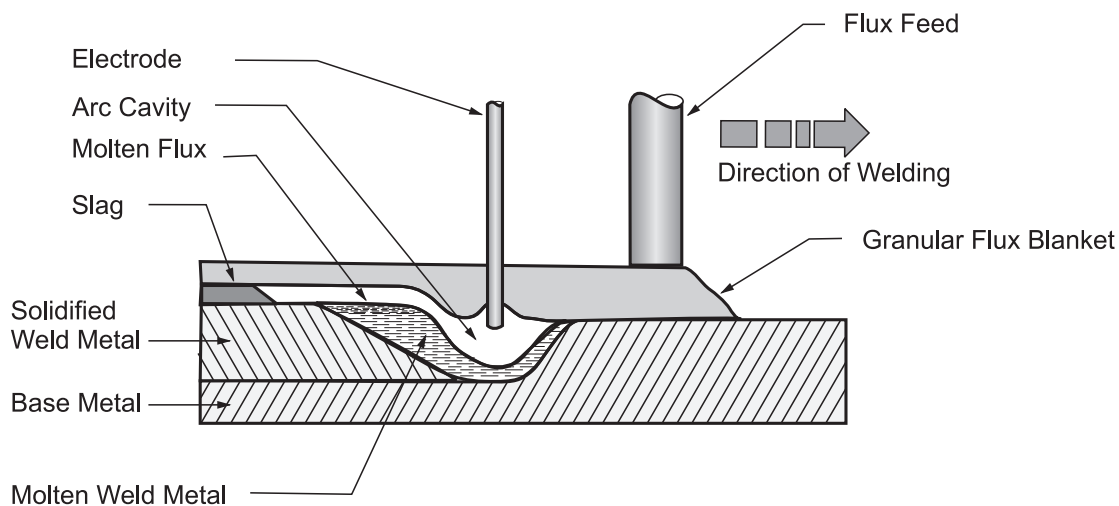


Figure 4.32: Schematic representation of the submerged arc welding process.

The arc is struck beneath the flux between the bare electrode and the workpiece, which melts a small amount of the flux. Although a non-conductor when cold, the flux becomes highly conductive when molten (about 1300°C) providing a current path to sustain the arc between the continuously fed metal electrode and the workpiece. The heat generated by the arc melts the end of the electrode, the flux, and part of the base metal at the weld seam. The arc transfers the molten metal from the tip of the melting electrode to the workpiece, where it becomes the deposited metal. As the molten flux combines with the molten metal, certain chemical reactions occur that remove some impurities and/or adjust the chemical composition of the weld metal.

While still molten, the flux, which is lighter than the weld metal, rises to the surface of the weld pool and protects it from oxidation and contamination. On further cooling, the weld metal solidifies at the trailing edge of the moving weld pool, and the weld bead usually has a smooth surface due to the presence of the molten glass-like slag (molten flux resulting from all the chemical reactions) above it. The slag freezes next and continues to protect the weld metal as it cools. Frozen or solidified slag is readily removable, sometimes popping off the bead spontaneously. Excess, unmelted flux can be recovered and reused after proper processing.

The complete welding operation takes place beneath the flux without sparks, flash or spatter, and it is for this reason that the process is called “submerged” arc welding. As a result, the welding operator does not normally need a protective shield or helmet.

Since there is a need to lay granular flux along the weld seam and the molten weld pool can be quite large and fluid, submerged arc welding is best performed in the flat position, and if needed, in the horizontal position. Also, since the operator can not see the arc or the weld seam, submerged arc welding is best suited for situations where long welds with little or no geometric variation are to be made in the flat position. The process can be mechanized or used in a semi-automatic mode.

4.5.2 Current Type and Equipment

The equipment set-up for single wire submerged arc welding is shown in **Figure 4.33**. In addition to the power supply, a submerged arc welding system requires a wire feeder to maintain a continuous feed of the electrode wire through the torch. For single wire submerged arc welding, direct current electrode positive (DCEP) is used for most applications as it provides better control of bead shape, ease of arc initiation, and deeper penetration welds with greater resistance to porosity.

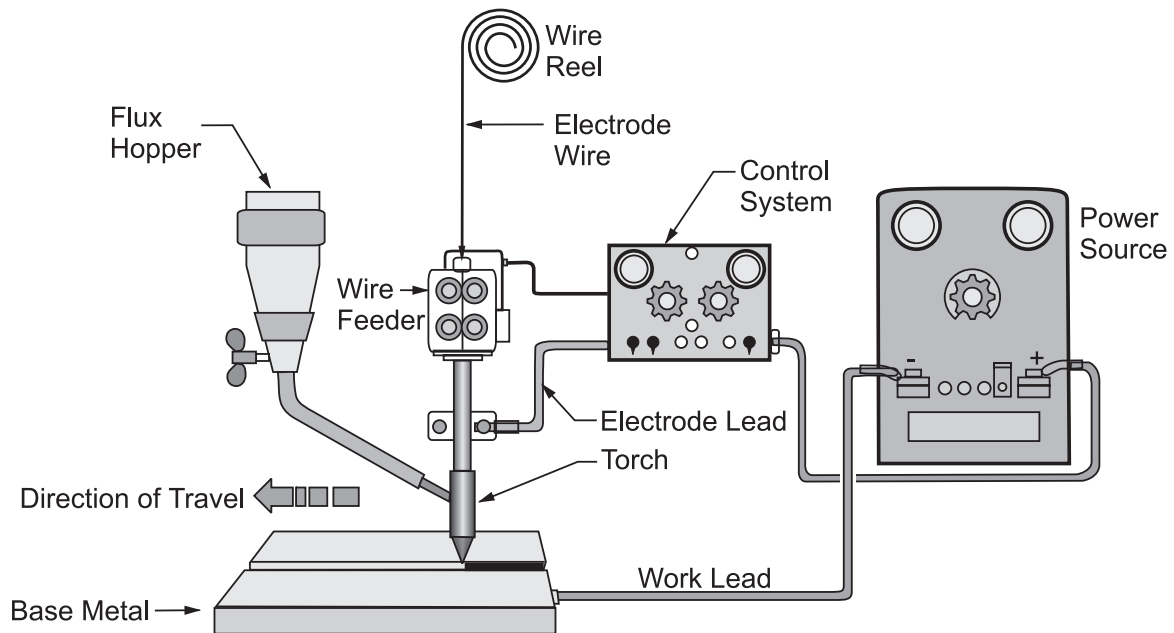


Figure 4.33: Equipment set-up for single wire submerged arc welding.

Direct current electrode negative (DCEN) polarity is also occasionally used to provide a greater deposition rate. However, penetration is reduced and there is some increased risk of lack of fusion-type flaws. From a practical point of view, a change from DCEP to DCEN may necessitate an increase in voltage of about 2 to 3 V if a similar bead shape is to be maintained.

Both constant voltage and constant current (drooping voltage characteristics) power sources can be used. With constant potential power sources, used in conjunction with constant speed wire feeders, the arc length self-adjusts to a nearly constant value depending on the voltage, as in GMAW. The wire feed speed and the electrode diameter control welding current, and the power source controls voltage. By comparison, a constant current power source tries to simulate a manual welder. Essentially, a voltage sensitive relay in a variable-speed wire feeder constantly adjusts the wire feed speed to maintain the target arc voltage and, therefore, a constant arc length. The power source controls current, and arc voltage depends on wire feed speed and electrode diameter. Modern power sources are available that operate in either constant voltage or constant current mode.

Power sources are available that can deliver up to 1500 A. However, direct current is usually kept below 1000 A since there can be excessive arc blow. Alternating current can be used to reduce arc blow in high current applications and other situations prone to arc blow, e.g., multiwire and narrow gap welding. Alternating current power sources are usually constant current type with a nearly square wave output voltage to assist in arc ignition at each polarity reversal. Square wave constant potential power sources have also become available that provide both voltage and current in square wave form and therefore have less difficulty in arc re-ignition at polarity reversals. The weld bead penetration obtained with alternating current is in between that for DCEP and DCEN.

A coil attached to the welding head provides a continuous feed of the metal electrode from the coil through wire straighteners and a contact tip to the workpiece, and a hopper provides flux in front of the metal electrode feed. The welding head is usually mounted on a carriage, where it moves at a predetermined travel speed, thus enabling complete mechanization of the welding process. Alternatively, the welding head can be fixed and the workpiece moves beneath it at a predetermined speed.

4.5.3 Advantages and Applications of Submerged Arc Welding

By far, the greatest advantage of the submerged arc welding process is its high productivity, resulting from high deposition rate and a high duty cycle. The high deposition rate is a consequence of the mechanized nature of the process as it enables use of higher travel speeds and larger diameter wires and therefore higher currents than possible with semi-automatic processes. Variations such as the use of multiple wires, and the addition of a controlled amount of iron powder to weld seams along with the granular flux can further increase deposition rate.

The weld deposit is considered to be a “controlled-hydrogen” type, provided due care has been taken in storage and handling of flux and wire. Heated flux storage units, similar to electrode storage ovens, are often used. Little fume is generated in the process and arc radiation and spatter are generally not a problem. When the weld joint design is appropriate and welding parameters are chosen correctly, sound welds with a smooth, uniform finish are easily obtained.

The main limitation of the submerged arc welding process is that it is limited to welding in the flat and horizontal positions only. The mechanized nature of the process implies more expensive equipment and greater set up time.

Most submerged arc welding applications are for carbon and low alloy steels. The process is also used for joining stainless steel and nickel based alloys. However, the fluxes are proprietary in nature and flux manufacturers must be consulted for optimum flux selection.

Because of the mechanized nature of the process, it is most effectively used when numerous similar welds are to be made (splicing of plates and panels in shipyards, fabricated structural shapes, welding longitudinal or spiral seams of large diameter oil and natural gas pipelines (see **Figure 4.34**) and when the thickness to be welded is large (circumferential and longitudinal seams in thick wall pressure vessels). Other applications of submerged arc welding include overlaying (stainless steel overlay on chromium-molybdenum steels for high temperature, high pressure hydrogen applications) and rebuilding and hard surfacing.

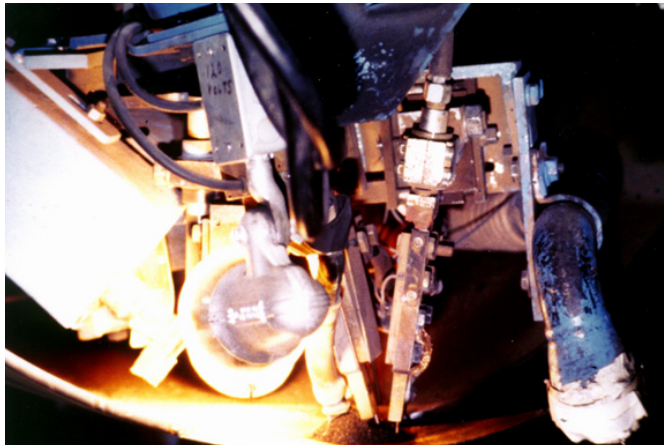


Figure 4.34(a) - Double submerged arc welding of spiral seam in large diameter line pipe - inside (Welland Pipe Inc.).

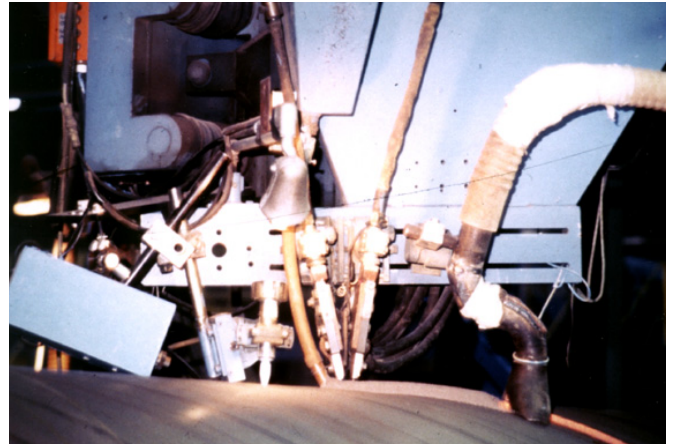


Figure 4.34(b) - Double submerged arc welding of spiral seam in large diameter line pipe - outside (Welland Pipe Inc.).

4.5.4 Multiple Wire Submerged Arc Welding

One of the great advantages of the submerged arc welding process is the ability to use multiple electrodes fed into the same weld pool thus considerably increasing the deposition rate. Some configurations (**Figure 4.35**) for multiple wire submerged arc welding are:

Parallel Electrode Welding: Also called twin wire welding, two electrode wires are connected in parallel to the same power source. Both electrodes are fed by means of a single wire feeder and through the same welding head. Welding current is the sum of currents for each electrode and a single deep penetrating weld pool is obtained.

Multiple Arc Welding: Also called tandem welding, two (or more) electrodes can be connected to individual power supplies and fed by separate drive rolls through separate contact tips. The lead electrode in such cases is connected to a DC power source and the trailing electrode to an AC source to reduce interaction between the magnetic fields of the two arcs. It is important to ensure that the spacing between the arcs is not too large. The trailing arc is usually positioned close enough to the leading arc that the slag cover does not solidify between deposits. The total current in multiple wire welding can be as high as 2000 A, although in most applications it does not exceed 1200 A.

Series Arc Welding: Two electrodes, fed through separate guide tubes, are connected in series. Separate sets of drive rolls and contact tips, insulated from each other, need to be employed. The current path is from one electrode to another, through the weld pool. The weld bead has relatively shallow penetration, making this arrangement useful for overlay welding.

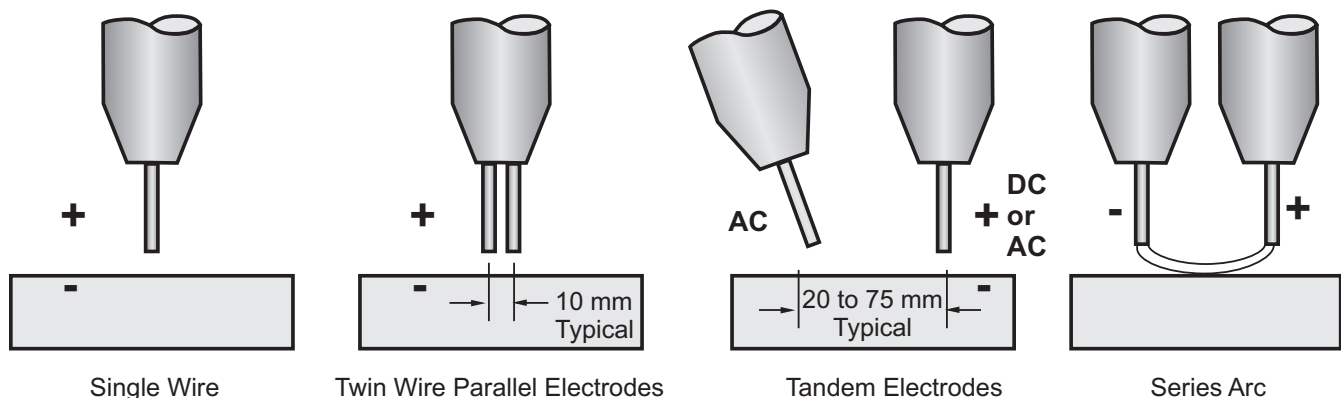


Figure 4.35: Submerged arc welding process.

4.5.5 Wires and Fluxes for Submerged Arc Welding of Carbon and Low Alloy Steels

Traditionally, solid wires similar to those for GMAW have been used for submerged arc welding. The electrode size tends to be larger and the composition may be different, since one must consider the influence of the flux and the greater dilution from the base metal on the weld metal composition (**Figure 4.36**). For this reason consumables for submerged arc welding are selected as a wire-flux system rather than on an individual basis. More recently, composite wires (tubular wires with alloy powder and other ingredients in the core) are being used for submerged arc welding. The advantages of a tubular electrode is the wide range of deposit chemistry possible and the ability to increase travel speeds.

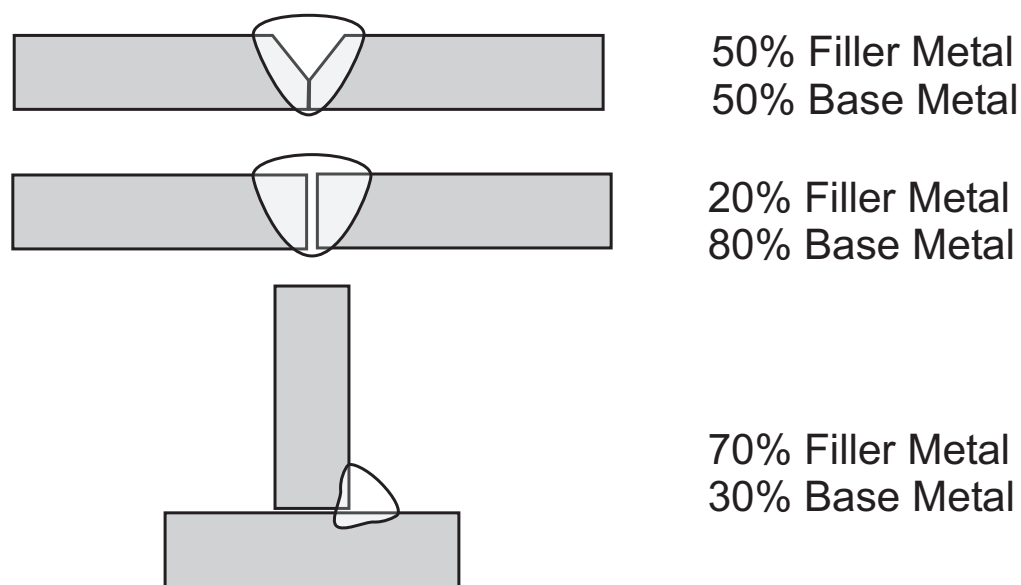


Figure 4.36: Dilution ratios of some common weld joints.

Fluxes for submerged arc welding can be categorized by method of manufacture or effects on weld metal composition. There are two types of fluxes: **fused fluxes** and **bonded fluxes**. The manufacture of fused fluxes involves melting together various ingredients to provide a homogeneous mixture, which is then allowed to solidify by pouring it onto a large chilling block. The glass-like, solidified particles are crushed, screened for sizing and then packaged for use. The main advantages of fused fluxes are their chemical uniformity (irrespective of the flux particle size), resistance to moisture absorption and easy recycling without changes in particle size or composition. The disadvantage of fused fluxes is that it is difficult to add deoxidizers and ferroalloys because these compounds tend to oxidize during the melting process.

In comparison, **bonded fluxes** are made by finely grinding the individual components of the flux, mixing them in appropriate proportions and then adding a binder, typically potassium and/or sodium silicate. The wet mixture is then baked at a relatively low temperature and ground to size for packaging. The main advantage of bonded fluxes is that it is easier to add deoxidizers and ferroalloys. On the negative side, such fluxes are prone to moisture pick up, and to local changes in composition due to segregation or removal of fine mesh particles.

Fluxes that significantly influence the composition of the weld metal through slag/metal reactions are termed **active fluxes**. Typically, these fluxes add manganese, silicon and chromium to the weld metal. The extent of this addition increases with arc voltage, since higher arc voltage leads to increased flux consumption (**Figure 4.37**). Very active fluxes may be used to deposit single or two pass welds only, since the increase in the Si and Mn content of subsequent passes may be sufficiently large to impair the weld metal ductility and also make it more prone to hydrogen cracking. Certain active fluxes, termed alloy fluxes, add elements such as Ni and chromium. Such fluxes enable the welding of weathering steels (containing chromium, nickel or copper) using carbon steel wires, and compensate for the loss of chromium from the wire by oxidation when welding stainless steels.

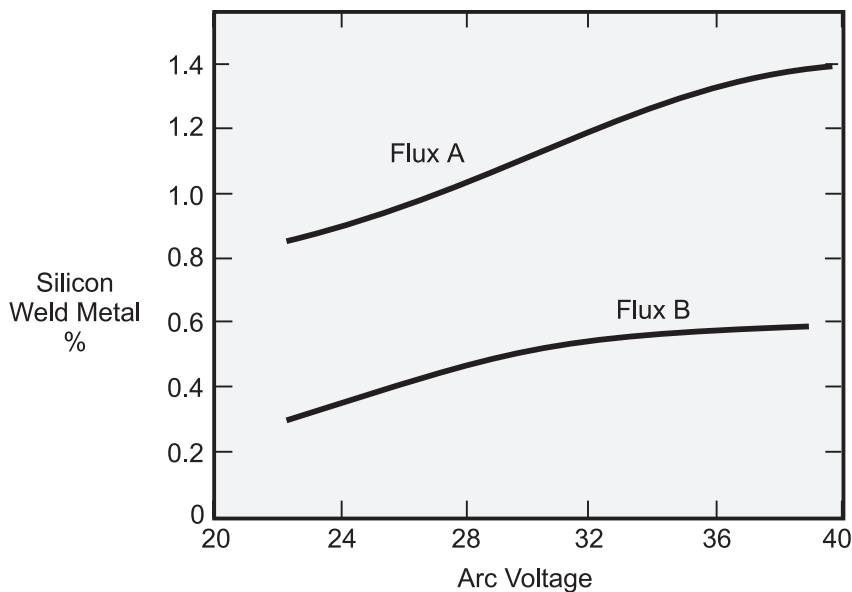


Figure 4.37: Effect of arc voltage on weld metal silicon content for two active fluxes.

Neutral fluxes also participate in slag-metal reactions but the changes in silicon and manganese are smaller and not dependent on arc voltage (**Figure 4.38**). There is little build up of elements and such fluxes are therefore well suited for multipass welds.

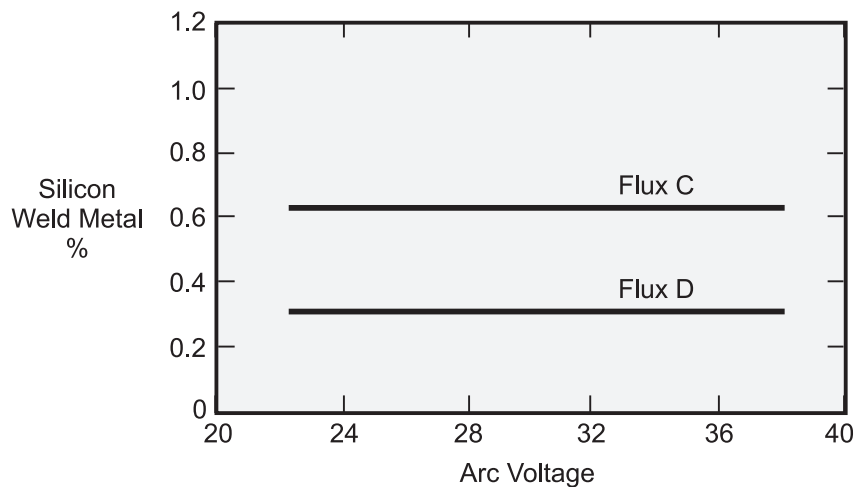
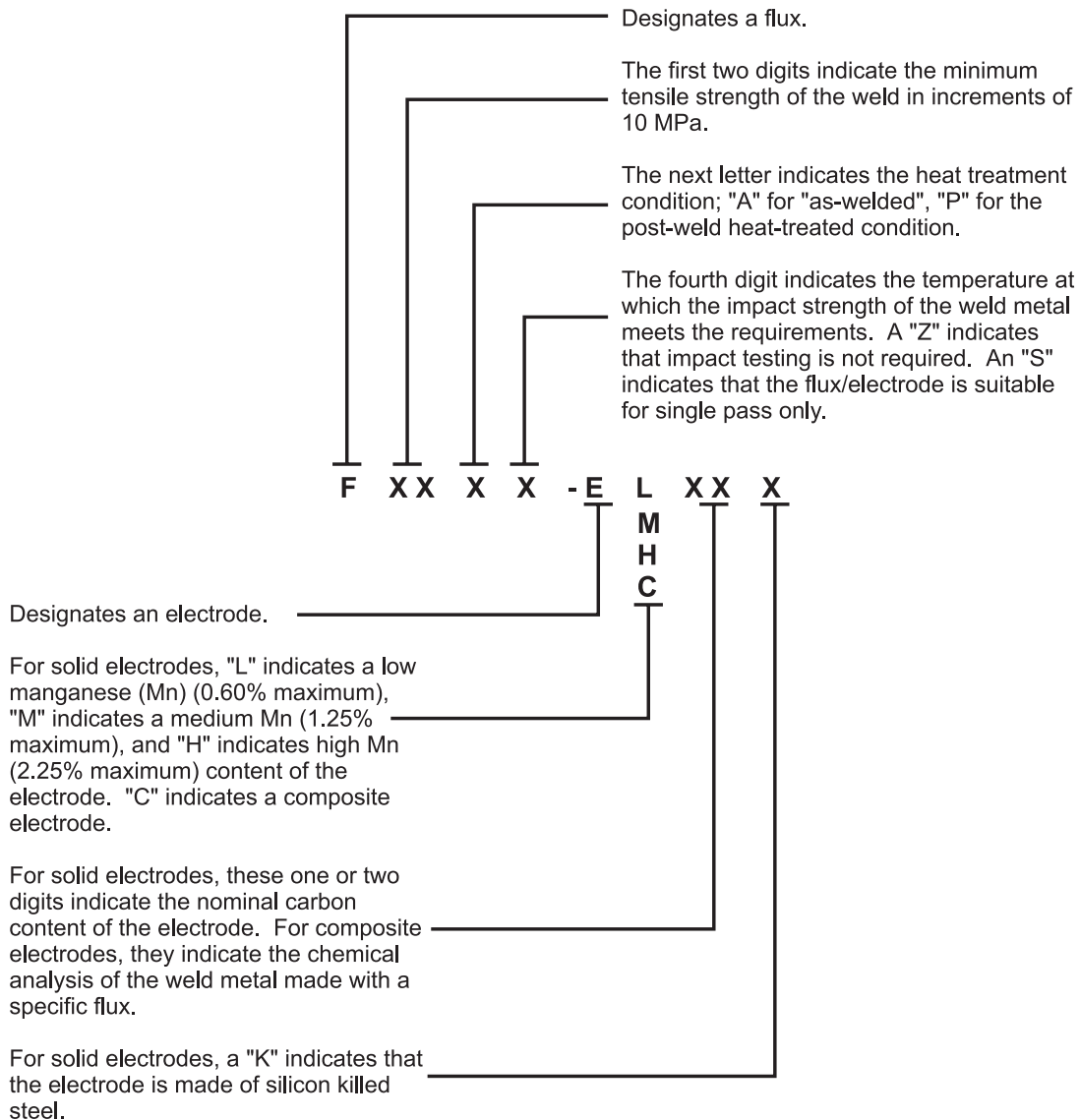


Figure 4.38: Effect of arc voltage on weld metal silicon content for two neutral fluxes.

Fluxes are also referred to as **chemically basic, neutral** or **acidic**. Chemically basic fluxes have Calcium Oxide (CaO) and Magnesium Oxide (MgO) as the major ingredients. Chemically acidic fluxes have Silicon Oxide (SiO₂) as the main ingredient. When the ratio of basic oxides to acidic oxides present is greater than 1, the flux is chemically basic and when it is less than 1, it is chemically acidic. Ratios near 1 imply a chemically neutral flux. Basic fluxes transfer smaller amounts of Si, Mn and oxygen to the weld metal, and therefore are preferred for critical applications.

Requirements and selection for carbon steel wires and fluxes providing weld metal with minimum specified ultimate strength of 490 MPa are detailed in CSA Standard W48-01, and for higher strength weld metals, one can consult AWS Specification A5.23. Submerged arc welding wires are classified based on their composition, whereas fluxes can only be classified in conjunction with a welding wire and their classification indicates the weld metal strength and toughness. The classification scheme for flux-wire combinations is shown in **Figure 4.39**. Thus, a flux-wire combination conforming to the designation F49A5-EM12K indicates that: (i) the electrode wire has a medium (M) manganese content, nominally 0.12% C (12) and is made from a silicon killed steel (K); and, (ii) when used with the specified flux in a standardized test, will provide weld metal that, in the as-welded condition (without post-weld heat treatment), will meet the requirements of minimum 490 MPa ultimate tensile strength, and minimum 27 J Charpy Vee notch impact strength at -50°C.



**Figure 4.39: Classification system for submerged arc welding wires and fluxes.
(as per CSA W48-01)**

It is important to note that as a result of the above classification scheme, a particular flux can assume a different designation when used in conjunction with another wire. For example, Lincon weld 882 flux when used with Lincoln weld LA-71 (EM14K) wire is classed as F49A4-EM14K or F49P5-EM14K but when used with Lincoln weld L-61 wire, it is classed as F49A5-EM12K. Another consequence of the joint effect of wire and flux on weld metal properties is that once a specific flux-wire system has been approved to a particular classification, then no other flux or wire of the same designation but different trade name may be substituted for it without a complete new series of tests to demonstrate that all the requirements are still met. For more details on submerged arc welding consumables, see Module 6.

Flux Usage

Following are some of the precautions that should be taken in the storage and use of fluxes:

- ◆ Fluxes can absorb moisture and thus compromise the controlled hydrogen characteristics of the process. It is therefore important that once a flux bag is opened, it is stored in a dry environment. If there is any doubt of its condition, the flux should be baked before use, following the manufacturers recommendations.
- ◆ Fluxes look alike and therefore if a flux is transferred to a different container for proper storage, it should be properly identified.
- ◆ In recovering and reusing flux, it should be ensured that particle size distribution is maintained. Too many fines in the flux make it difficult to feed, and loss of fines may change the flux composition, which may change the chemistry of the deposit.
- ◆ When active or alloy fluxes are used, the specified welding parameters must be followed diligently otherwise the weld deposit properties will be different from those expected.
- ◆ Do not use an active or alloy flux where a neutral flux is required, and vice versa.

4.5.6 Submerged Arc Welding of Carbon and Low Alloy Steels

Joint Design

Because of the high currents and deep penetration possible with submerged arc welding, steels up to 12 mm may be welded in one pass without any edge preparation. With edge preparation, steels with thickness up to 25 mm are weldable in one pass. However, it assumes that the joint is suitably designed to prevent burn-through and that the weld zone mechanical properties achieved are acceptable. **Figure 4.40** shows a typical prequalified joint configuration for submerged arc welding. Clause 10.2 of CSA W59 lists all the prequalified joint configurations.

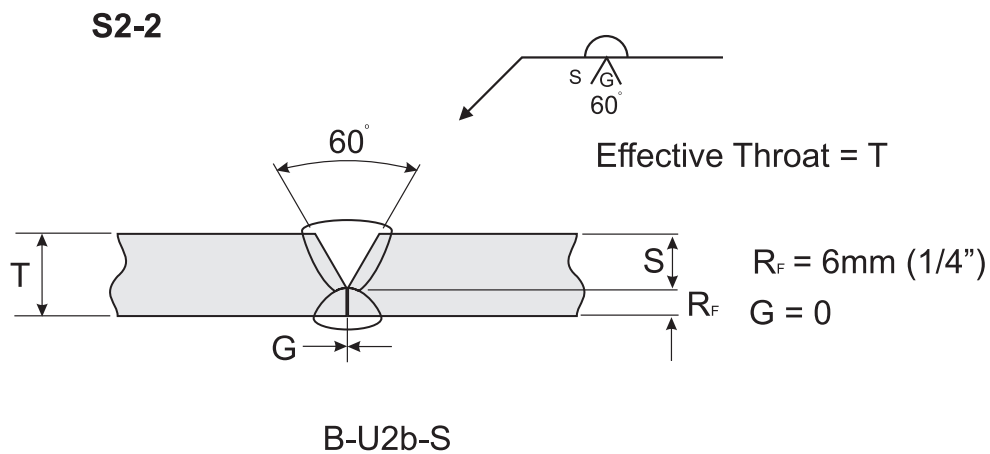


Figure 4.40 - Prequalified joint from CSA Standard W59 for submerged arc welding of carbon and low alloy steels.

Welding Procedures

For welded construction in accordance with CSA Standard W59, the following limitations are specified for pre-qualified joints:

- ◆ fillet welds up to 12 mm may be deposited in a single pass in the flat position; in the horizontal position, the maximum single pass fillet size is 8 mm; in any case, the current must not exceed 1000 A for the single electrode and 1200 A for the parallel electrode variation of the process;
- ◆ to prevent burn-through, either appropriate backing bars should be used or the root face must be at least 6 mm; for root face less than 6 mm, a shielded metal arc weld pass may be manually deposited on the back side;
- ◆ the largest wire that may be used for submerged arc welding is 6 mm;
- ◆ in groove welds, current for the root pass should be less than 10 times the groove angle; this is to control the bead shape and dilution so as to reduce the likelihood of weld metal solidification (centerline) cracking; for subsequent passes, welding parameters should be chosen so that in cross section, the depth of the weld bead or its width at any point along its depth does not exceed the surface width of the weld bead (**Figure 4.41**);

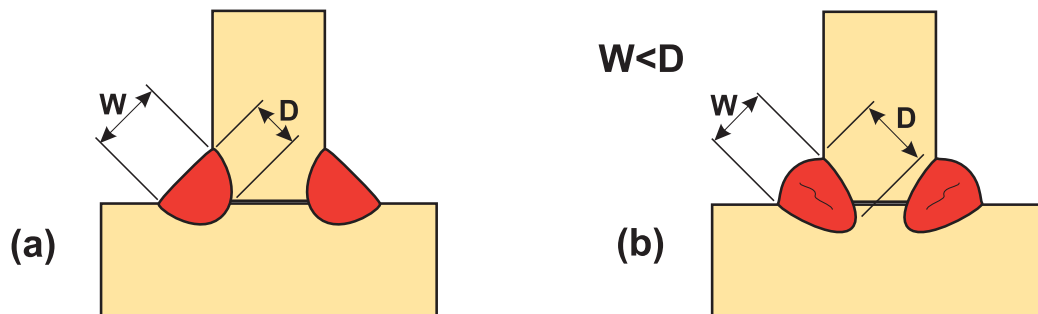


Figure 4.41: Depth and width of weld bead.

- ◆ with a single electrode wire, the layer thickness in groove welds is limited to 6 mm except for the root and capping passes; this limitation does not apply to welds made with parallel electrodes; also, split passes are required when the root opening is more than 13 mm, or when the layer width exceeds 16 mm in multipass welds.

The limitations for multiple arc welds are slightly different; a fabricator can design welding procedures outside the W59 limitations as long as a procedure qualification test is carried out to demonstrate the adequacy of the welded joint.

As mentioned earlier, the submerged arc welding process is treated as a controlled hydrogen process subject to proper storage and conditioning of the electrode and flux. Due to its mechanized nature, it is capable of providing a sound weld deposit of uniform and consistent properties. In some cases, taking advantage of these two process characteristics allows for the elimination of preheating. Minimum size fillet welds for steels of different thickness and carbon equivalent that may be deposited without preheat and without hydrogen induced heat affected cold cracking are shown in **Table 4.5**. The minimum fillet size represents a certain minimum heat input that, depending on the steel thickness and carbon equivalent, is expected to keep the heat affected zone hardness below a critical level for cold cracking.

**Table 4.5 : Minimum single pass submerged arc fillet weld sizes to eliminate preheat .
(from CSA W59)**

Plate Thickness (t), mm	Carbon Equivalent*					
	0.35	0.40	0.45	0.50	0.55	0.60
T < 12 welded to t > 40	8	8	8	10	10	12
T > 12 welded to t > 40	8	8	10	10	12	16

*Carbon Equivalent = $C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni+Cu)/15$

When joining quenched and tempered steels, caution must be exercised in using high heat inputs (high deposition rates). The accompanying slower cooling rate can adversely affect the weld joint mechanical properties. **Table 4.5** is not applicable to quenched and tempered steels.

Chapter 5

Welding Metallurgy

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5.1 Introduction

Metallurgy is an ancient science begun when our ancestors started to use metal tools thousands of years ago. It has come a long way since cavemen discovered that when stones were heated, dark lumps were left in the bottom of the fire pit. The lumps were hard and strong and they did not know why – black magic was born. Today, metallurgists explore the atomic structures of metals. Welding metallurgy is the latest application of metallurgy.

We all know that “metallurgy and materials science” is a major discipline, as is civil engineering. It is a formidable task to explain this subject to its full extent in this chapter. Therefore, we will present only the basic principles of metallurgy with brief explanations that are essential for understanding welding.

To understand what is happening in welding, we must learn some fundamental principles of metallurgy. With the ever-increasing demand to join vast arrays of materials in all types of manufacturing industries, it is of the utmost importance to design weld joints to meet loading and environmental conditions.

The phase diagram is an important tool to explain metallurgical make-up, changes or transformations of alloy interactions at various temperatures. The students are advised to study the following CWB modules to supplement this chapter:

Module 9	Introduction to Welding Metallurgy
Module 20	Structure and Properties of Metals
Module 21	Welding Metallurgy of Steels
Module 22	Welding Metallurgy of Stainless Steels
Module 23	Welding Metallurgy of Non-Ferrous Metals and Cast Iron

The development of our modern industrial society is closely related to the development of metallic materials. In fact, materials like steel have been at the centre of most major industrial breakthroughs.

So as not to overextend our effort to all aspects of welding metallurgy, this chapter concentrates on welding metallurgy of steels, which every civil engineer will likely be involved with at one time or another. Once you are familiar with the metallurgy of steels, you should be able to venture into other metals with the study of related technical references, which are numerous and readily available.

5.2 Basic Concepts of Iron and Steel

Elements such as carbon, oxygen, iron or copper have distinctive properties such as:

- ◆ atomic weight
- ◆ atomic diameter
- ◆ density
- ◆ melting point
- ◆ boiling point

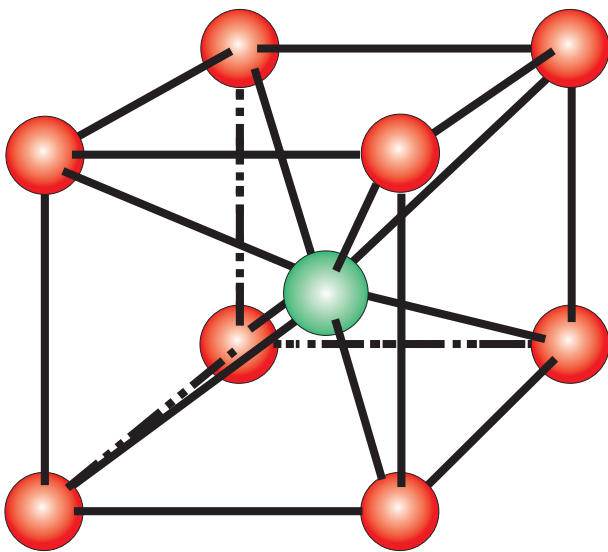


Figure 5.1: Body centered cubic arrangement of iron atoms (BCC).

To create solid structures like metals, atoms have to be joined strongly. In fact, atoms in metals are joined in specific patterns. Iron arranges its atoms in a cube, as shown in **Figure 5.1**. This basic arrangement is a cube with one atom on each corner and one in the middle. This cube arrangement is the basic cell or building block of steel (like bricks in a wall). It is called “Body Centered Cubic”.

Alloys have properties that may differ greatly from the parent elements. Adding carbon to iron changes its properties, producing a new material from the two elements – steel.

Matter can normally be found in three states, depending on the energy contained in the atoms. When energy level is low, matter is solid. As energy or temperature is gradually increased, matter transforms from solid to liquid and finally to gas. A good example of this is water, shown in **Figure 5.2**. It can be found as a solid (ice), as a liquid (water) or as a gas (steam).

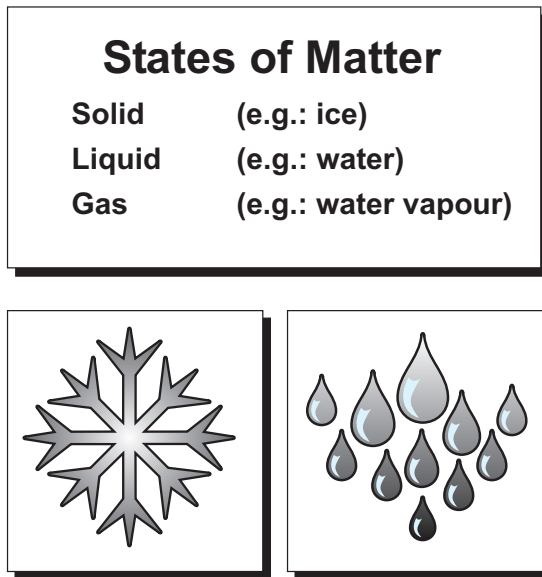


Figure 5.2: States of matter.

During welding all three states of matter are present. Metals to be welded are in the solid state. The heat generated by the welding arc will melt the metal and gases will be produced. Metallurgy is a science that studies these changes of states in metals and the compounds they form.

Since welding is concerned with solid matter, we will concentrate our efforts on elements that can be worked within the solid state. Changes to a material can happen in the solid state; metals are particularly useful in this regard. For example, the properties of steel can be changed while it is solid. One of the best ways to change properties is to heat and cool the material. Welding metallurgy not only studies the weld metal, but it is also used to predict changes in the base metal that happened due to the welding heat. Welding locally “heat treats” the parts being joined.

Welding metallurgy attempts to predict the effect of this heat treatment on the structure and properties of the material.

5.3 Iron, Cast Iron and Steel

Iron alloys can be subdivided into two groups - Steels and Cast Irons. Depending on the amount of carbon contained in the mixture, the alloy will be called cast iron or steel. Cast iron contains more carbon than steel.

1) *Cast Iron*

Cast Iron has different grades and each has specific properties. However, three properties characterize all grades of cast iron:

- ◆ high carbon content (higher than 1.7%)
- ◆ lower melting points than other iron-carbon alloys (1150°C to 1200°C)
- ◆ cannot be forged

2) *Steel*

Steel is the major product of iron-carbon alloys. In contrast to cast iron, steel has a carbon content ranging from 0.01% to 1.7%. Surprisingly, reducing the carbon content in iron-carbon alloys produces stronger, tougher and harder steels. Weldable grades of steels must keep the carbon content low – usually less than 0.4% by weight.

All commercial steel contains four main elements and some impurities:

- ◆ iron
- ◆ carbon
- ◆ manganese
- ◆ silicon

Steel mills spend millions of dollars to remove impurities from the metal while it is still in a liquid state. As well, certain metallic compounds are added to improve the properties of the steel.

5.4 Phase Transformation During Heating and Cooling

In steel certain constituents may undergo changes in the solid state as temperature rises or decreases. These changes are called *phase transformations*. When heated, metals (solids) will gradually transform into liquids and gases. As stated previously, all matter can be found in these three distinctive states.

Each state has specific properties that can be summarized as follows:

Gas	◆ fills all space available ◆ can be compressed ◆ number of atoms in a given volume depends on pressure and temperature
Liquid	◆ cannot be compressed ◆ atoms are relatively free to move
Solid	◆ well defined volume ◆ properties specific to a given orientation

Except for mercury (Hg), metals are normally found in the solid state. In solids, atoms are joined by directional forces that hold them according to specific arrangements. Metallic atoms group themselves in crystalline patterns (arrangements).

Metals arrange their atoms into three principal cubic patterns, which are shown in **Figure 5.3**.

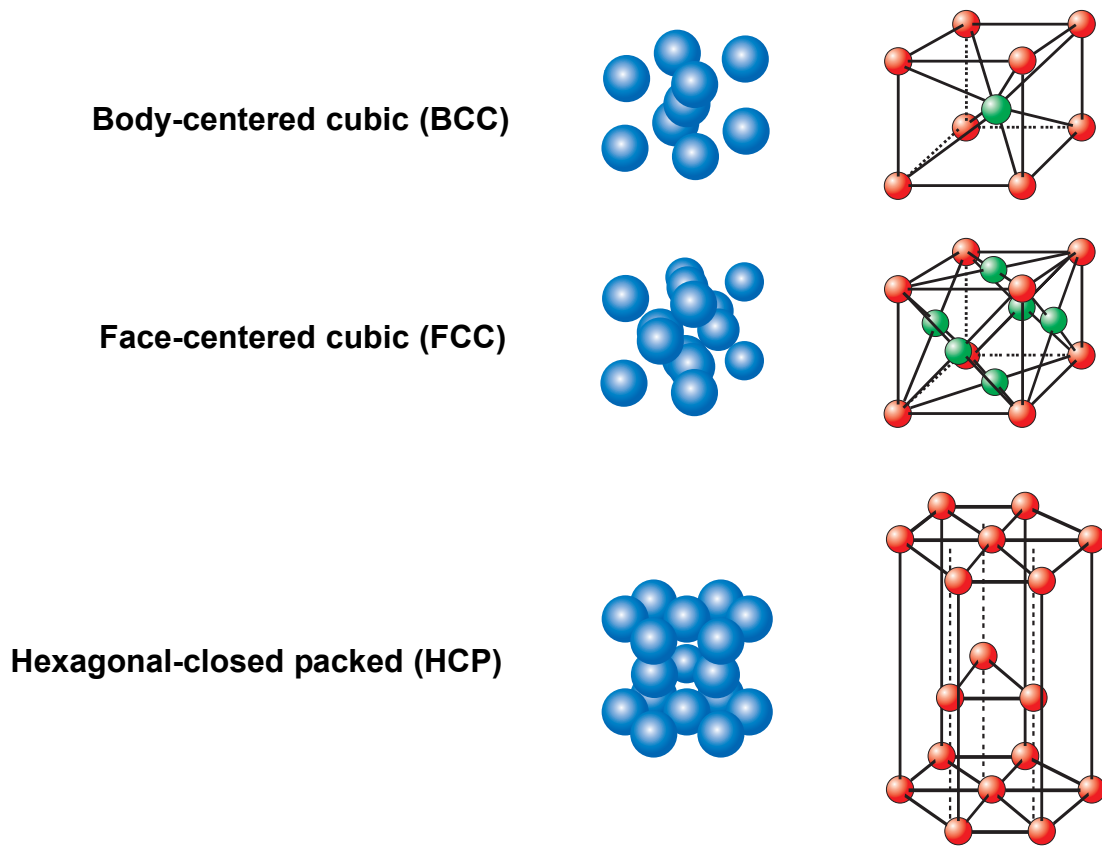


Figure 5.3: Crystalline structure of metals.

Each crystal-type pattern has specific properties. For instance, an FCC structure is more compact (dense) and ductile than a BCC. Most metals will have only one pattern, but steel has two – BCC and FCC. In steel, BCC is called ferrite and FCC is called austenite. Common structural steels are BCC at room temperature and change to FCC when heated above 723°C. Welding, of course, deposits liquid metal into the joint and melts some base material. Therefore, the weld deposit and the area around the joint go through these changes in arrangement as the temperature rises during welding and falls while cooling.

This ability to change arrangement (phase) while solid is what makes steel such a popular material with which to work. While in the solid state, steel can be BCC or FCC. It is through this transformation that different properties can be created. The material can be purchased in one condition, fabricated into a useable shape and then have its properties changed completely through heat treatment.

To understand what really happens to steels when heated, metallurgists have developed a diagram showing the relationship between temperature, structure transformation and chemistry of different steels. This diagram is called a phase diagram.

5.4.1 Phase Diagrams (Iron-Carbon Equilibrium Diagram)

Basically, the welding operation rapidly heats a metal to a temperature higher than its melting point. During the heating process, atoms absorb energy and expand. When the metal reaches the melting point, it transforms into a liquid. When the heat source is removed, the process is reversed. Solidification of the weld puddle (from liquid to solid state) produces the weld bead. **Figure 5.4** shows a simplified iron-carbon diagram. This diagram allows metallurgists to see how adding carbon changes the response of the steel to temperature changes. Phase diagrams are sometimes called “equilibrium phase diagrams”. These diagrams show what structures are most stable at a given composition and temperature.

Phase diagrams are created by cooling the material very slowly and thereby allowing the most preferred phases to form. During welding, cooling rates are much faster than the equilibrium diagram.

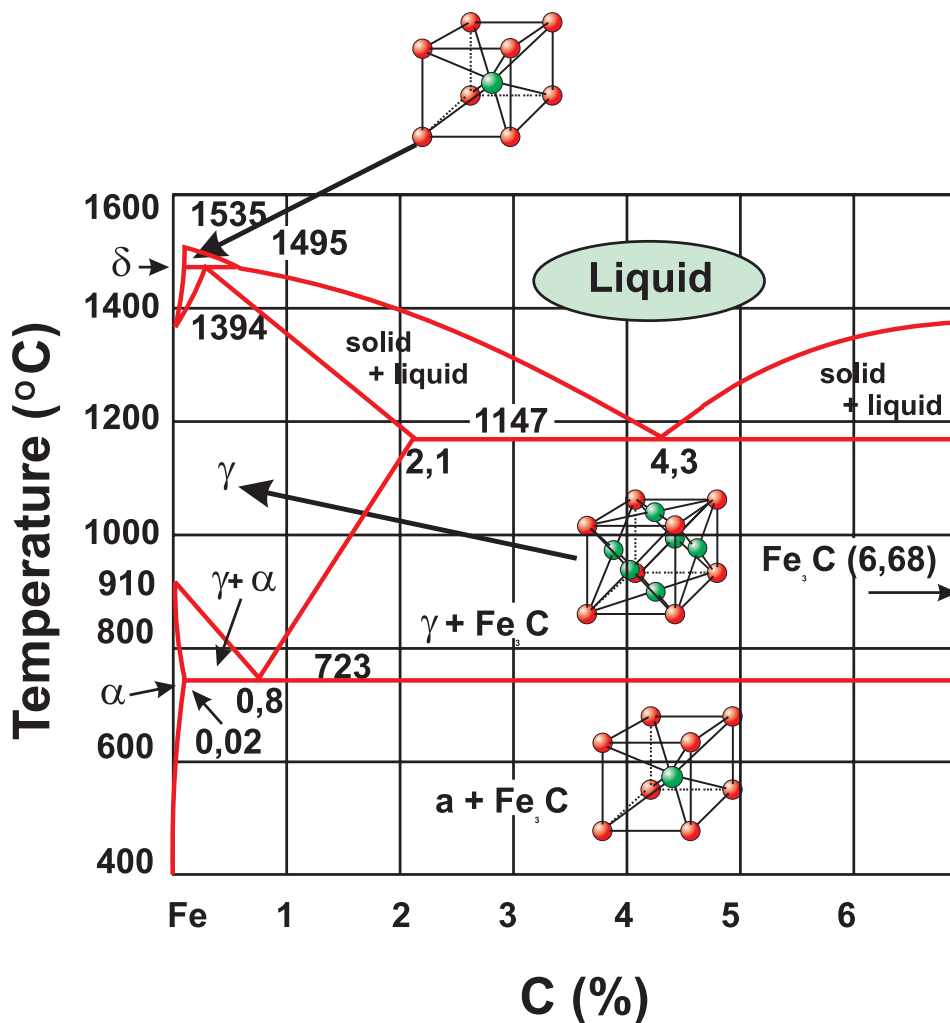


Figure 5.4: Iron-iron carbide phase diagram.

5.5 Effect of Heating and Cooling on Steel

Understanding the effect of heating and cooling on steel is important, not only because these effects are used to enhance the properties of the steel as mentioned above, but also because the welding operation involves similar effects, and final properties of the weld and its soundness can depend on the rate at which the weld cools after the weld metal has been deposited.

5.5.1 Slow Cooling of Steel from Above 910°C

From the previous sections, you have learned that:

- ♦ In pure iron at temperatures above 910°C, the atoms are arranged in a face centered cubic (FCC) pattern or lattice. On slow cooling at 910°C, the arrangement of the atoms changes to a body centered cubic (BCC) lattice and stays like that on further cooling to room temperature (see **Figure 5.5**).

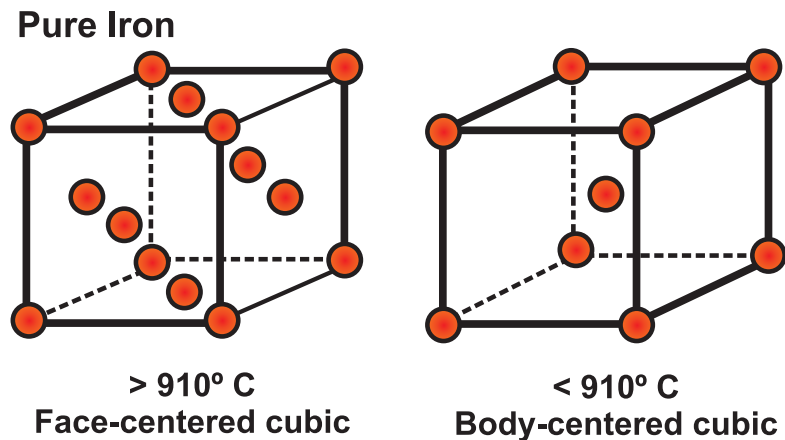


Figure 5.5: Face centered and body centered cubes.

Under microscope, the microstructure of the pure iron at room temperature will show a large number of grains, which look like soap bubbles viewed against a piece of glass (**Figure 5.6**). In each grain, the atoms are arranged in the BCC pattern, but the orientation of the cubes is different in each grain. At the surface where two grains meet, the orderly arrangement of the atoms is disturbed and this surface is called a grain boundary (**Figure 5.7**).

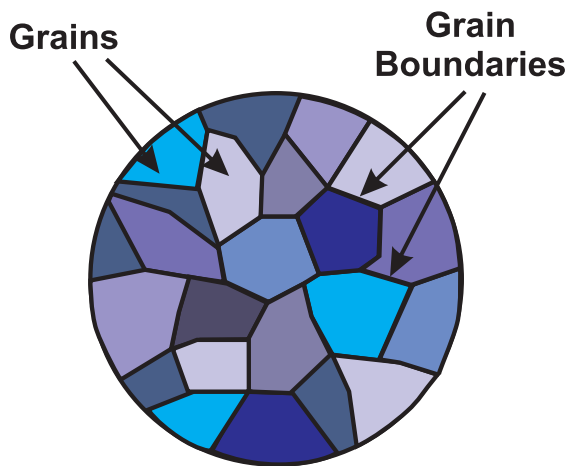


Figure 5.6: Grains and grain boundaries.

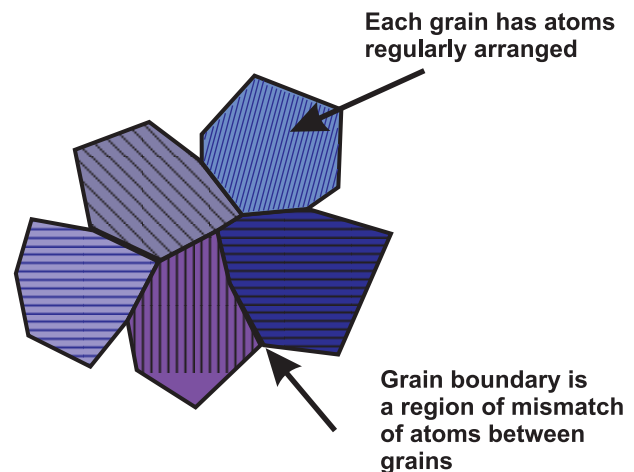


Figure 5.7: Grain boundaries are areas of mismatch.

The term “ferrite phase” describes metal grains having the BCC lattice structure; the main difference between these and the soap bubble example is that the boundaries between metal grains are not always straight.

At temperatures above 910°C, iron with the FCC structure can dissolve more than 1 wt% carbon. The carbon atoms, being smaller than the iron atoms, fit in the spaces between the larger iron atoms as shown in **Figure 5.8**, and the overall crystal structure remains as FCC. If one were to examine the steel at 920°C under microscope, there will be no evidence of the carbon in the steel and one will again see grains similar to pure iron ferrite at room temperature but, because of their different crystal structure (FCC), these are called the austenite phase.

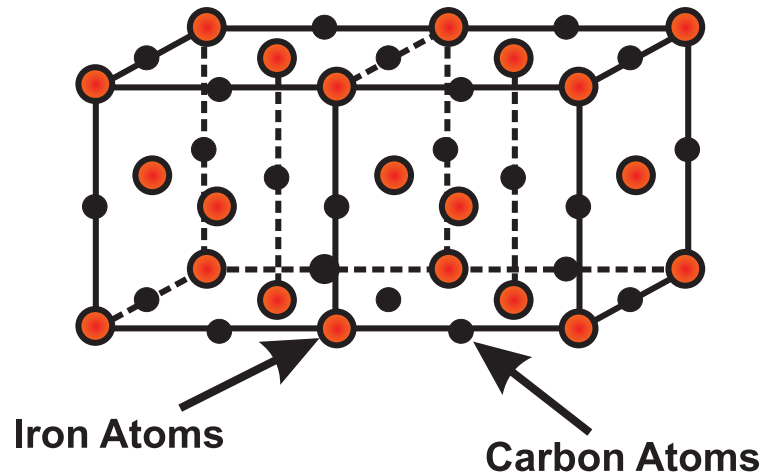


Figure 5.8: Carbon atoms dissolved in austenite.

Compared to the high-temperature austenite phase, the low-temperature ferrite phase can hold very little carbon, and therefore the carbon has to come out during the slow cooling of the austenite phase. This is how the layered structure called “pearlite” is formed.

Looking first at the example of slow cooling and separating out of carbon in a steel containing 0.8 wt% carbon, its microstructure at room temperature as seen in a microscope, will again show a large number of grains, but within each and every grain there will be alternate layers (or lamellae) of ferrite (almost pure iron) and iron carbide (a chemical compound of iron and carbide, more commonly called cementite). This type of structure (alternate layers of ferrite and cementite) is called pearlite (**Figure 5.9**).

The pearlite phase in this case of 0.8% steel formed from the austenite at 723°C (**Figure 5.9**). One can imagine that at this temperature two things occur. First, the carbon chemically combines with iron to form cementite (Fe_3C) in each grain of austenite and at various locations within each grain. Second, when all the carbon is exhausted the remaining face centered cubic iron (FCC austenite) changes to ferrite, the body centered cubic (BCC) form.

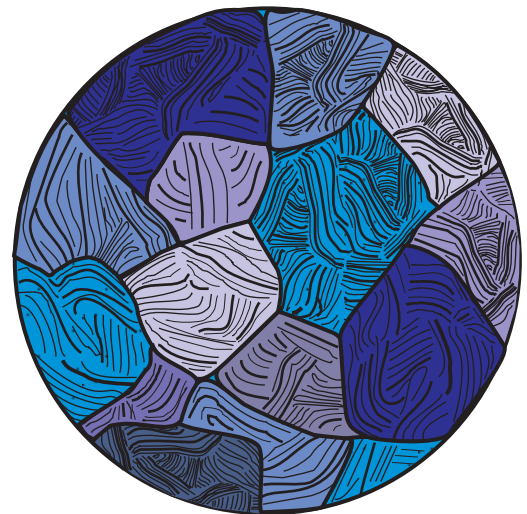


Figure 5.9: Pearlite from slow cooling.

- ◆ Steels containing intermediate levels of carbon behave in an intermediate manner. For example, a steel containing 0.15 wt% carbon will have about 19% (0.15 / 0.8 x 100%) pearlite phase and remaining 81% ferrite phase.

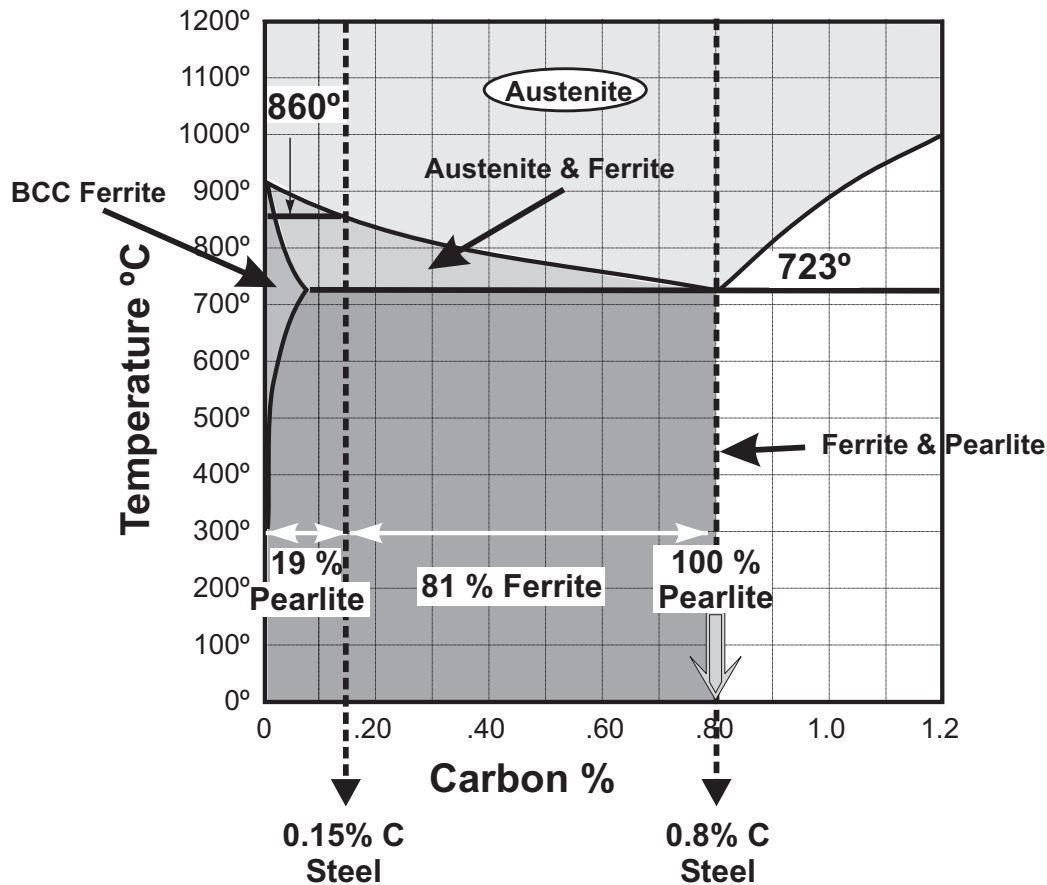


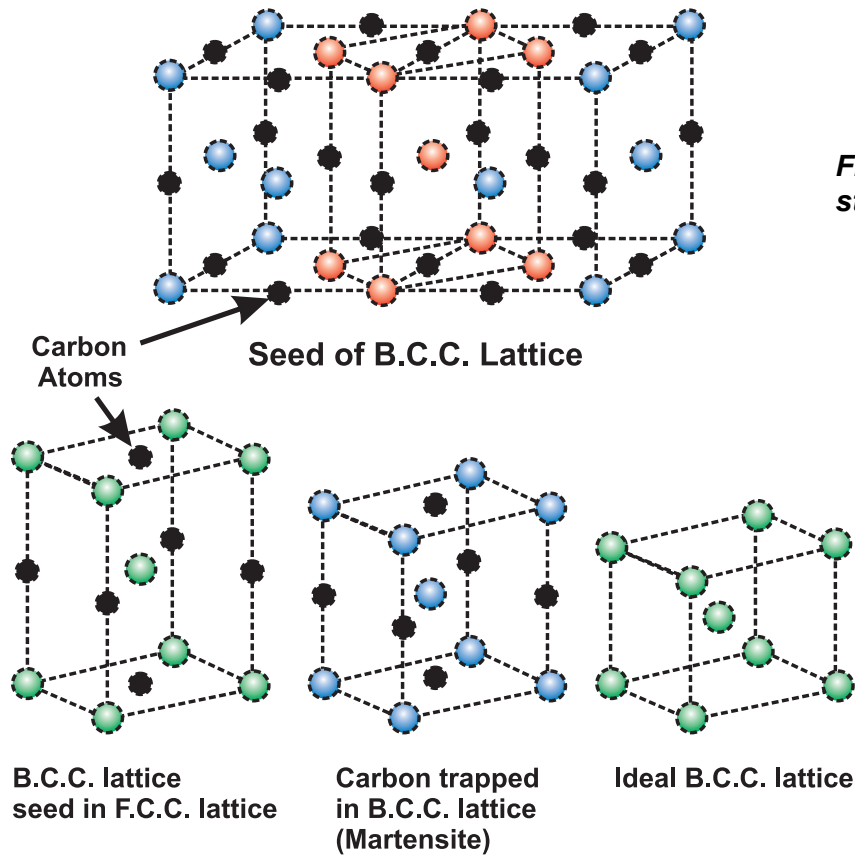
Figure 5.10: Structures formed on slow cooling.

The changes also occur over a range of temperatures (**Figure 5.10**), starting at about 860°C (this temperature will depend on the carbon content) and always finishing at 723°C. In between these two temperatures, an increasing amount of ferrite forms first as the temperature decreases until, at 723°C, there is about 19% austenite and 81% ferrite. Then, at 723°C, the austenite changes to pearlite for the 0.8%C steel (**Figure 5.10**).

In slow-cooled steels (hot rolled or normalized), increasing the amount of carbon increases the amount of pearlite in the microstructure and increases the tensile strength of steels.

5.5.2 Fast Cooling of Steel from Above 910°C

You will recall that above 910°C, the steels are in the face centered cubic (austenite) form. Now, when the steel is cooled very fast from this temperature (hot steel quickly put in ice-cold water, i.e., quenched), the carbon atoms do not have the time to diffuse and form cementite. But the steel still tries to change its crystal structure to a body centered cubic form. The result is that the carbon atoms are trapped in the BCC crystal structure and distort the lattice (**Figure 5.11**).



This distorted, body centered cubic phase is called martensite and its properties depend mainly on the carbon content of the steel. The higher the carbon content of the steel, the more distorted the crystal structure is and the resulting martensite becomes harder and stronger (higher strength) but also more brittle. **Figure 5.12** shows how the maximum hardness of the martensite changes with the steel carbon content.

At cooling rates that are in between slow cooling and quenching in water, various amounts of ferrite, pearlite, martensite and some other phases form. The main point is that hardness (strength) varies in between the extreme values for the slow cooled and quenched conditions of the steel, and higher hardness values indicate greater amounts of martensite present. In welding we usually experience fast cooling rates. Therefore carbon content has a strong effect on weld zone hardness and consequently on the weldability of the steel.

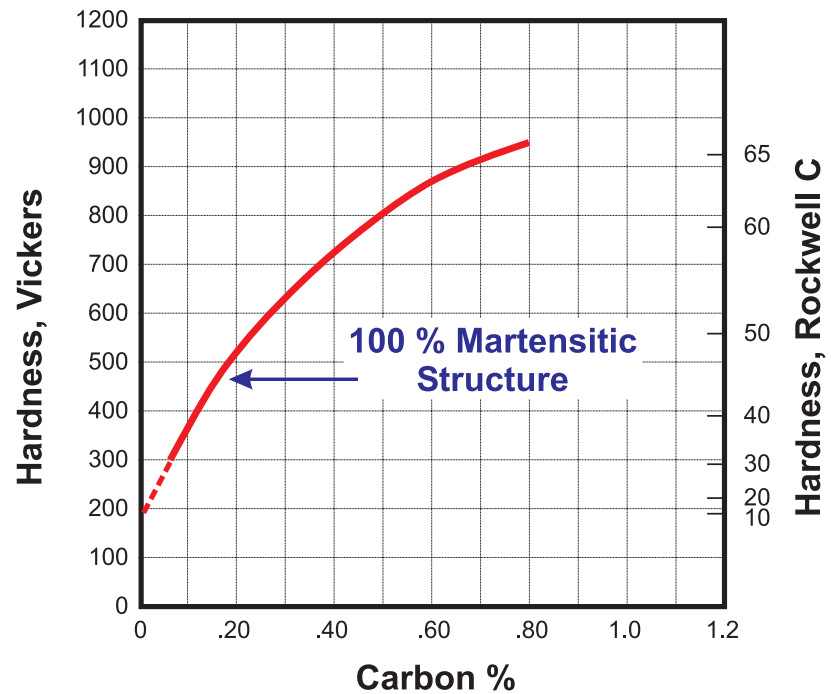


Figure 5.12: Hardness of martensite vs. carbon content.

5.5.3 How Fast a Cooling Rate is Fast Enough to Form Martensite?

This depends on the composition of the steel and can be judged from the hardening curve of the steel. A hardening curve is a plot of the hardness of the steel when it is cooled at different rates over a wide range. **Figure 5.13** shows the effect of steel's carbon content on the hardening curve. The Mn and Si contents of three steels are assumed to be the same (1.2% Mn and 0.2% Si) and with 0.1% to 0.3% C, these steels can be considered as typical of weldable structural and pressure vessel steels. It is seen that an increase in carbon content from 0.1% to 0.3% increases the maximum hardness that is possible for the steels at very high cooling rates.

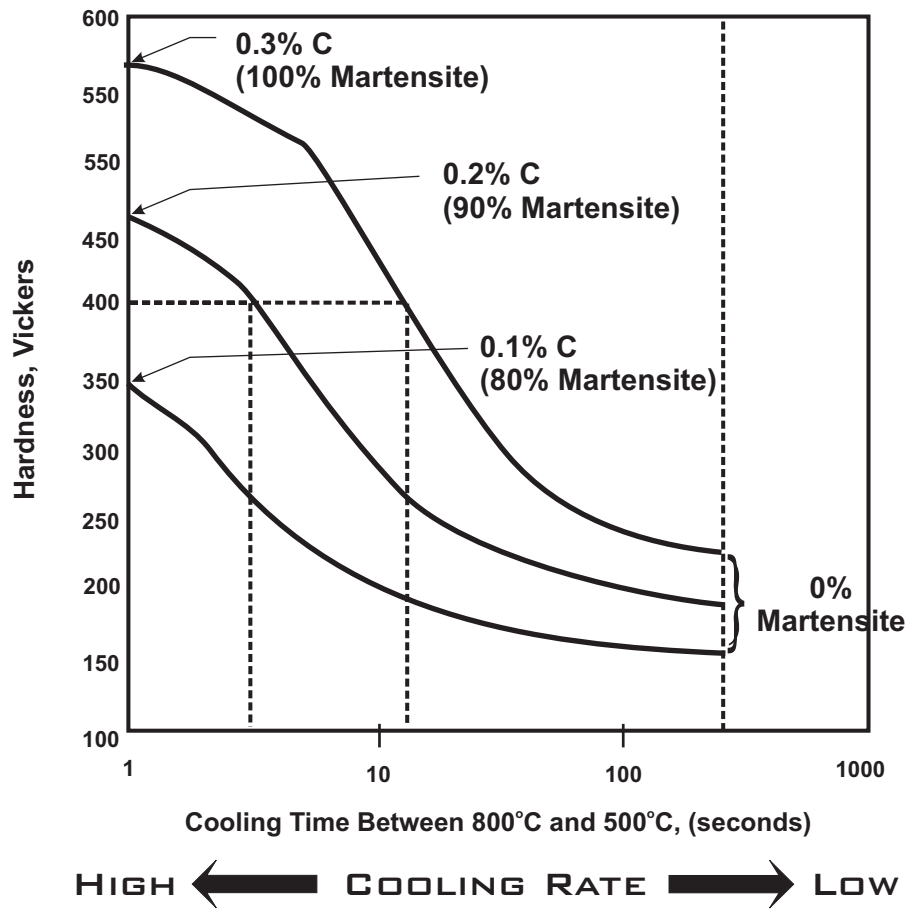


Figure 5.13: Hardening curves for three C-Mn structural steels.

Also, increasing carbon allows a given level of hardness to be achieved at a lower cooling rate. For example, if one wanted the hardness not to exceed 400 HV, then one would be assured that there is no danger of reaching or exceeding the allowable hardness level when welding the 0.1% C steel. But, with increasing carbon content, the steel must cool more slowly in order to not exceed the maximum hardness requirement.

The effect of other elements when added to a 0.2% C, 1.2% Mn, 0.2% Si steel is shown in **Figure 5.14**. You can see that these elements do not significantly increase the maximum hardness that is possible at very high cooling rates. However, the hardening curve can become flatter, and to not exceed a given level of hardness, the steel must be cooled progressively more slowly. In this regard, Mo is most effective in increasing the hardening capacity since the hardening curve is the flattest, so one can say that Mo increases the hardening capacity the most. Nickel on the other hand, does not change the curve too much and therefore is the least effective in increasing the hardening capacity.

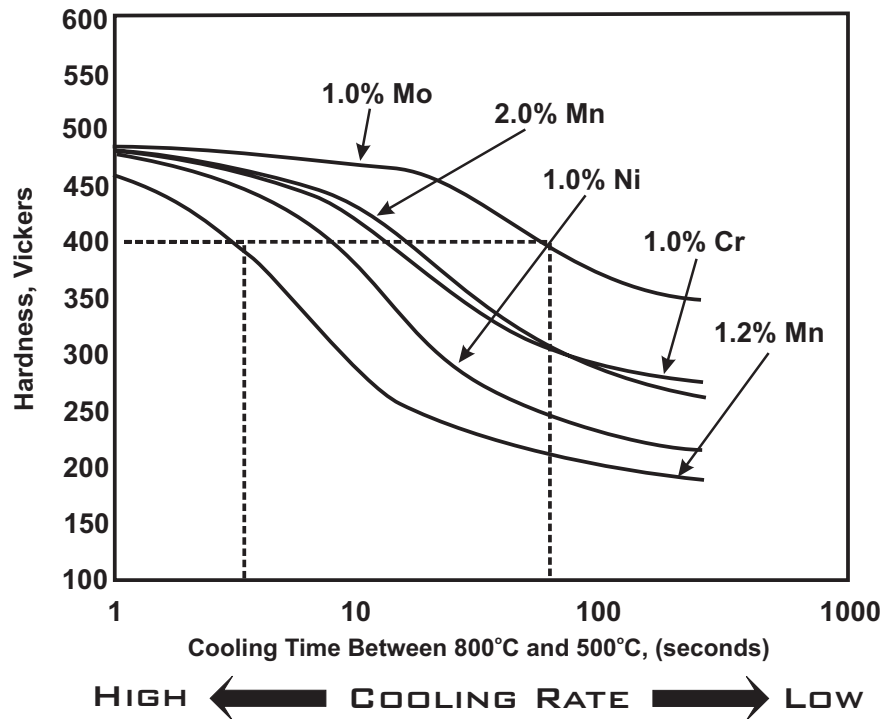


Figure 5.14: Hardening curves for steels with different amounts of Mn, Ni, Cr, Mo.

In the context of welding, martensite can form in the heat affected zone as a result of fast cooling of the weld. If the steel's carbon content is high, the martensite formed will be harder and brittle.

The resulting structure will be more prone to cracking in the presence of hydrogen coming from the welding arc. Also, if large amounts of alloying elements are present, then martensite will form more easily unless the cooling rate is controlled to be quite slow. It is in light of this background that the weldability of the steel is said to decrease when its carbon content or the alloying element content is high.

5.5.4 Heat Treatment of Structural Low Alloy and Quenched and Tempered Steel

Steel plates are always hot rolled in the still mills. Earlier it was mentioned that besides the hot rolled condition, the steels may be provided with a heat treatment after normalizing or quenching. Various heat treatments are illustrated in **Figure 5.15**.

In both of these heat treatments, the steel is first heated to a temperature where the normal ferrite and pearlite phases, present at room temperature, change back to the austenite phase (FCC structure). This temperature for structural steels is typically about 900°C and this part of the heat treatment is called austenitizing.

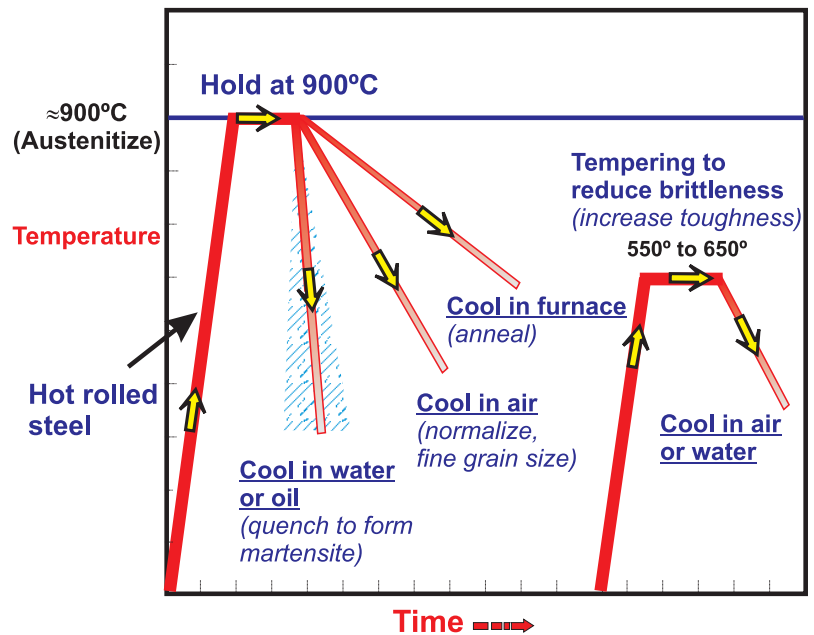


Figure 5.15: Heat treatments.

If the steel is now taken out from the furnace and allowed to cool in the air, then it is said to have been

normalized. For structural steels, the microstructure of the normalized steels is generally similar to that of the hot rolled steel (ferrite and pearlite) except that, due to the presence of such elements as aluminum, vanadium, etc., the grain size of the normalized steel is smaller than that of the hot rolled steel. Smaller grain size increases the strength and low-temperature toughness of the steel.

If instead, the steel is taken out of the furnace and immediately immersed in cold water, the steel is said to have been quenched. The objective here is to obtain a hard, strong martensitic structure. Since this structure also makes the steel brittle, the quenched steel is always tempered, by putting the steel back into a furnace at about 550°C to 650°C. The tempering temperature has to be less than 723°C to prevent transformation to austenite. If austenite begins to form again the effect of quenching and tempering will be lost.

During fabrication the steel temperature should not exceed the temperature at which the steelmaker tempered the steel since this will lead to a lower steel strength, possibly below the minimum specified requirements.

The tempering step allows the trapped carbon to come out of the distorted BCC structure in the form of fine, round cementite particles, leaving behind an undistorted, fine-grained ferrite matrix (**Figure 5.16**). The quenched and tempered steel obtained is tougher than the as-quenched martensite, but of lower hardness and strength. Generally, the higher the tempering temperature (still below 723°C), the greater the improvement in toughness and reduction in strength.

Compared to the normalized steel of the same composition, the quenched and tempered steel should have higher strength and toughness.

Remember that for the quenching and tempering treatment to be effective, one should be able to achieve 100% martensite as a result of the quenching.

As a result, the steel should have sufficient carbon and/or alloying element content to allow 100% martensite at the cooling rate achievable during quenching. Since thicker steel will cool at a slower rate than thinner steel in the water spray, it follows that thicker quenched and tempered steels require greater amounts of alloying elements. (This is partly true for hot rolled and normalized steels as well, in that thicker plates cool more slowly in the air and, therefore, have less strength than the thinner plates. To compensate for this, thicker plates are likely to have slightly higher amounts of carbon or other alloying elements.) In regards to welding, thicker material of the same designation presents increased possibility of cracking due to greater hardenability as well as fast cooling.

A third heat treatment is called the “annealing treatment”. It is similar to normalizing in that the steel is austenitized first but then cooled in the furnace itself rather than in air. The objective here is to control the cooling rate to be even slower than cooling in air. Annealing treatment is used for steels that have relatively high carbon and/or alloy element content so that even cooling in air is fast enough for the steel to form at least some martensite. Therefore, to get a completely soft, martensite-free structure, such steels need to be cooled in the furnace, i.e., annealed.

Spheroidized Cementite Particles

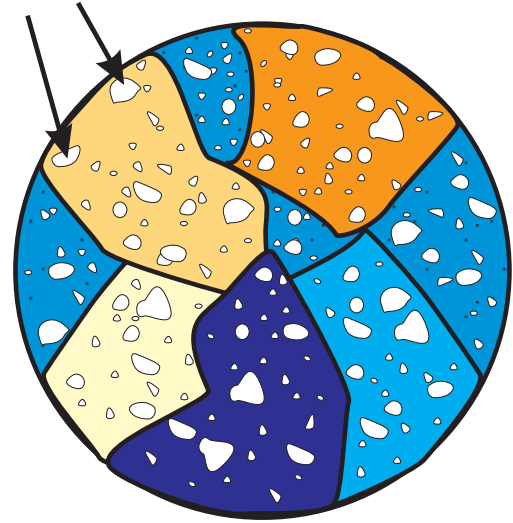


Figure 5.16: Spheroidized cementite in matrix of ferrite.

5.6 Alloying Elements in Steels

As mentioned before, the steels that you may be asked to weld at different times are likely to belong to different specifications, or even to the same specification, and will have different compositions depending on the steel mill supplying the steel. Alloy atoms are of a different size than the iron atoms. Some are smaller, some are larger. In either case their intended effect is to cause small distortions in the cubic structure of the steel, as shown in **Figure 5.17**.

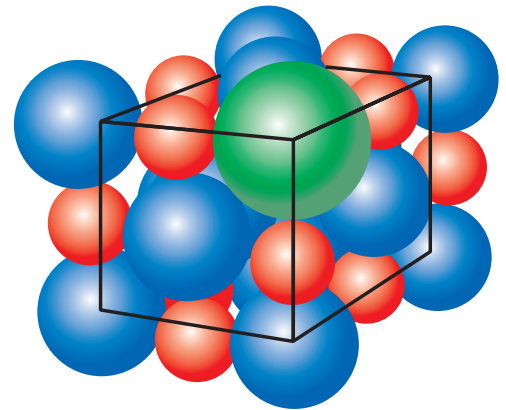


Figure 5.17: Alloy elements in FCC cube.

At this stage it is useful to note the intended functions of the alloying elements, including carbon, that are added to the steel, and then in later sections, we can consider their effects on welding.

1) Carbon (C)

Increases the tensile strength of steels by increasing the amount of carbide present. Increases the hardening capacity of the steel so that it may be effectively quenched and tempered.

Decreases the toughness of the steels. More so when present as lamellar (layered) cementite in pearlite rather than round (globular/spheroidal) particles.

2) Silicon (Si)

Added as a deoxidizer during steel melting. Increases strength. Moderate increase in hardening capacity.

3) Manganese (Mn)

Present in amounts up to 1.8 wt%. Combines with sulfur to form less harmful manganese sulfide inclusions in high sulfur steels. Increases the steel's strength but less than silicon. Increases the steel's toughness to some extent. Considerably increases the steel's hardening capacity.

4) Nickel (Ni)

Little effect on steel's strength and hardening capacity but considerably improves its low temperature toughness. Also increases the atmospheric corrosion resistance of the steel.

5) Chromium (Cr)

Little effect on steel's strength but increases the steel's hardening capacity. Increases the steel's resistance to scale/oxide formation when heated to elevated temperatures. Also, combines with carbon to form chromium carbides that are more stable than cementite, i.e., they do not break down with time at elevated temperature applications. Chromium helps to maintain the steel's strength and reduces its flow (creep) at higher temperatures and for longer periods of time.

6) *Molybdenum (Mo)*

Has a small effect in increasing the steel strength. Increases hardening capacity, slightly more than chromium. Forms more stable carbide than cementite. Increases the steel's resistance to deformation (creep).

7) *Vanadium (V)*

Forms carbides. Added for strength and toughness via grain refinement in as-rolled (control) as well as normalized steels. Helps retain higher hardness and strength after tempering in quenched and tempered steels. Also added in some steels meant for elevated temperature applications.

8) *Niobium (Nb)*

Forms nitrides and carbides. Added for strength and toughness since a fine dispersion of niobium carbides promotes grain refinement. It also helps retain fine grain size in the heat affected zones of welds.

9) *Copper (Cu)*

Added to increase the steel strength. The effects on toughness and hardening capacity are small. Increases the atmospheric corrosion resistance of the steel. Total amounts of copper added are small to prevent hot shortness.

10) *Boron (B)*

Added to relatively low carbon steels in very small amounts to increase the hardening capacity of steels meant to be quenched and tempered. A very strong strengthening agent when used in combination with molybdenum, titanium or vanadium.

11) *Nitrogen (N)*

Intentionally added only when other elements like vanadium are present so that vanadium nitrides can improve strength and help refine the grain size.

In summary, and in order of decreasing effectiveness, various alloying elements are added to steel for the following purpose:

Increased Strength:	C, Si, Cu, Mn, Mo (also Nb and V; their exact effect depends on other factors such as the rolling temperature and time, amount of carbon and nitrogen present, etc.)
Hardening Capacity:	C, Mn, Mo, Cr, Ni, Cu, B
Toughness:	Ni, grain refinement (achieved via the presence of Nb, V, Al , Ti)
Elevated Temperature Properties:	Cr, Mo, V
Atmospheric Corrosion Resistance:	Cu, Ni

5.7 How Does Hardness Effect Welding?

Hardness is a measure of the resistance of the material to plastic deformation. Hardness is a comparative measurement that uses a standardized indenter to create an indentation in the surface of the material. The size of the indentation created is measured against a standardized scale. Softer materials will exhibit a larger indentation. A hardness test is described in **Figure 5.18**.

A weld contracts as it cools. Hot weld metal is much weaker than the surrounding parent material. As the temperature of the weld area drops its volume must decrease. Since it is prevented from uniformly shrinking in three dimensions, it must compensate in those directions which are free to contract (**Figure 5.19**). The atoms of the material must move in order for the contraction to occur in a manner without cracking.

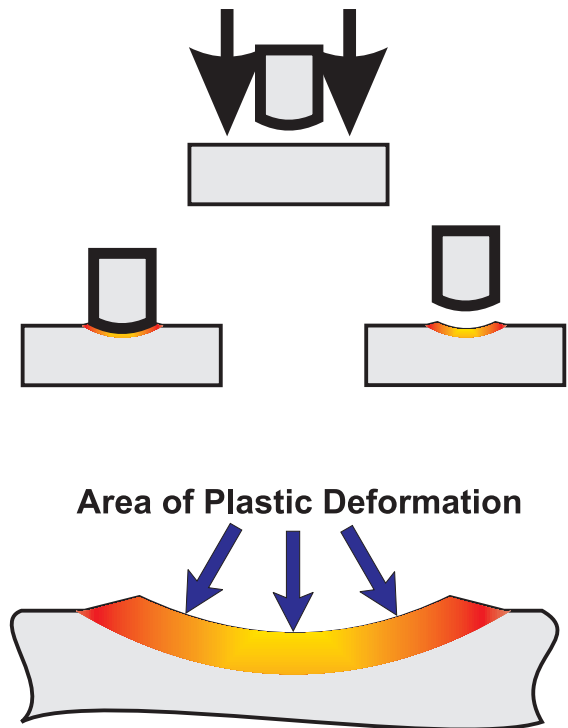


Figure 5.18: Hardness test.

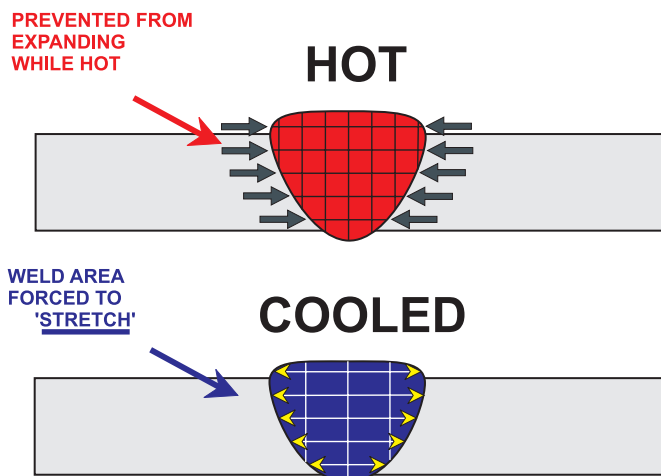


Figure 5.19

High hardness prevents the flow of the atoms past one another increasing the likelihood of cracking. For this reason we are concerned with predicting and controlling weld zone hardness.

5.8 Heat Affected Zone (HAZ)

Most people think that a weld is only the portion of metal fused during welding. This is a very limited way of looking at a weld. A more accurate way is to consider a weld as the area affected by the heat input during welding. According to this definition, a weld is composed of three main parts illustrated in **Figure 5.20**:

- ◆ fused zone (weld metal)
- ◆ bonding zone (fusion line)
- ◆ base metal heat affected zone (HAZ)

Weld Metal

A mixture of base metal and filler metal (when used) combined during the welding process.

Fusion Line

A line or zone where the temperature was just under the melting point of base metal.

Heat Affected Zone

The area of the base metal next to the weld that does not melt but is changed by the heat from the welding process. In a way, this area is heat treated by the welding process, that is, its mechanical properties have been altered.

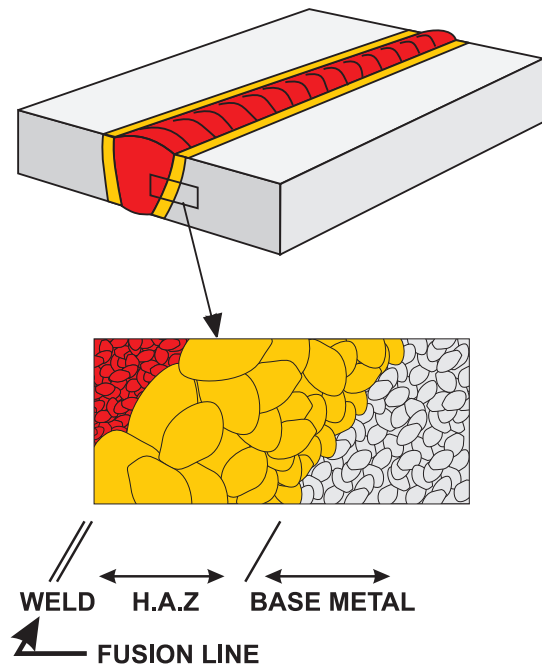


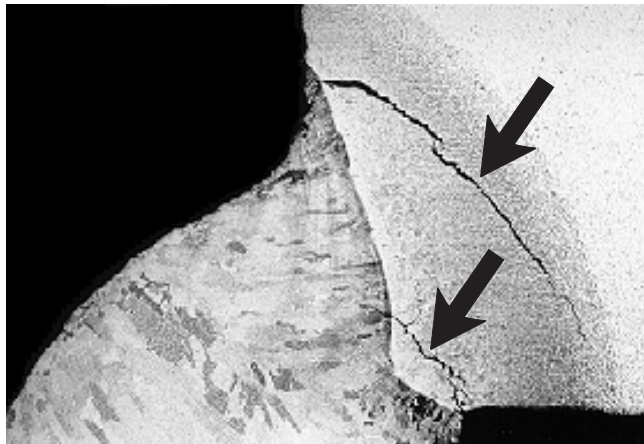
Figure 5.20

In theory, the HAZ refers to all areas of the base metal heated to above ambient temperature during welding. In practice, the term HAZ is used to describe the areas altered by welding heat input.

The width of the HAZ depends primarily on heat input and thermal conductivity (heat dissipation in base metal). If heat input is decreased or thermal conductivity increased, the HAZ size will decrease. This means that a weld made with SMAW process will normally produce a narrower HAZ than one made with FCAW (using a large diameter electrode). Similarly, stainless steels will have a larger HAZ than carbon steels, since the thermal (heat) conductivity is lower than steel.

Example

According to the iron-carbide phase diagram, the width of HAZ in carbon steels will extend from the weld interface to where the temperature reached 723°C. In practice the HAZ will extend a bit further.



The iron-carbon phase diagram shows that a phase transformation starts when the temperature reaches 723°C. At that temperature BCC transforms into FCC. Since weld cooling rates from temperatures above 723°C may be rapid, hardening of the weld area is common. The heat affected zone (HAZ) is a very important area because weld faults may occur in this zone (**Figure 5.21**). A weld that contains a crack in the HAZ is likely to fail in service. Cracks in the HAZ are often small and difficult to detect.

Figure 5.21: Cracks in the HAZ.

Properties of the HAZ depend on:

- ◆ type of base metal
- ◆ welding process
- ◆ welding procedure

Since different categories of steels behave differently to various heat treatments, the properties of the HAZ will vary with the type of base metal. The welding procedure will affect the HAZ through the heat input and cooling rate. Effects of welding on the HAZ are similar to heat treatments involving high temperatures (as in annealing), and fast cooling rates (as in quenching).

As can be seen in **Figure 5.22**, the transformations that take place in the HAZ depend on the highest temperature attained at each point of the zone during welding. This figure illustrates what happens to a steel that has been cold worked before welding. This is the case for most rolled plates that did not receive a heat treatment after rolling.

Where the temperature is minimal, grains (deformed by rolling) will use the heat provided by the welding process to recrystallize. Long grains (deformed by rolling) will transform into several smaller grains. Areas where the temperature rises above 723°C will show the effects of phase transformations (BCC – FCC – BCC). Near the weld fusion line, where temperatures are just below the melting point, very large grains form. This is generally the weakest part of a weld.

When it is important to limit grain growth in the HAZ, the welder should be following strict welding procedures and limit heat input by using small (stringer) weld beads when possible. Weaving is commonly used, but should be limited to plain low-carbon steels where heat treatments have lesser effects.

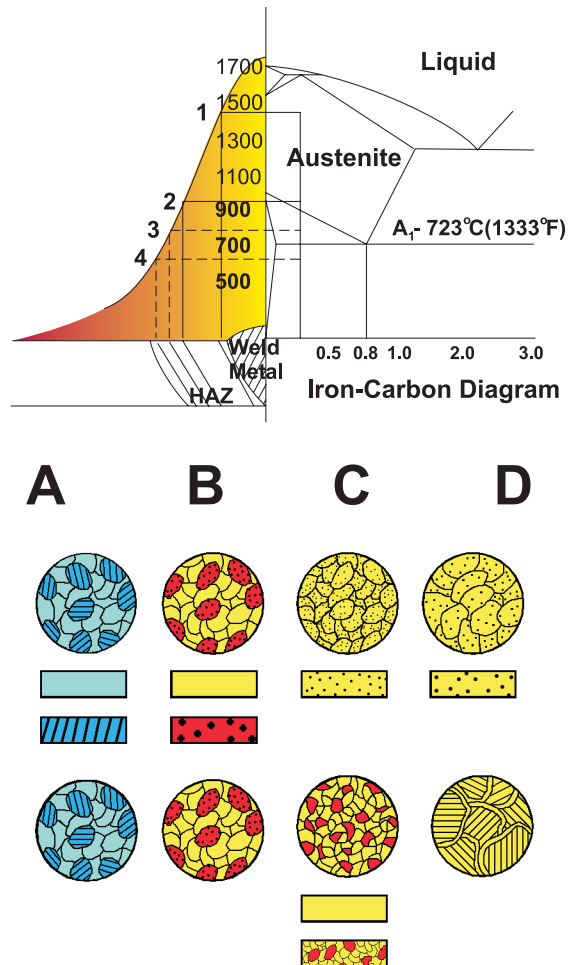


Figure 5.22

5.9 Weldability of Metals

Definition

The weldability of the steel is defined as the ease with which it can be welded without affecting the performance of the welded joint in the intended application, that is, with adequate properties and without harmful defects.

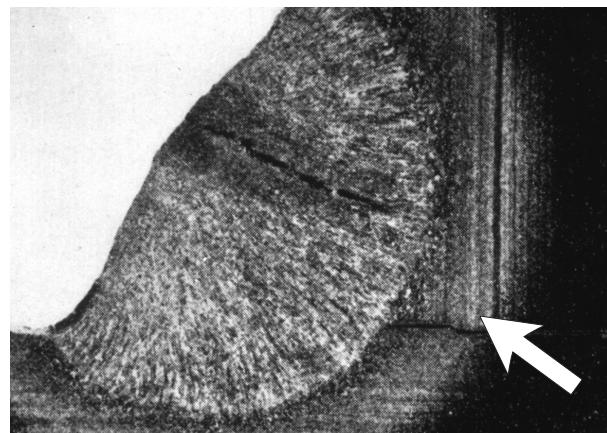


Figure 5.23: Heat affected zone in fillet weld.

Students have previously studied the weld process/technique-related flaws. Their presence does not really depend on the type of steel being welded and, therefore, these are not discussed further in this chapter. Other elements of good weldability (mechanical properties and the absence of metallurgical flaws) do however, depend on the type of steel being welded.

Prevention of hydrogen cracking, one of the potential metallurgical flaws that can be present in the weld zone, is one of the most important considerations in designing welding procedures. Besides the steel type/composition, two other factors determine if hydrogen cracking can occur in the weld joint. These factors are: the rate at which the weld cools once it has been heated by the welding arc; and, the presence of locked-in stresses.

5.9.1 Weld Cooling Rate

During welding, the steel next to the molten weld pool (beyond the fusion line) very nearly reaches the melting temperature, but not quite. As one moves further away from the fusion line, the peak temperature becomes less and less, until at some large distance and beyond, no significant rise in temperature occurs. Thus, at the fusion line, the temperature reaches more than 1350°C. The further from the fusion boundary, the lower the peak temperature reached. (Figure 5.24).

From the earlier discussion, we know that there is a change in the microstructure of any part of the steel that gets heated above approximately 700°C. This region next to the fusion boundary is called the heat affected zone.

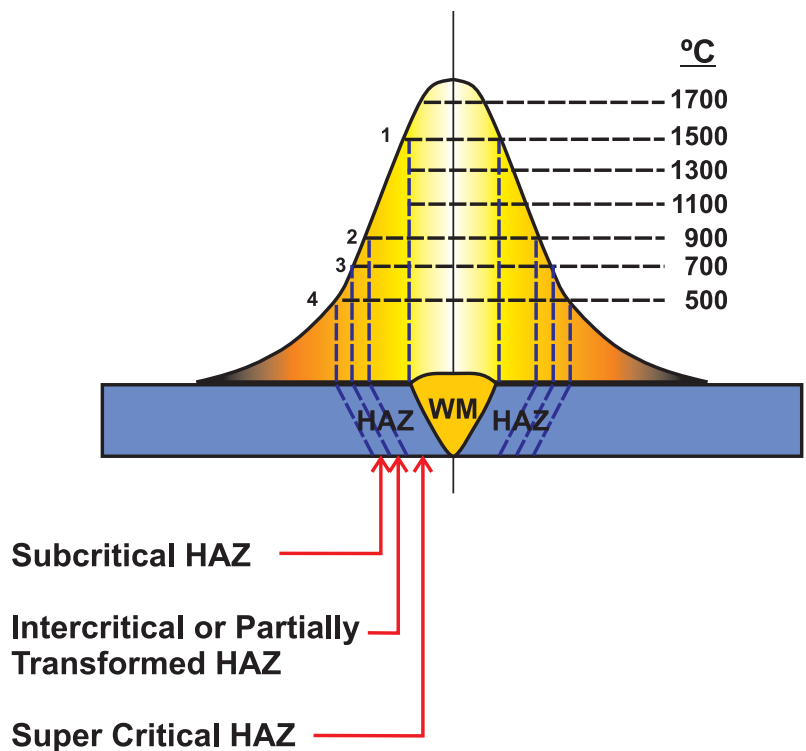


Figure 5.24: Heat Affected Zone (HAZ)

Also, from Section 5.5, we know that:

- ◆ When the temperature reached in the heat affected zone is more than about 900°C, the steel changes to 100% austenite phase, that is, it is fully transformed. The width of this region is rather small, from a fraction of a millimeter to a few millimeters depending on the weld heat and workpiece thickness. Once the welding arc has passed by such a location, the austenite phase formed changes to phases such as ferrite, pearlite, or martensite depending on the steel composition (hardening capacity) and the cooling rate. The properties (strength, hardness, toughness) of this part of the heat affected zone, also called the supercritical heat affected zone, depend on the microstructure.
- ◆ The region next to the supercritical heat affected zone that gets heated to a temperature between about 700°C and 900°C is called the intercritical heat affected zone or the partially transformed heat affected zone. The latter term indicates that the temperature did not exceed about 900°C in this region and therefore, the amount of austenite formed was less than 100%, the other phase present being ferrite. Therefore, this region cannot form 100% martensite on cooling.
- ◆ The next region after the partially transformed or the intercritical heat affected zone is the untransformed (no austenite formed at all) or the subcritical heat affected zone. The maximum temperature reached in this region is about 700°C. The microstructural changes in this region can be hard to detect with an ordinary microscope. For quenched and tempered steels, the region of the subcritical HAZ that reaches peak temperature above the tempering temperature (say 620°C) can suffer some reduction in strength. Also, in the presence of microalloying elements (Nb, V), there is potential for some reduction in notch toughness in the subcritical heat affected zone.

From the point of view of hydrogen cracking, it is the supercritical, fully transformed heat affected zone next to the fusion boundary that has the highest hardness and highest tendency to form hydrogen cracks. Whether hydrogen cracking would indeed occur or not in a given steel depends partly on the exact microstructure which, in turn, depends on the steel composition and the local cooling rate. If these two parameters are accurately known, it becomes possible to design a welding procedure that will prevent hydrogen cracking. Since one generally knows the composition (or at least the type) of steel being welded, at this stage it is important to understand what factors determine the weld zone cooling rate.

The cooling rate indicates how fast the weld zone cools. Therefore, it is measured as the average decrease in temperature of the weld zone (weld metal or the heat affected zone next to the fusion boundary) in one second. A cooling rate of 70°C/s is a much higher (or faster) cooling rate than 10°C/s. Conversely, if one looks at the time to cool from 800°C to 500°C, then smaller cooling times imply high cooling rate and larger cooling times imply slow cooling.

The cooling rate of the weld zone depends on the following three factors: weld heat, the thickness of the steel and whether the steel has been preheated.

- ♦ **Weld Heat:** also called the arc energy, is the amount of electrical energy (**Figure 5.25**) that is supplied to the welding arc over a given weld length (an inch or a mm). The greater the weld heat (arc energy) used to deposit the weld metal, the longer it takes to remove the heat from the weld and, therefore, the slower it cools.

Arc energy is calculated as follows:

$$\text{Arc Energy} = \frac{\text{Arc Current} \times \text{Arc Voltage} \times 60}{\text{Arc Travel Speed} \times 1000}$$

where, arc energy is in kJ/mm (kJ/in)
 current is in amperes
 voltage is in volts
 travel speed is in mm/min
 (in/min)
 (Note that 1kJ/mm = 25 kJ/in)

In the above equation, Arc Current x Arc Voltage is the electric energy being supplied to the arc in one second (J/sec), and when this is divided by the distance traveled in one second (travel speed in mm or inches per minute divided by 60), one obtains the arc energy (Joules per mm or Joules per inch; a kJ is simply equal to 1000 J).

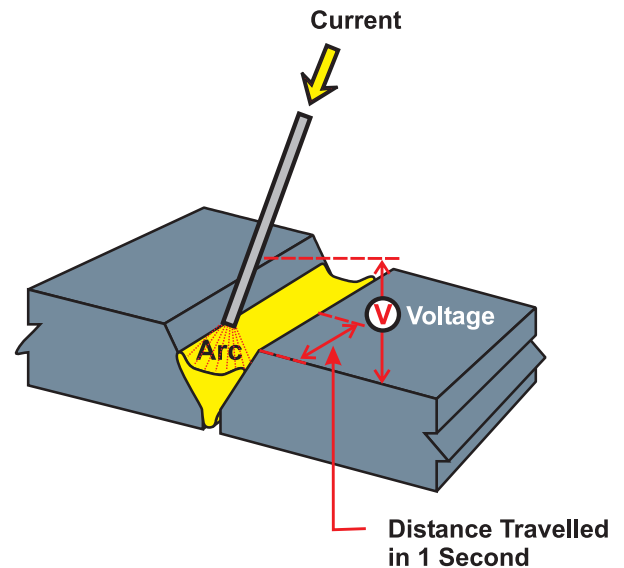
For example, if you use the SMAW process (E4918 electrode, 4 mm diameter) for depositing a weld pass using the following parameters:

Current = 160 A; Voltage = 22 V; Travel Speed = 8 in/min (203 mm/min)

$$\text{Arc Energy} = \frac{160 \times 22 \times 60}{203 \times 1000} = 1.04 \text{ kJ/mm}$$

OR

$$\text{Arc Energy} = \frac{160 \times 22 \times 60}{8 \times 1000} = 26.4 \text{ kJ/inch}$$



$$\text{Energy Input} = \frac{\text{Current} \times \text{Voltage}}{\text{Distance Travelled in 1 Second}}$$

Figure 5.25: Arc energy or energy input.

To slow down the weld cooling rate, you can increase the arc energy. This can be done by running the arc hotter, i.e., increasing the welding current, or by decreasing the travel speed.

For example, increasing the current to 180 A will increase the arc energy to

$$\frac{180 \times 22 \times 60}{8 \times 1000} = 29.7 \text{ kJ/inch} = 1.17 \text{ kJ/mm}$$

and decreasing the travel speed to 6 in/min (2.5 mm/min) instead will increase the arc energy to:

$$\frac{160 \times 22 \times 60}{6 \times 1000} = 35.2 \text{ kJ/inch} = 1.4 \text{ kJ/mm}$$

Note that if you use a weaving technique instead of depositing stringer beads, then the arc travel speed is reduced and the arc energy increases.

An important factor to note is that if you have the same weld heat or arc energy for the SMAW process (5 mm diameter electrode, 220 A, 22 V, 6 in/min; arc energy = 48.4 kJ/in = 1.9 kJ/mm) and the SAW process (3.2 mm diameter wire, 500 A, 30 V, 18.6 in/min travel speed, arc energy = 48.4 kJ/in = 1.9 kJ/mm), the cooling rate will not be the same in the two cases. This is because, in the open arc processes (SMAW, FCAW, GMAW), some of the weld heat is lost to the surrounding atmosphere whereas in the SAW process, almost all of the electrical energy gets into the weld zone as heat energy. The energy that goes into the steel is called heat input and,

Heat Input = Arc Efficiency x Arc Energy

Arc efficiency takes into account the fraction of the arc energy that goes into the workpiece and is not lost to the surrounding atmosphere. Submerged arc welding process has the highest arc efficiency and gas tungsten the smallest. Different people use different values and, later on when preheat requirements are estimated, the arc efficiency will need to be taken into account.

- ◆ **Thickness of Steel:** the loss of heat from the weld zone to the surrounding steel is much faster than to the surrounding air, therefore, one can intuitively see that for a fixed arc energy (heat input), as the steel thickness increases, the heat is sucked out more quickly and the weld zone cools faster, that is, the cooling rate increases.
- ◆ **Preheat:** if the steel has been preheated first, then the cooling rate decreases again because the hotter surrounding material has a reduced ability to pull heat from the weld zone. However, the effect is greater in the low temperature range (less than 300°C) and rather small in the higher temperature range (500 to 800°C) where the transformed microstructures form.

Because of the several factors that affect the weld cooling rate, its calculation can be complex. Fortunately, graphs have been developed that help to calculate the cooling rate. For example, **Figure 5.26** shows one such scheme developed by Graville¹ for the SAW process.

Nomogram to Calculate Submerged Arc Weld Cooling Rates

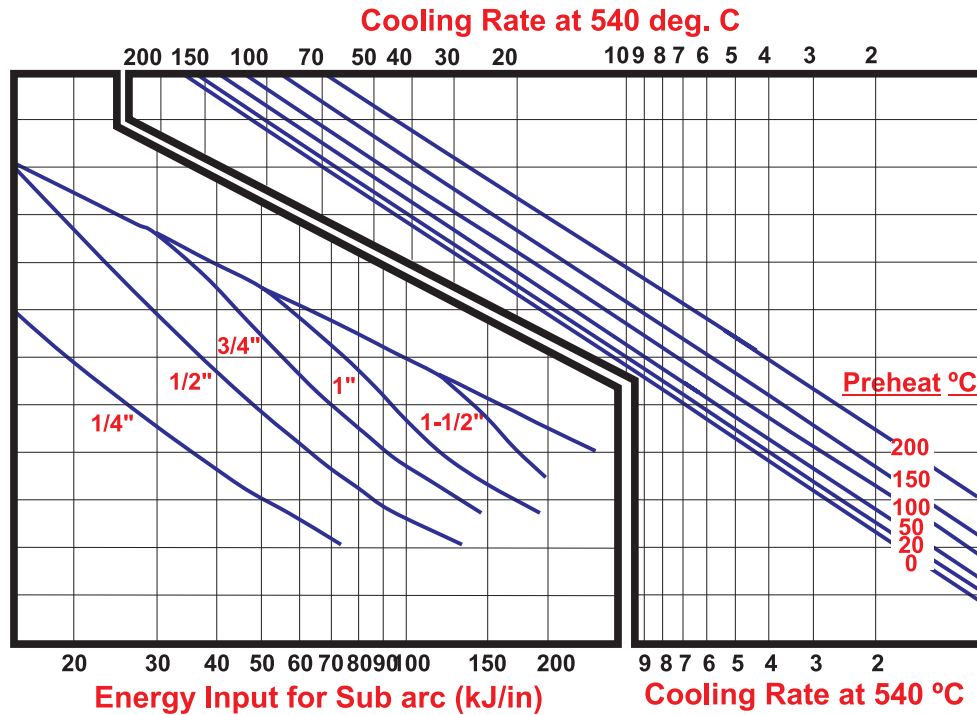


Figure 5.26: Graph to determine cooling rate in bead-on plate for submerged arc process.

1 Brian A. Graville, The Principles of Cold Cracking Control in Welds, (Dominion Bridge Company Ltd., 1975).

Let us consider two examples here:

- ◆ In the first example, let us say that the SAW process is being used to make a butt joint in a 1" thick plate using the following parameters: 600 A, 30 V, 18in/min travel speed, 100°C preheat. Therefore, arc energy = $600 \times 30 \times 60 / 18 \times 1000 = 60 \text{ kJ/in}$. Now, going to **Figure 5.27(a)**, we start at point A at 60 kJ/in at the bottom line and go up vertically to hit the line for 1" thickness at point B; next, we go towards the right from point B until we intersect the 100°C preheat line at point C. Now go up vertically again and at point D, read the cooling rate as about 11°C/sec at 540°C (1000°F). The cooling rate is estimated at 540°C because the development of microstructures like ferrite and pearlite occurs in the temperature range of about 500°C to 600°C during the relatively fast cooling of welds and it is the cooling rate in this temperature range that is important.

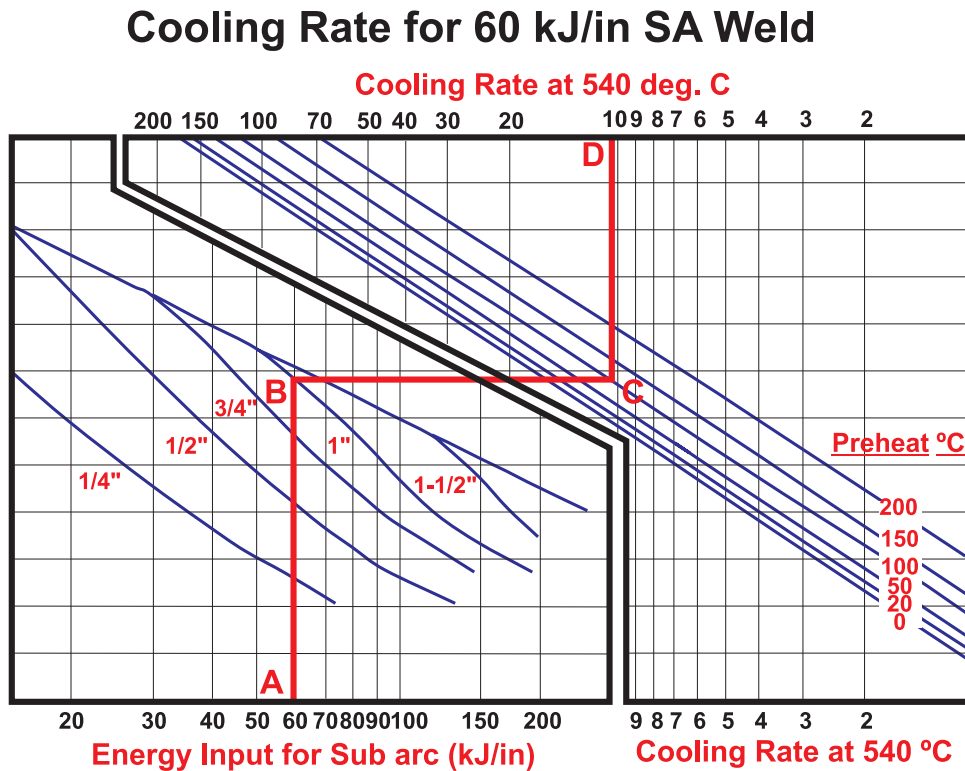


Figure 5.27(a)

- ◆ In the second example, let us say that the SMAW process is being used to weld 0.5" thick plate using the following parameters: 170 A, 22 V, no preheat (room temperature) and 8 in/min travel speed. Then, the arc energy =

$$170 \times 22 \times 60 / 8 \times 1000 = 28 \text{ kJ/in}$$

However, due to the open arc, not all this energy goes into the weld pool. Therefore, if **Figure 5.27(b)** is to be used to calculate the cooling rate for processes like SMAW, FCAW and GMAW, then the calculated arc energy for these processes should be multiplied by a correction factor (arc efficiency) which can be taken as 2/3 for the SMAW process and 4/5 for FCAW and GMAW processes. Therefore, for the example at hand, heat input (= arc energy x arc efficiency) will be

$$28 \times 2/3 = 18.7 \text{ kJ/in}$$

Now following the same procedure, one starts at point A', goes to point B' and C' and reads out the cooling rate to be between 40° and 50°C/sec at 540°C.

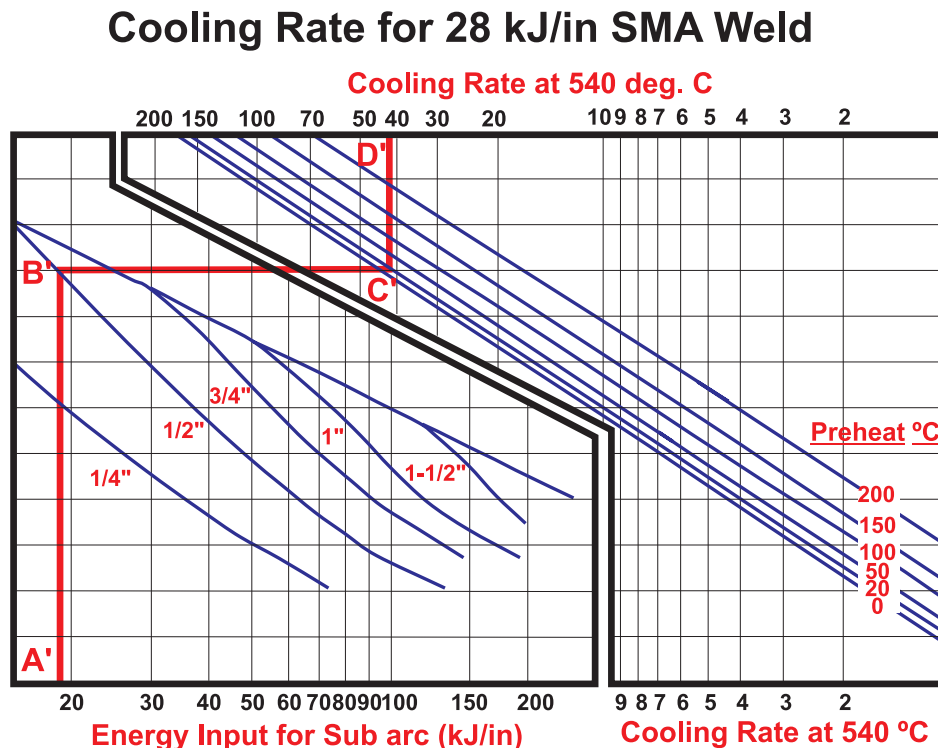
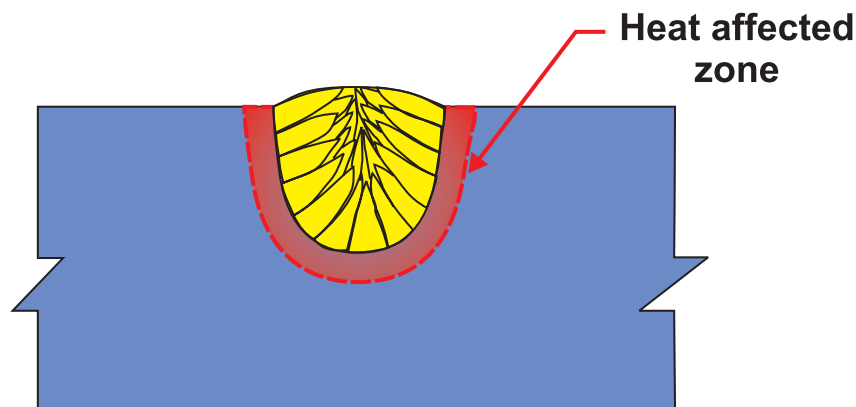


Figure 5.27(b)

5.10 Solidification Cracking

Consider that the weld puddle solidifies like a small casting. The process of solidification starts with the formation of several crystals (or dendrites) at the unmelted heat affected zone and continues as these crystals grow towards the center of the puddle. Where two crystals meet, they form a grain boundary and a sound weld should result (**Figure 5.28**).

However, in the presence of such elements as carbon, sulfur and phosphorous in the weld metal, small amounts of liquid metal enriched in sulfur and phosphorous are trapped between the crystals before the solidification is completed. As the weld metal shrinks further during cooling, a crack may form in the region where the liquid was trapped. The liquid that solidifies last, near the grain boundaries, has a lower melting point because of the impurities such as sulfur and phosphorous.

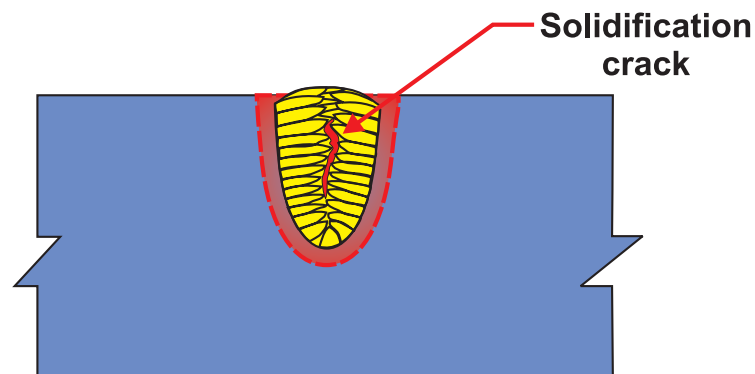


Shallow, Wider Weld Bead - More Resistant

Figure 5.28: Solidified weld – no hot cracking.

Solidification cracks are more common in welds that are deep and narrow (a submerged arc weld deposited at a high travel speed) because it is easier for the liquid metal to get trapped between the solidifying crystals (**Figure 5.29**). These cracks are also called centre-line cracks or hot cracks because they form near the center of the weld nugget and when the weld metal is still hot. Cracks seen in craters also form by the same mechanism, and are called crater cracks because of their location.

The steel being welded affects the possibility of solidification cracking when it has high content of such elements as carbon, sulfur and phosphorous and the welding procedure selected is such that there is considerable dilution of the weld metal by the base material. Minimizing dilution, controlling weld bead shape and employing lower arc energy are some of the approaches used to prevent solidification cracking.



Deeper, Narrower Weld Bead - Prone to Cracking

Figure 5.29: Solidification crack.

5.11 Strength and Toughness in the Weld Zone

It is difficult to predict the effect of the welding procedure (arc energy, welding consumable, pass sequence, welding technique, etc.) on the strength and toughness of the various regions of the welded joint, namely, the weld metal and heat affected zone. (One cannot easily measure the strength of the heat affected zone and, therefore, it is more common to talk in terms of the hardness of the heat affected zone). The fabricator usually performs a procedure qualification test, which demonstrates that with the selected procedure, the minimum specified properties (heat affected zone and weld metal toughness, if specified, maximum allowed heat affected zone hardness, strength in a cross-weld tensile test) are achieved.

In this section, one can only point out that arc energy (more accurately, the heat input) is one of the most important parameters that determines the properties of the heat affected zone and the weld metal (**Figure 5.30**). What effect this will have depends on the composition of the steel or the weld metal.

Generally speaking:

- ◆ at low arc energies, the weld metal and heat affected zone hardness (strength) tend to be high; as the arc energy increases, the hardness and strength decrease.

- ♦ if at low arc energy the hardness is too high, then the notch toughness of the heat affected zone tends to be poor. Conversely, if the arc energy is too high, the grain size in the microstructure becomes too large and this also reduces the toughness. The best level of notch toughness will be obtained at intermediate levels of arc energy, .
- ♦ the optimum level of arc energy for maximum notch toughness depends on the chemical composition; as the hardening capacity increases, the optimum arc energy level will increase. The preheat and interpass temperatures act in the same direction as the arc energy but the effect is usually smaller.

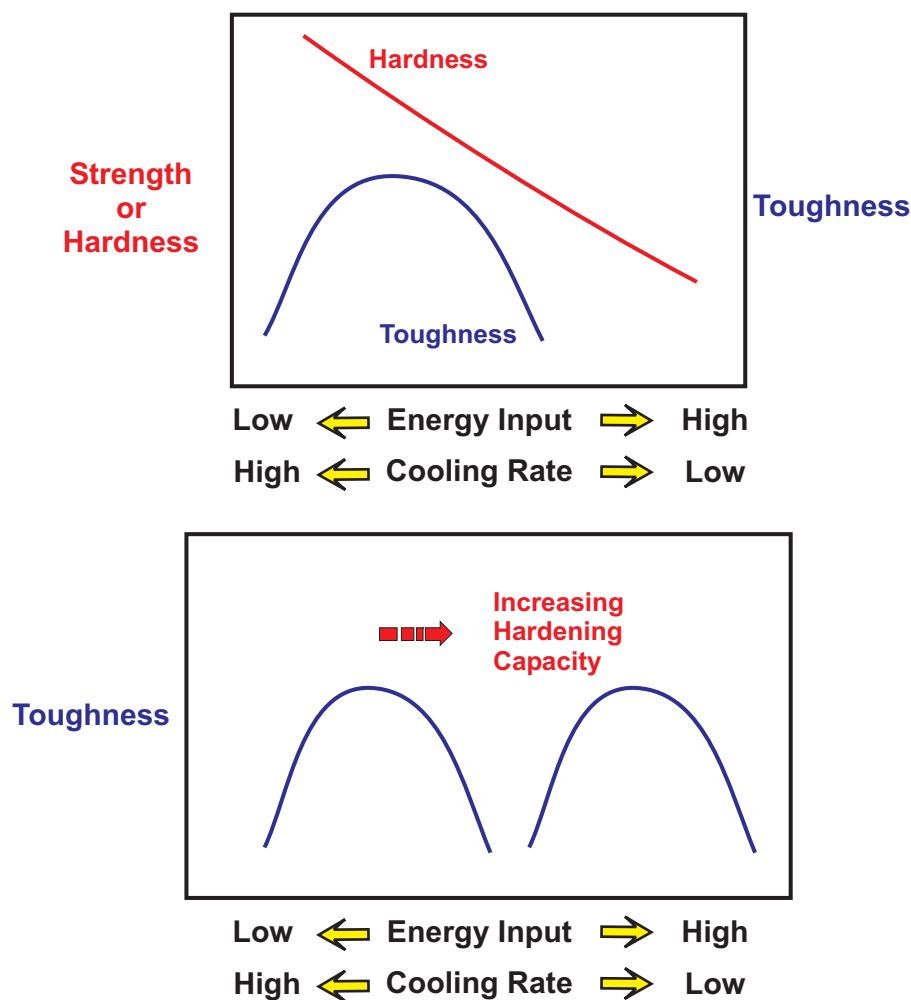


Figure 5.30: Cooling rate effect on properties.

5.12 Hydrogen Cracking

It is known that a certain amount of hydrogen is usually present in the weld pool. This comes from the breakdown of moisture that is generally present in fluxes (electrode coating, submerged flux, filling in flux cored wires) and that may also be present in shielding gases. Occasionally, high humidity on certain days can also increase the amount of hydrogen that might be introduced into the weld pool.

At room temperature, hydrogen is known to affect the properties of steels, basically, hydrogen embrittles the steel and reduces its ductility. In the case of welds, the hydrogen may also lead to the formation of cracks in the heat affected zone or the weld metal. If cracks do form, then some of their typical locations are shown in **Figure 5.31**.

Such cracks are completely unacceptable in welds and all precautions must be taken to ensure their absence. Their importance can be judged from the fact that sometimes weldability is narrowly defined as the ease with which steels may be welded without the formation of hydrogen cracks. (Hydrogen cracking is also called:

- ◆ cold cracking because cracks form only when the weld has cooled down to below about 100°C; and
- ◆ delayed hydrogen cracking because cracks can form several hours or days after weld completion.)

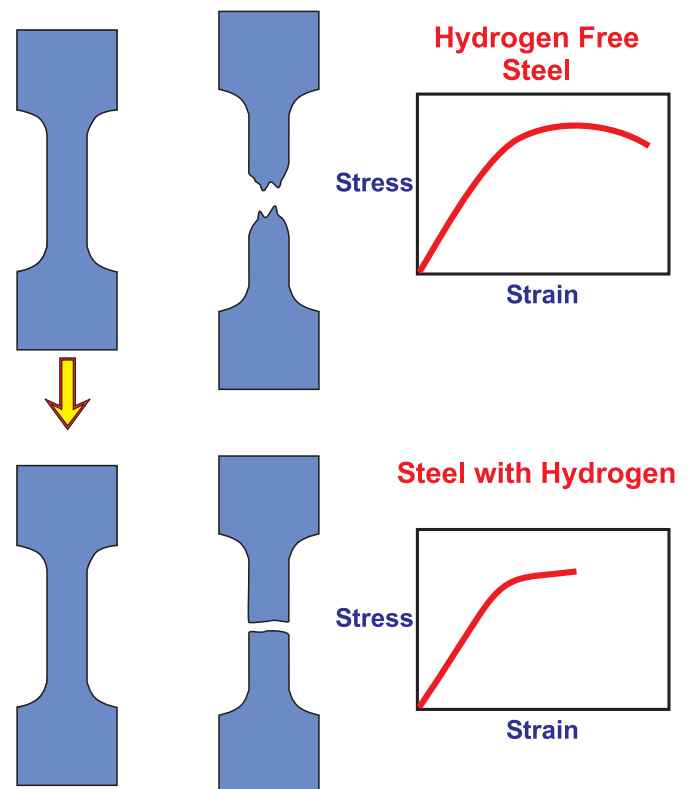
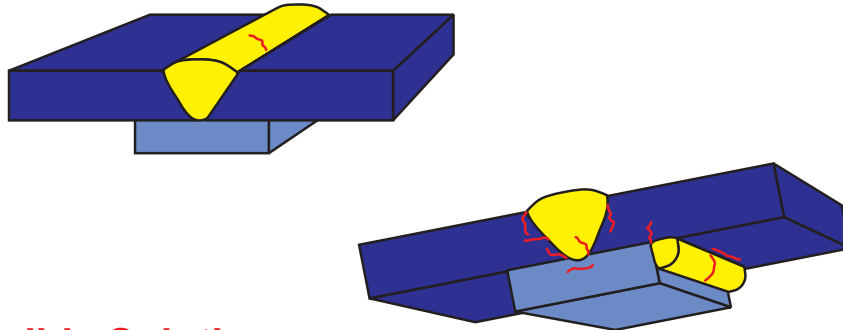


Figure 5.31: Hydrogen embrittlement.

Locations of Hydrogen Cracks



Possible Solutions

- Reduce sources of hydrogen
- Use preheat, check if properly applied and maintained
- Increase preheat and/or interpass temperature
- Increase welding energy, (soften weld zone)
- For multiple-pass welds, increase interpass time while maintaining interpass temperature
- Consider slowing cooling rate after weld completion or postweld heat for thick welds
- Minimize all fit-up gaps (to $< 1/16''$)
- Reduce joint rigidity by assembly or weld sequence
- For cracks that appear in the weld metal only, consider the use of lower-strength electrodes, subject to the owner's approval
- Ensure tacks incorporated in final weld are proper size and not cracked

Figure 5.32: Cracks in and around welds.

5.12.1 Factors Affecting the Formation of Hydrogen Cracks

The tendency to form hydrogen cracks depends on the following factors:

- ◆ **Amount of hydrogen present in the weld pool:** The greater the amount of hydrogen present in the weld pool, the greater the chance of forming hydrogen cracks. The amount of hydrogen introduced into the pool depends on such factors as the welding process used; the design of the welding consumable and its storage conditions; and the presence of moisture, oil, grease, etc. on the workpiece to be welded. Generally, the GTAW and GMAW introduce the smallest amount of hydrogen into the weld pool and these are called low-hydrogen processes.

The amount of hydrogen introduced in SMAW and FCAW processes will depend on the electrode designation, electrode manufacturer and the conditions under which the electrodes have been stored. For example, E4918 electrodes can be provided in vacuum-sealed packaging and these electrodes should introduce a very low amount of hydrogen into the weld pool. However, if after opening the package and before use, the electrodes are allowed to stay in the open in a high humidity environment for a period of a few hours or days, then the amount of hydrogen getting into the weld pool will be higher and this will increase the chances of hydrogen cracking.

- ◆ **Locked-in stresses present:** The higher the magnitude of the locked-in stresses, the easier it is for the hydrogen cracks to form. Residual stresses (weld zone shrinkage against the colder steel) are always present in welds. In addition, stresses may be present due to high restraint (the workpiece is too rigid to move).

Also, if notches are present, then stresses are magnified at these locations and hydrogen cracks can form more easily. Some such locations include the root pass in a groove weld, one-sided weld on backing bar or unspliced backing bar for a longitudinal weld (**Figure 5.32**).

- ◆ **Steel hardness/microstructure:** Generally speaking, the harder the heat affected zone, the greater its tendency to form hydrogen cracks. A harder microstructure means that it has a smaller proportion of ferrite and more of martensite-like phases. Depending on the hydrogen content and stress, the hardness above which hydrogen cracking may occur varies from 300 to 400 HV. Whether a hard heat affected zone forms on welding or not depends on the steel's hardening capacity, which in turn depends on the composition of the steel (amount of C, Mn, Cr, Ni, Mo, etc.) and the rate at which the weld cools. As mentioned in the previous Section, the rate at which the weld cools depends on the arc energy, steel thickness and preheat.

5.12.2 Avoiding Hydrogen Cracking

Once a steel has been selected and purchased for welding, the options available to counter the possibility of hydrogen cracking include:

- ◆ minimize weld joint restraint
- ◆ avoid notches in the area of the weld
- ◆ use a low hydrogen process
- ◆ use low hydrogen consumables and ensure their proper storage
- ◆ use high arc energy to reduce the cooling rate (but this may reduce other properties such as strength and toughness)
- ◆ use preheat (and post heat); its main function is to slow down the cooling rate below 100°C and give more time for hydrogen to diffuse out.

It is obvious that not all of the above factors can be controlled easily and that some of the above steps may entail additional costs. Therefore, one has to be sure of the need and effectiveness of the above steps. This depends on the type of the steel being welded and can be judged from the zone diagram developed by Graville² shown in **Figure 5.33**.

In this Figure, the vertical scale is the carbon content of the steel. You will recall that the carbon content determines the maximum hardness that is possible for the heat affected zone if it is cooled fast enough. The higher the carbon content, the higher the HAZ hardness possible and the greater the likelihood of hydrogen crack formation.

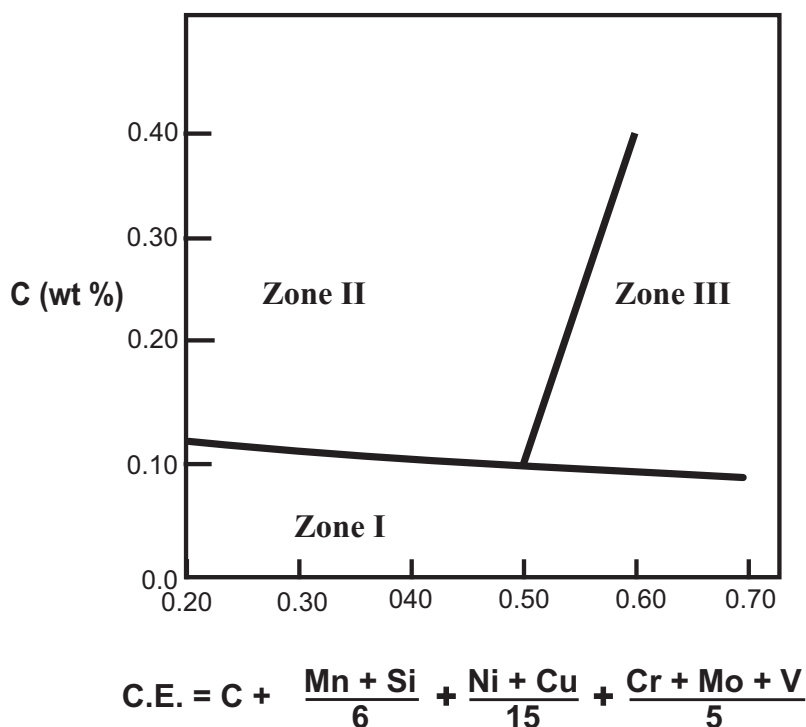


Figure 5.33: Zone diagram for classifying steels based on their weldability.

The horizontal axis in the diagram is a steel composition factor ($C.E. = C + (Mn+Si)/6 + (Ni+Cu)/15 + (Cr+Mo+V)/5$) called the carbon equivalent. It includes the carbon content of the steel as well as other elements that affect the hardening capacity of the steel. The higher the carbon equivalent of the steel, the greater its hardening capacity, and greater the hardening capacity, the easier it becomes to get high hardness in the heat affected zone at slower cooling rates.

² B.A. Graville, The Principles of Cold Cracking Control in Welds (Dominion Bridge Co., 1975).

The possibility of hydrogen cracking and the suitable means to avoid it can then be obtained from the location of the steel on this Zone diagram. For example, for steels that fall within Zone I, the carbon content is usually less than 0.10 wt% so that even if the hardening capacity is high (high carbon equivalent), the maximum hardness possible in the heat affected zone, even at fast cooling rates, is relatively low, typically less than 300 HV. (See the hardening curve for the 0.1% C steel in **Figure 5.13**.) Therefore, the possibility of hydrogen cracking is small. There should be no need for preheat (unless the thickness is very large), and good welding practices (control of consumables) should be enough to prevent hydrogen cracking.

Within Zone II, the carbon content is greater than 0.1 wt% and therefore, the maximum possible hardness achievable (fast cooling rate) in the HAZ is high. But the addition of alloying elements that increase the hardening capacity, and therefore the carbon equivalent, is limited (see the hardening curve for the 0.3% C steel in **Figure 5.13**). Therefore, if the weld can cool slowly (small workpiece thickness, high arc energy), then the maximum possible hardness is not achieved. In fact, the hardness may be sufficiently low for thin plates/high arc energies so that no preheat is required to prevent hydrogen cracks.

But it should be kept in mind that increasing the arc energy can have undesirable side effects such as reduced strength and toughness. Also, as the plate becomes thicker, it becomes difficult to slow down the cooling rate and then one must minimize the hydrogen content and/or use some preheat.

Within Zone III, the carbon content is greater than 0.1 wt% and, in addition, sufficient alloying elements are present (high carbon equivalent) so that high hardness values are obtained even at slow cooling rates (see the hardening curve for the 1%Mo steel in **Figure 5.14**). Consequently, heat input control cannot be used to prevent hydrogen cracking. Therefore, one has to focus on minimizing the initial hydrogen content and its removal by preheat and occasionally, by postweld heat (i.e., maintaining a temperature of about 100°C to 200°C for a length of time after completion of welding, depending on the thickness of the weld/steel plate).

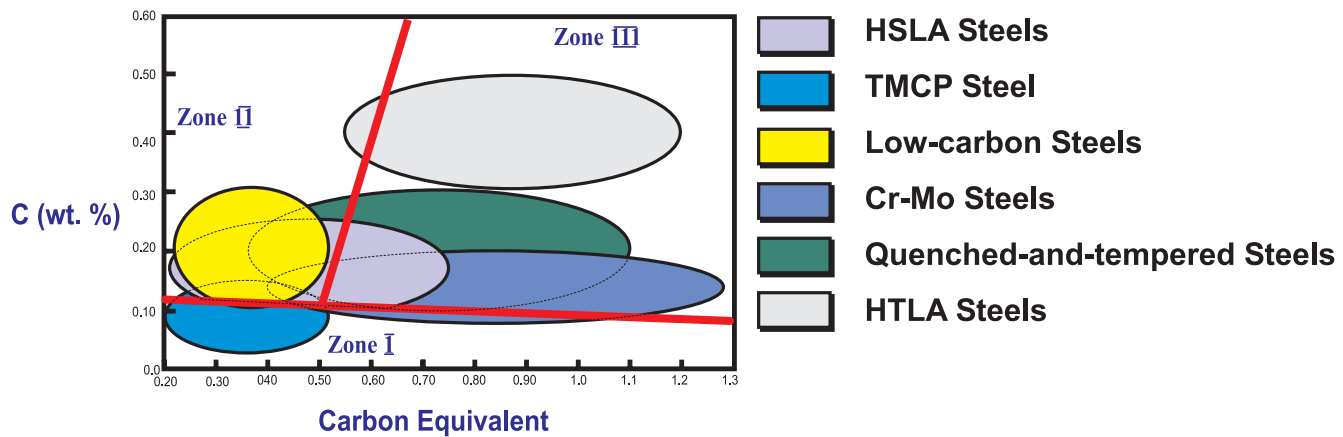


Figure 5.34: Location of different types of steels in the zone diagram (reproduced from ASM Handbook, Vol. 6, on Welding, Brazing and Soldering, 1993).

5.13 Heat Treatment of Steels

Heat treatment can be defined as an operation or combination of operations involving the heating and cooling of a metal or alloy in the solid state. Steel properties can more easily be controlled by heat treatment than by mechanical work.

By heat treatment, steel can be made strong and hard, or it can be made soft and ductile. By varying the carbon and alloy contents, and the heat treatment of steels, a wide range of mechanical properties can be produced. Since alloyed steels are more expensive than plain carbon steels, they are usually heat treated to take full advantage of their properties.

What is a heat treatment? Heat treatments basically consist of a three-step process:

- ◆ heating the steel to a specific temperature
- ◆ maintaining the steel at that temperature for a certain length of time
- ◆ cooling the steel at a specific rate

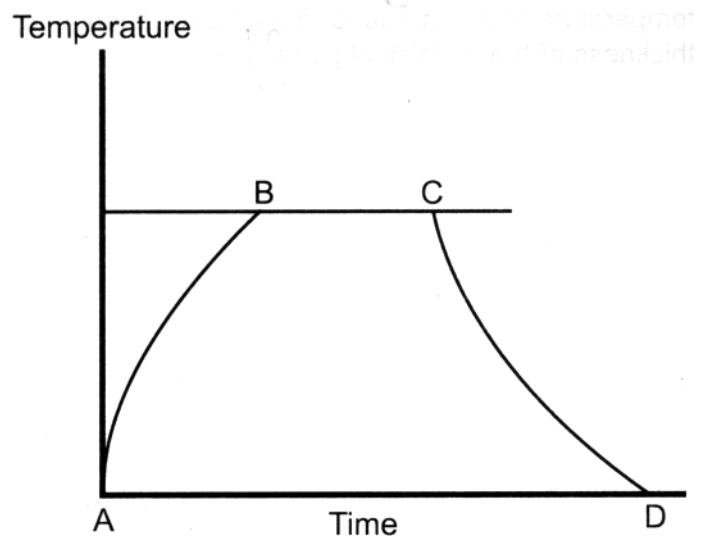


Figure 5.35: Typical heat treatment cycle.

Heat treatments, with a few exceptions, always involve some phases and/or grain transformations. Heat treatments may be subdivided into two broad categories:

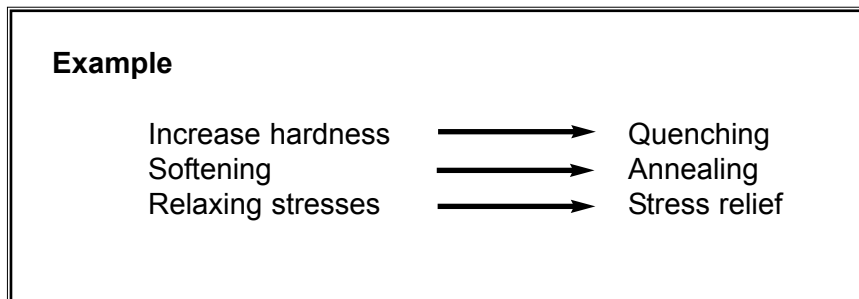
Conventional Heat Treatments

- ◆ annealing
- ◆ normalizing
- ◆ quenching
- ◆ tempering
- ◆ stress relieving

Special Heat Treatments

- ◆ flame hardening
- ◆ hot shots
- ◆ case hardening

Since this is a vast subject, we will concentrate on conventional heat treatments. As mentioned previously, heat treatments, when applied to heat treatable steels, will modify steel properties to regenerate some properties or to improve existing ones.



5.13.1 Annealing

Annealing is most often a softening process, where steel is heated to an elevated temperature, held for a certain time at this temperature, and allowed to cool slowly to room temperature.

In annealing, sufficient time (approx. 1 hour per 25 mm thickness) has to be allowed at the specific temperature to ensure complete transformation to austenite (FCC). Slow uniform heating and cooling are desirable. Furnace cooling is typically used.

5.13.2 Normalizing

Normalizing is similar to annealing except that the rate of cooling is increased by allowing steel to cool in the air instead of in a furnace. Normalizing is used to control grain size and lessen residual stresses. Normalized steels are harder and have higher strengths than steels that have been annealed.

5.13.3 Quenching

Quenching is probably the most common and well-known heat treatment. Quenching can be described as an operation that provides for rapid cooling of steel from the austenitic temperature (FCC) to lower temperatures such as room temperature. If cooling is rapid enough, steel will become much harder and stronger. Different rates of cooling can be obtained by immersing the piece in air, water, oil, brine and molten salts or molten metals.

Quenching is particularly useful for tools that must be hard and that must maintain their sharpness under severe conditions. Note that maximum hardness is generally accompanied by brittleness. To optimize mechanical properties, applying a subsequent heat treatment is often necessary. The treatment is called tempering.

5.13.4 Tempering

Quenched steels exhibit a wide range of mechanical properties. Hardness, tensile and yield strength, and brittleness will be very high. On the other hand, toughness and ductility will be much lower.

Tempering is an operation designed to modify steel properties resulting from quenching. Tempering is essentially a reheating process and is always done at temperatures where no structure change occurs. Its usual purpose is to increase toughness, reduce brittleness and alleviate high internal stresses.

5.13.5 Stress Relief

Stress relief is the heating of steel to a temperature below the transformation temperature, as in tempering, but it is done primarily to relieve internal stresses and to prevent distortion or cracking during machining.

When a metal is heated, expansion occurs. Upon cooling, the reverse reaction takes place and contraction is observed. In welding, when a part is heated more at one point than at another, internal stresses develop. Internal, or residual stresses, are bad because they can generate warping during machining. To relieve stresses, steel is heated uniformly and cooled slowly to room temperature.

5.13.6 Concept of Hardening

Some words that are universally understood are often misused. Hardening is one of these words. We frequently use the word “hard” to describe something that is firm or solid. In people’s mind a hard substance will not wear easily. This is only partially true and to understand what hardness really means, we will look at how hardness is achieved.

The hardening process is often associated with heat treatments like quenching or aging. The process is described as the increasing of hardness by suitable treatments, usually involving heating and cooling or cold working.

Hardness, in fact, is a measure of the resistance of a material to plastic deformation usually by indentation. Plastic deformation is a change in shape (no matter how small), which will remain permanent after removal of the force which caused it. The term may also refer to stiffness or temper, or to resistance to scratching, abrasion or cutting. Indentation hardness may be measured by various tests such as Brinell (B), Rockwell (HR) and Vickers (HV).

Hardness testing methods measure the size of an indentation made in the surface of a material. The indentation size made with the same load and indenter is compared (soft material has a large indent, hard material a small indent).

Hardness is achieved by a hardening process, and the effects of this treatment will depend on the grade of steel being treated. The response of a given steel to a hardening treatment is called hardenability.

Hardenability	The relative ability of a ferrous alloy to form martensite when quenched from high temperatures.
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Hardenability is closely related to the formation of a hard microstructure called martensite. Martensite is the hardest steel microstructure. It is the result of rapid quenching from above the transformation temperature (723°C). As discussed previously, when the transformation from FCC to BCC is forced to occur quickly, carbon and alloy elements cannot separate from the material to make pearlite; they will create a distorted body-centered phase called martensite.

Hardness is often considered as a good indicator of wear resistance. This is only partially true, since wear may take many forms such as grinding wear, sharp particle wear or friction wear. One has to be very careful to not automatically select the hardest material for a given wear action. Hardness is also associated with brittleness. Except in a few situations, brittleness normally increases when hardness increases.

Example

Steel with a hardness of 50 HR_C is more brittle than a steel with a hardness of 20 HR_C. HR_C is a commonly used hardness scale called Rockwell “C” Hardness.

In earthmoving equipment, a combination of hardness and toughness is often required. This is achieved by alloying steels with manganese. Hadfield or manganese steels are very hard on the surface (martensite) and soft inside (austenite).

5.13.7 Ways to Harden Steel

Three main ways to harden steel are:

- ◆ introduction of alloying elements (**Figure 5.36**)
- ◆ mechanical deformation (cold work)
- ◆ heat treatments

1) *Alloying Elements*

The introduction of alloying elements to the crystalline patterns (such as BCC or FCC) will deform the pattern and harden the metal. Carbon is one of the main alloying elements because it is cheap and has a tremendous impact on hardness and strength. Carbon has a dual effect on steel, as it fixes the maximum attainable hardness and contributes substantially to determine the hardenability.

Several other alloying elements are manganese (Mn), silicon (Si), chromium (Cr), and nickel (Ni). The most important function of these elements, in heat treatable steels, is to increase hardenability, making the hardening of large sections possible while using moderate quenching methods.

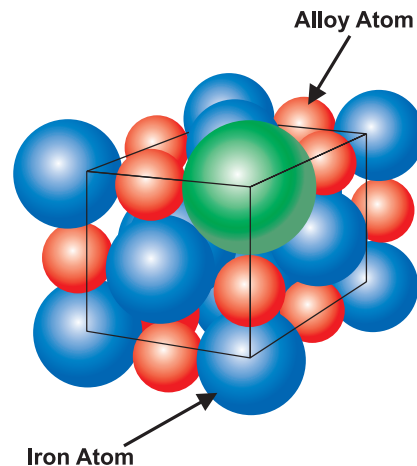
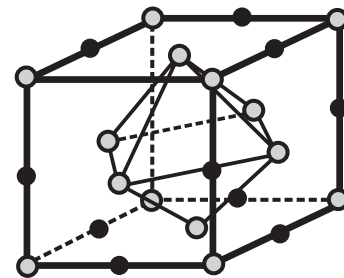


Figure 5.36: Positions of alloying elements.

5.13.8 Cold Work (Mechanical Deformation)

Cold working is deforming a metal plastically, at a temperature below the recrystallization temperature.

During cold work (such as during the rolling of the plate), hardening is produced by severe plastic deformation. Cold work increases hardness, yield strength, and tensile strength and lowers ductility.

Hardness and elongation react differently to work hardening. As cold work increases, hardness increases and elongation decreases down to a minimum after which the piece will break. This is what happens when a wire is broken after repeated bending in the same place, or when it is formed over a radius that is too small, as in brake press work.

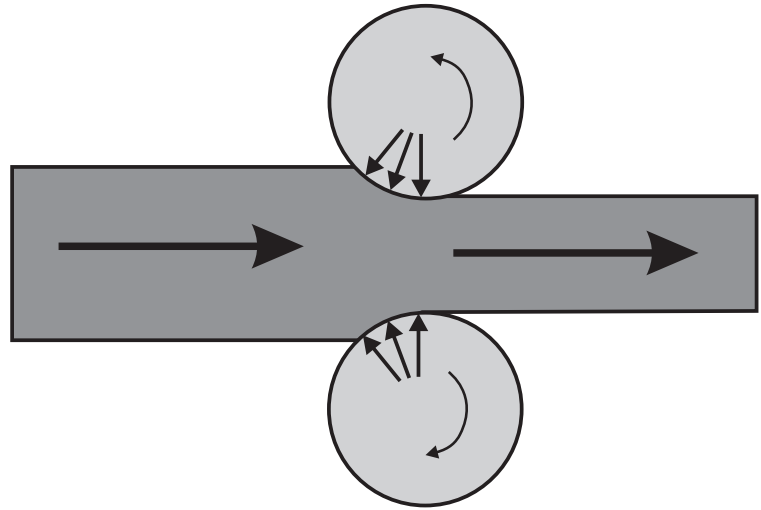


Figure 5.37: Plate rolling.

5.13.9 Heat Treatments

Hardening steels by heat treatment can only be accomplished if the steel has a suitable alloy content. Some steels, like plain low-carbon steels, do not have enough alloying to respond to standard hardening treatments.

Requirements for hardening steels by heat treatment:

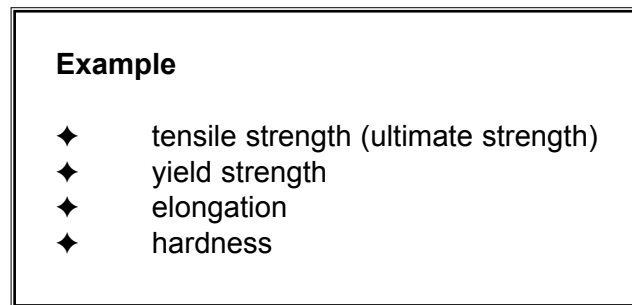
- ◆ sufficient carbon content in the steel
- ◆ steel must first be completely austenitized (FCC)
- ◆ austenitized steel must be cooled rapidly to a temperature range at which hard phases are formed (before pearlite can form)

Quenching is the most common hardening heat treatment. When steel is quenched, carbon and other alloying elements are trapped in areas where there is not enough space. This produces a deformed structure that can be associated with bainite or martensite. These structures are called hard phases or hard constituents.

5.14 Influence of Welding on Mechanical Properties

In previous sections, we mentioned that mechanical properties could be affected by heat treatments and by welding. Before talking about the effects of welding on mechanical properties, it is necessary to define what mechanical properties are.

Mechanical properties are the features of a material that show how it responds to force. They are a good indication of the material's suitability for mechanical applications.



Mechanical properties, like hardness, can be changed by mechanical work, with the addition of alloying elements and by heat treatment. Surprisingly, mechanical properties are often mistaken for physical properties.

Physical properties are properties of a metal or alloy that are insensitive to structure and can be measured without the application of force.

5.15 Designation of Steels

There are multiple grades of steels to suit numerous service demands. They are grouped into four major categories as shown in **Figure 5.38**.

Steel can be classified according to the carbon content and the type of alloying elements added.

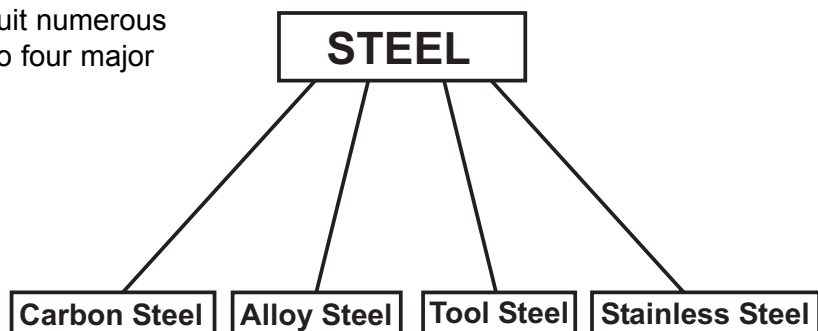


Figure 5.38

5.15.1 Carbon Steel

Carbon is the principal alloying element.

low-carbon	0.01% to 0.30% C
medium-carbon	0.30% to 0.45% C
high-carbon	0.45% to 1.70% C

(Medium and high-carbon steels can be heat treated.)

5.15.2 Alloy Steel, Tool Steel and Stainless Steel

To improve specific steel properties, quantities of elements such as chromium, nickel, molybdenum and vanadium are added. The resulting steel is much stronger than plain carbon steels, but is more expensive. Stainless steels are alloy steels that exhibit high corrosion resistance. High alloy steels are often called “tool steels”.

Having a good understanding of the properties of different steels is important because each category of steel requires specific welding procedures. Since carbon and low alloy steel represent more than 80% of all welded steel, we will focus our attention on these.

5.16 Classification of Steels (Numbering System)

Several codes classify steel according to chemical composition, applications and/or mechanical properties.

The common numbering systems used in North America are:

CSA G40.21	Canadian Standards Association
SAE	Society of Automotive Engineers
AISI	American Iron and Steel Institute
ASTM	American Society for Testing Materials

5.16.1 CSA G40.21 – Canadian Standards Association

This specification normally refers to structural steels. Eight different types of steel are produced under this classification.

Table 5.1: Types of steel.

G	General construction steel
W	Weldable steel
WT	Weldable notch toughness steel
R	Atmospheric corrosion resistant steel
A	Atmospheric corrosion resistant weldable steel
AT	Atmospheric corrosion resistant weldable notch toughness steel
Q	Quenched and tempered low alloy steel
QT	Quenched and tempered low alloy notch toughness steel

The eight types and seven strength levels have been combined into twenty-two grades:

Table 5.2: Grades of steel.

Type	Yield Strength, MPa (ksi)						
	230 (33)	260 (38)	300 (44)	350 (50)	400 (60)	480 (70)	700 (100)
G	230G	--	--	350G	400G	--	--
W	--	260W	300W	350W	400W	480W	--
WT	--	260WT	300WT	350WT	400WT	480WT	--
R	--	--	--	350R	--	--	--
A	--	--	--	350A	400A	480A	--
AT	--	--	--	350AT	400AT	480AT	--
Q	--	--	--	--	--	--	700Q
QT	--	--	--	--	--	--	700QT

5.16.2 SAE – AISI

The SAE-AISI numbering system normally consists of four digits. The first two digits (e.g., 86) provide information about the elements used as alloys. The last two digits refer to the percentage of carbon in the steel in hundredths of 1 percent. (e.g., 20 means 0.20% C). For example, AISI 8620:

86	20
alloy content	carbon content

Table 5.3: Designation system for AISI and SAE steels.

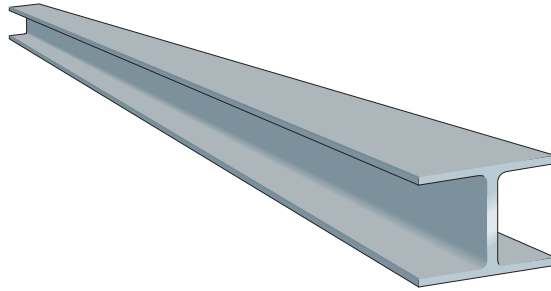
AISI or SAE Number	Composition
10xx	Plain carbon steel
11xx	Plain carbon (resulfurized for machinability)
13xx	Manganese (1.5% – 2.0%)
23xx	Nickel (3.25% – 3.75%)
25xx	Nickel (4.75% – 5.25%)
31xx	Nickel (1.10% – 1.40%), chromium (0.55% – 0.90%)
33xx	Nickel (3.25% – 3.75%), chromium (1.40% – 1.75%)
40xx	Molybdenum (0.20% – 0.30%)
41xx	Chromium (0.40% – 1.20%), molybdenum (0.08% – 0.25%)
43xx	Nickel (1.65% – 2.00%), chromium (0.40% – 0.90%), molybdenum (0.20% – 0.30%)
46xx	Nickel (1.40% – 2.00%), molybdenum (0.15% – 0.30%)
48xx	Nickel (3.25% – 3.75%), molybdenum (0.20% – 0.30%)
51xx	Chromium (0.70% – 1.20%)
61xx	Chromium (0.70% – 1.10%), vanadium (0.10%)
81xx	Nickel (0.20% – 0.40%), chromium (0.30% – 0.55%), molybdenum (0.08% – 0.15%)
86xx	Nickel (0.30% – 0.70%), chromium (0.40% – 0.85%), molybdenum (0.08% – 0.25%)
87xx	Nickel (0.40% – 0.70%), chromium (0.40% – 0.60%), molybdenum (0.20% – 0.30%)
92xx	Silicon (1.80% – 2.20%)

xx Carbon content, 0.xx%
Mn All steels contain 0.50% + manganese
B Prefixed to show bessemer steel
C Prefixed to show open-hearth steel
E Prefixed to show electric furnace steel

5.16.3 ASTM

ASTM classification is widely used for structural and pressure vessel steels. In this classification, steels are given a reference number, for example

Example	ASTM A-36
	ASTM A-285
	ASTM A-516
	ASTM A-572



The number refers to a set combination of chemical composition and mechanical properties. Some ASTM steels are comparable to Canadian steels. For instance, Grade G40.21-300W can be used as a substitute for ASTM A-36. The ASTM number is sometimes followed by a grade number (ex. ASTM A-572 Grade 42 or 50). Here, different Canadian grades have to be selected. Grade G40.21-300W can be considered as equivalent to ASTM A572 Grade 42 and Grade G40.21-350W will be used as an equivalent to ASTM A572 Grade 50.

The ASTM publishes specifications of various special purpose steels, which are updated regularly. Detailed information of ASTM designated steel can be found in its individual specification.

Table 5.4: Index of steel specifications in welding procedure table.

ASTM Steels	Item No.	Specification Title
A27-83	1	Steel castings, carbon, for general application
A36-81	2	Structural steel
A53-83	3	Pipe, steel, black and hot-dipped, zinc-coated welded and seamless
A105-83	5	Forgings, carbon steel for piping components
A106-83	6	Seamless carbon steel pipe for high-temperature service
A108-81	7	Steel bars, carbon, cold-finished, standard quality
A120-83	8	Pipe steel, black and hot-dipped zinc-coated (galvanized) welded and seamless for ordinary uses
A131-82	9	Structural steel for ships
A134-80	10	Pipe steel, electric-fusion (arc) welded steel plate pipe (sizes 16 inch and over)
A135-83	11	Electric-resistance-welded steel pipe
A139-74	12	Electric-fusion (arc) welded steel pipe (sizes 4 inch and over)
A148-83	13	Steel castings, high-strength, for structural purposes
A161-83	14, 18	Seamless low-carbon and carbon-molybdenum steel still tubes for refinery service (2 inch – 9 inch outside diameter)
A176-83	37	Stainless and heat-resisting chromium steel plate, sheet and strip
A178-83	15	Electric-resistance-welded carbon steel boiler tubes (1/2 inch – 5 inch outside diameter)
A179-83	16	Seamless cold-drawn low-carbon steel heat-exchanger and condenser tubes (1/8 inch – 3 inch outside diameter)
A181-83	17	Forgings, carbon steel, for general purpose piping
A182-82	18,22,23, 26,28,30, 32,35,36, 37	Forged or rolled alloy-steel pipe flanges, forged or rolled alloy-steel pipe flanges, forged fittings and valves and parts for high-temperature service
A184-79	38	Fabricated deformed steel bar mats for concrete reinforcement
A185-79	39	Welded steel wire fabric for concrete reinforcement
A192-83	40	Seamless carbon steel boiler tubes for high-pressure service (1/2 inch – 7 inch outside diameter)
A199-83	26,27,28 29,30,32, 35,36	Seamless cold-drawn intermediate alloy-steel heat-exchanger and condenser tubes
A200-83	26,27,28, 29,30,32, 35,36	Seamless intermediate alloy steel still tubes for refinery service
A202-82	41	Pressure vessel plates, alloy steel, chromium-manganese-silicon
A203-82	42	Pressure vessel plates, alloy steel, nickel
A204-82	18	Pressure vessel plates, alloy steel, molybdenum
A209-83	18	Seamless carbon-molybdenum alloy-steel boiler and superheater tubes
A210-83	43	Seamless medium carbon steel boiler and superheater tubes (1/2 inch – 5 inch outside diameter)
A213-83	22,23,25 26,27,28, 30,32,33, 34,35,36	Seamless ferritic and austenitic alloy-steel boiler, superheater and heat-exchanger tubes
A214-83	44	Electric-resistance-welded carbon steel heat-exchanger and condenser tubes
A216-83	45	Steel castings, carbon, suitable for fusion welding for high-temperature service
A217-83	34,36,37, 46	Steel castings, martensitic stainless and alloy for high-temperature service
A225-82	47	Pressure vessel plates, alloy steel, manganese-vanadium-nickel

ASTM Steels	Item No.	Specification Title
A226-83	48	Electric-resistance-welded carbon steel boiler and superheater tubes for high-pressure service (1/2 inch – 5 inch outside diameter)
A234-82	18,23,26, 28,32,35, 36,49	Piping fittings of wrought carbon steel and alloy steel for moderate and elevated temperatures
A240-83	37	Heat-resisting chromium and chromium-nickel stainless steel plate, sheet and strip for pressure vessels
A242-81	50	High-strength low-alloy structural steel
A250-83	18	Electric-resistance-welded carbon-molybdenum alloy steel boiler and superheater tubes
A252-82	51	Welded and seamless steel pipe piles
A266-83	52	Forgings, carbon steel, for pressure vessel components
A268-83	37	Seamless and welded ferritic stainless steel tubing for general service
A276-83	37	Stainless and heat-resisting steel bars and shapes
A283-81	53	Low and intermediate tensile strength carbon steel plates, shapes and bars
A284-81	54	Low and intermediate tensile strength carbon-silicon steel plates for machine parts and general construction
A285-82	55	Pressure vessel plates, carbon steel, low and intermediate tensile strength
A299-82	56	Pressure vessel plates, carbon steel, manganese-silicon
A302-82	57	Pressure vessel plates, alloy steel, manganese-molybdenum and manganese-molybdenum-nickel
A311-79	58	Stress-relieved, cold-drawn carbon steel bars subject to mechanical properties
A321-81	59	Steel bars, carbon, quenched and tempered
A322-82	60	Steel bars, alloy, standard grades
A328-81	61	Steel sheet piling
A331-81	60	Steel bars, alloy, cold-finished
A333-82	62	Seamless and welded steel pipe for low-temperature service
A334-83	63	Seamless and welded carbon and alloy steel tubes for low-temperature service
A335-81	18,20,22, 23,26,28, 30,32,33, 34,35,36	Seamless ferritic alloy steel pipe for high-temperature service
A336-83	18,19,23, 26,28,30, 31,32,36, 37	Steel forgings, alloy, for pressure and high-temperature parts
A350-82	64	Forgings, carbon and low-alloy steel, requiring notch toughness testing for piping components
A352-83	65	Steel castings, ferritic and martensitic, for pressure containing parts suitable for low-temperature service
A353-82	66	Pressure vessel plates, alloy steel, 9% nickel, double-normalized and tempered
A356-83	18,21,22, 24,26,28, 67	Steel castings, carbon and low-alloy, heavy-walled, for steam turbines
A369-79	18,22,23, 26,27,28, 30,32,35, 36,68	Carbon and ferritic alloy steel forged and bored pipe for high-temperature service
A372-82	69	Carbon and alloy steel forgings for thin-walled pressure vessels
A381-81	70	Metal-arc welded steel pipe for use with high-pressure transmission systems

ASTM Steels	Item No.	Specification Title
A387-83	22,23,26, 28,30,32, 35,36	Pressure vessel plates, alloy steel, chromium-molybdenum
A389-83	24,26	Steel castings, alloy, specially heat-treated for pressure-containing parts suitable for high-temperature service
A405-81	24	Seamless ferritic alloy-steel pipe specially heat treated for high-temperature service
A420-83	71	Pipe fittings of wrought carbon steel and alloy steel for low-temperature service
A423-83	72	Seamless and electric-welded low-alloy steel tubes
A426-80	18,20,22, 23,26,28, 30,32,33, 35,36,37	Centrifugally cast ferritic alloy steel pipe for high-temperature service
A434-81	73	Steel bars, alloy, hot-wrought, or cold-finished, quenched and tempered
A441-81	74	High-strength low-alloy structural manganese-vanadium steel
A442-82	75	Pressure vessel plates, carbon steel, improved transition properties
A455-82	76	Pressure vessel plates, carbon steel, high-strength manganese
A473-82	32,35,36, 37	Stainless and heat-resisting steel forgings
A486-82	77	Steel castings for highway bridges
A487-83	37,78	Steel castings suitable for pressure service
A498-68	80	Seamless and welded carbon ferritic, and austenitic alloy steel heat exchanger tubes with integral fins
A500-82	81	Cold-formed welded and seamless carbon steel structural tubing in rounds and shapes
A501-83	82	Hot-formed welded and seamless carbon steel structural tubing
A508-81	83	Quenched and tempered vacuum-treated carbon and alloy steel forgings for pressure vessels
A511-79	37	Seamless stainless steel mechanical tubing
A512-83	84	Cold-drawn butt weld carbon steel mechanical tubing
A513-82	85	Electric-resistance-welded carbon and alloy steel mechanical tubing
A514-82	86	High-yield-strength, quenched and tempered alloy steel plate, suitable for welding
A515-82	87	Pressure vessel plates, carbon steel for intermediate and higher-temperature service
A516-83	88	Pressure vessel plates, carbon steel, for moderate and lower-temperature service
A517-82	89	Pressure vessel plates, alloy steel, high-strength, quenched and tempered
A519-82	90	Seamless carbon and alloy steel mechanical tubing
A521-76	91	Steel, closed-impression die forgings for general industrial use
A522-81	66	Forged or rolled 9% nickel alloy steel flanges, fittings, valves and parts for low-temperature service
A523-81	92	Plain end seamless and electric-resistance-welded steel pipe for high pressure pipe-type cable circuits
A524-80	93	Seamless carbon steel pipe for atmospheric and lower temperatures
A529-82	94	Structural steel with 42 ksi minimum yield point (1/2 inch maximum thickness)
A533-82	95	Pressure vessel plates, alloy steel, quenched and tempered, manganese-molybdenum and manganese-molybdenum-nickel
A537-82	96	Pressure vessel plates, heat treated, carbon-manganese-silicon steel
A541-81	26,28,97	Steel forgings, carbon and alloy, quenched and tempered, for pressure vessel components

A542-82	28	Pressure vessel plates, alloy steel, quenched and tempered chromium-molybdenum
A543-82	98	Pressure vessel plates, alloy steel, quenched and tempered nickel-chromium-molybdenum
A553-82	66	Pressure vessel plates, alloy steel quenched and tempered 8% and 9% nickel
A562-82	99	Pressure vessel plates, carbon steel, manganese-titanium for glass or diffused metallic coatings
A572-82	100	High-strength low-alloy columbium-vanadium steels of structural quality
A573-81	101	Structural carbon steel plates of improved toughness
A575-81	102	Steel bars, carbon, merchant quality, M-grades
A576-81	103	Steel bars, carbon, hot-wrought special quality
A587-83	104	Electric-welded low-carbon steel pipe for the chemical industry
A588-82	105	High-strength low-alloy structural steel with 50 ksi minimum yield point to 4 inch thick
A589-83	106	Seamless and welded carbon steel water-well pipe
A592-74	107	High-strength quenched and tempered low-alloy steel forged fittings and parts for pressure vessels
A594-69	108	Carbon steel forgings with special magnetic characteristics
A595-80	109	Steel tubes, low carbon tapered, for structural use
A612-82	110	Pressure vessel plates, carbon steel, high-strength, for moderate and lower-temperature service
A615-82	111	Deformed and plain billet-steel bars for concrete reinforcement
A618-81	112	Hot-formed welded and seamless high-strength low-alloy structural tubing
A633-79	113	Normalized high-strength low-alloy structural steel
A645-82	114	Pressure vessel plates, 5% nickel alloy steel, specially heat treated
A656-81	115	Hot-rolled structural steel, high-strength low-alloy plate with improved formability
A660-79	45	Centrifugally cast carbon steel pipe for high-temperature service
A662-82	116	Pressure vessel plates, carbon-manganese, for moderate and lower temperature service
A663-82	117	Steel bars, carbon, merchant quality, mechanical properties
A668-83	118	Steel forgings, carbon and alloy, for general industrial use
A671-80	119	Electric-fusion-welded steel pipe for atmospheric and lower temperatures
A672-81	120	Electric-fusion-welded steel pipe for high-pressure service at moderate temperatures
A675-82	121	Steel bars, carbon, hot-wrought, special quality, mechanical properties
A678-75	122	Quenched and tempered carbon steel plates for structural applications
A690-81	123	High-strength low-alloy steel H-piles and sheet piling for use in marine environments
A691-83	124	Carbon and alloy steel pipe, electric-fusion-welded for high pressure service at high temperatures
A692-83	18	Seamless medium strength carbon-molybdenum alloy-steel boiler and superheater tubes
A694-81	125	Forgings, carbon and alloy steel, for pipe flanges, fittings, valves and parts for high-pressure transmission service
A696-81	126	Steel bars, carbon, hot-wrought or cold-finished, special quality, for pressure piping components
A699-77	127	Low-carbon manganese-molybdenum-columbium alloy steel plates, shapes and bars
A706-82	128	Low-alloy steel deformed bars for concrete reinforcement
A707-83	129	Flanges, forged, carbon and alloy steel for low-temperature service
A709-81	130	Structural steel for bridges
A710-79	131	Low-carbon age-hardening nickel-copper-chromium-molybdenum-columbium and nickel-copper-columbium alloy steels
A714-81	132	High-strength low-alloy welded and seamless steel pipe
A724-82	133	Pressure vessel plates, carbon steel, quenched and tempered, for welded layered pressure vessels
A727-81	134	Forgings, carbon steel, for piping components with inherent notch toughness
A730-81	135	Forgings, carbon and alloy steel, for railway use
A734-82	136	Pressure vessel plates, alloy steel and high-strength, low-alloy steel, quenched and tempered

Chapter 6

Residual Stress and Distortion

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6.1 Introduction

The objective of this chapter is to discuss the phenomena of residual stress and distortion, explain their causes, behaviour, magnitude, how to avoid or minimize them and finally, how to rectify welding distortions when they occur beyond allowance. Residual stress is neither visible nor readily measurable, where distortion is both. The latter is always the manifestation of the former. The relation between residual stress and distortion will be discussed. In dealing with distortion problems, the adherence to established welding procedures and manufacturing plans is very important. Years of shop fabrication experience is still the best assurance. Knowledge of the fundamental theory and equations will help you grasp the nature of the problem but precise control is not always achievable. Due to the many variables involved, experience and theory are the best tools to avoid distortion.

It is often difficult to establish an exact, satisfactory welding procedure for an unsatisfactory design. The following lessons are of equal importance to both the designer and supervisor. The designer's work is not finished on the drawing board or on the computer, since the designer and supervisor must share the responsibility for the final product.

The development of welding procedures should begin with the understanding that the heat of welding will produce expansion, contraction and stress, and consequently their major objectives should be to:

1. Produce sound weldments
2. Maintain dimensions by controlling distortion
3. Reduce and balance internal residual welding stresses
4. Be easily accessible and economical

Obviously, welding procedures will involve the welding process, base metals, joint design and preparation, filler metals, power source, current and voltage, welding technique, heat treatment, etc. Even more important, however, is the pattern of heat input to the work as determined by the sequence of assembly and the sequence of welding.

To control distortion and residual stresses, the effort of each of these factors must be thoroughly understood and the welding procedure should be planned accordingly. The welding procedure, once planned, should be checked by trial run and modified when required. It should be clearly laid out and purposely followed by all personnel. It forms an important part of the shop's quality control system.

For further study the following CWB Modules provide more detailed discussions and practical examples:

- | | |
|-----------|--------------------------------|
| Module 7 | Residual Stress and Distortion |
| Module 39 | Weld Mechanics |

6.2 Expansion and Contraction of Metals

By nature, metals expand volumetrically when heat is applied. When the heat source is removed the metal contracts during cooling, also volumetrically. The expansion and contraction movement of heated metal can be illustrated by considering the movement of a metal ball. **Figure 6.1** shows a metal ball expanding freely under heat and contracting freely to its original volume and shape after cooling.

Figure 6.2 shows a metal ball that is fitted snugly between two rigid stops and heated, then cooled. **Figure 6.2B** shows that the ball is expanding in the open direction and restricted in the other direction by the stops. During this process the metal grains have undergone adjustment under force to expand to open space. This is called *restricted expansion*. When the metal is cooled it contracts again. Consequently, it leaves gaps between the stops as shown in **Figure 6.2C**. This is called *free contraction*. Another explanation is that metal becomes plastic at high temperatures and can be moulded and then retains that shape when cooled.

FOR EXAMPLE:

A steel ball is heated and allowed to EXPAND AND CONTRACT FREELY:

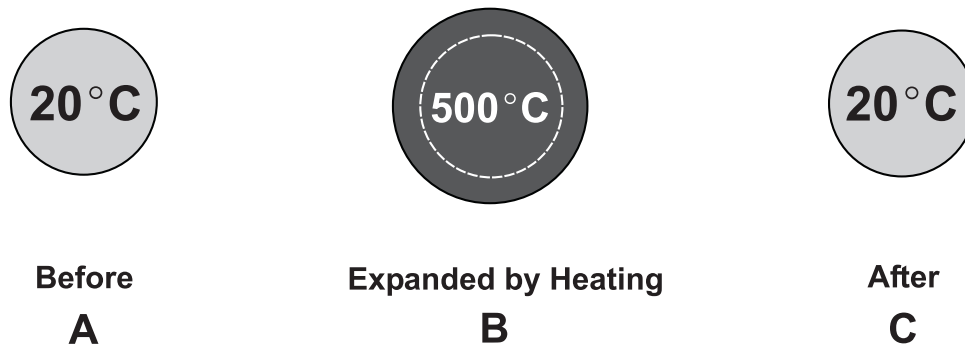
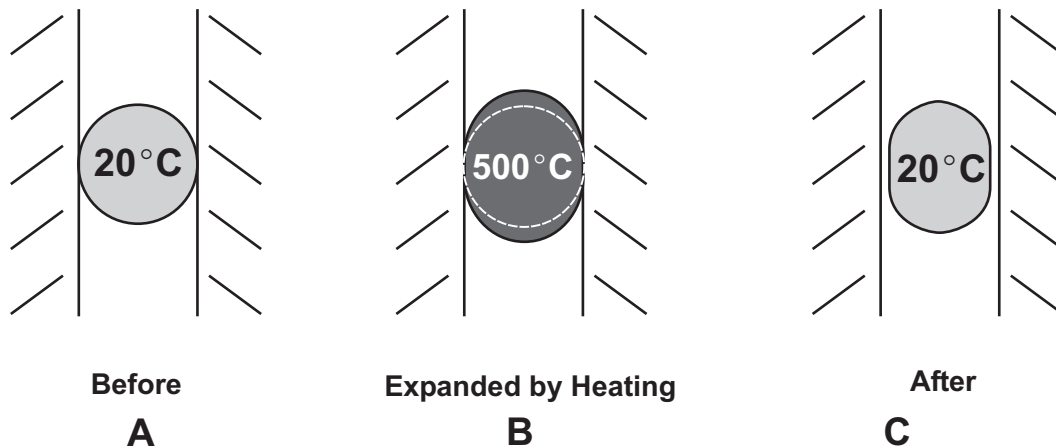


Figure 6.1: Free expansion and contraction.

A steel ball is heated between two barriers which CANNOT MOVE:



The grains (and atoms) in the material have rearranged themselves.

Figure 6.2: Restricted expansion and contraction.

We have illustrated free expansion and free contraction, and restricted expansion and free contraction. Let us now illustrate the third condition; restricted expansion and restricted contraction, as shown in **Figure 6.3**. The ends of a round metal bar are rigidly gripped between two solid stops. Heat is applied at any point on the bar causing it to expand, but it is not allowed to expand lengthwise. Therefore, during heating all the expansion takes place in the diameter of the heated portion because this part has to absorb all the volume of metal. The prevented expansion produces the same effect as if the bar were allowed to expand lengthwise and then compressed back to its original length. The upsetting (i.e., swelling of the heated part) is known as permanent deformation, that is, it will not disappear after the bar cools. Therefore, the bar is in compression during heating (**Figure 6.3A**) and in tension after cooling (**Figure 6.3B**). During heating, the metal is softened and forced to upsetting in diameter. During cooling, the bar is stretched by the rigid stops. If the bar is sufficiently elastic, tensile stress will be set up in the bar. If not, the bar will break as shown in **Figure 6.3B**.

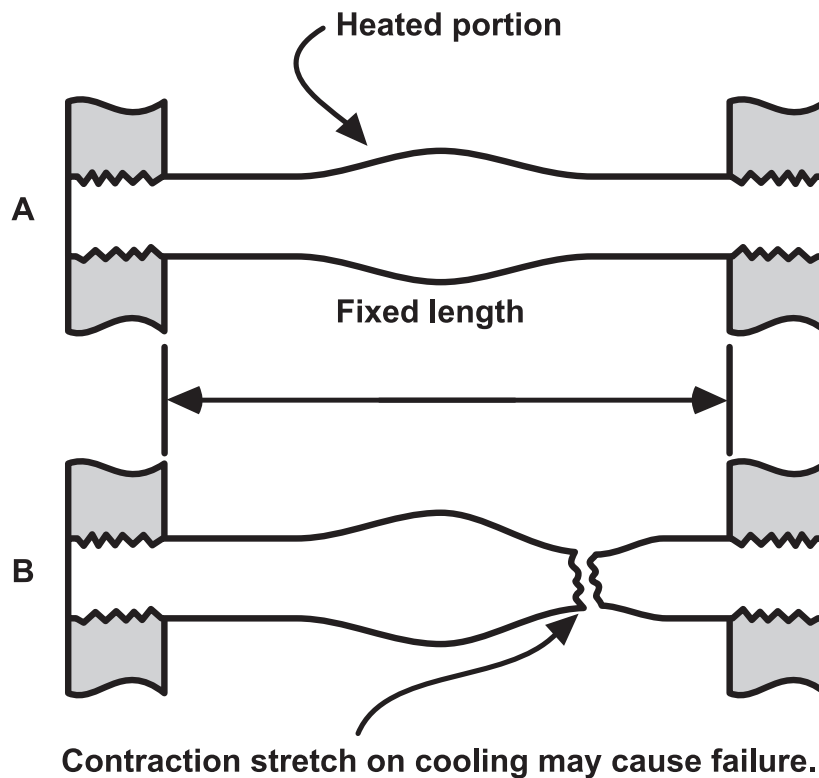


Figure 6.3: Behaviour of metal bar when heated and cooled while expansion and contraction are prevented.

6.3 Coefficient of Thermal Expansion and Thermal Stress

In the foregoing discussion we know that metals expand when the temperature is raised. In study of various metals, it is found that given the same temperature rise the amount of expansion differs for different metals. **Table 6.1** shows the coefficient of expansion of some common metals. The unit of the coefficient is in micrometre (10^{-6} metre) per metre per degree ($^{\circ}\text{K}$ or $^{\circ}\text{C}$). The coefficient is not a constant and can be seen in **Figure 6.4**.

Metal	Coefficient of Expansion $\mu\text{m/m } ^{\circ}\text{K}$
Mild Steel	11.8
Stainless Steel	
Austenitic	14.5
Martensitic	9.5
Nickel	13.3
Copper	16.5
Aluminum	23.1
Magnesium	27.1
Lead	29.3
Zinc	39.7

Table 6.1: Values for the coefficient of thermal expansion for a number of metals at room temperature. (Note: values are the same in units of micro inches per inch per $^{\circ}\text{C}$)

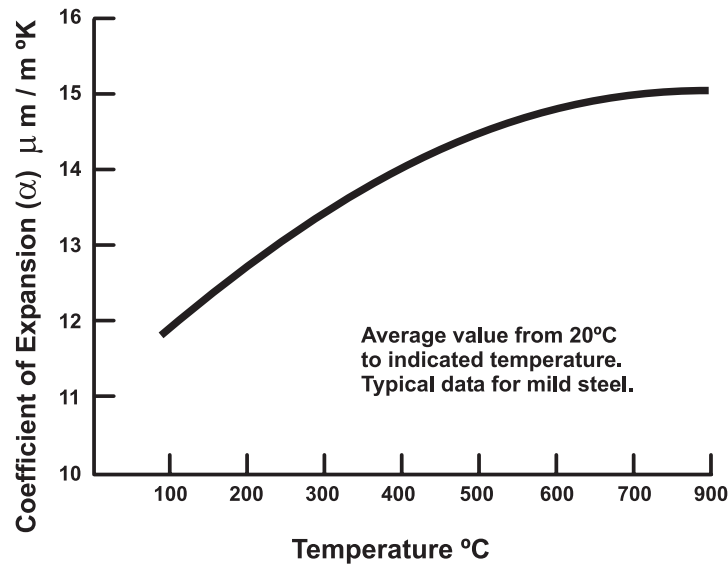


Figure 6.4: Typical values of the coefficient of thermal expansion for mild steel as a function of temperature.

Thermal stress is the stress induced by restricted thermal expansion or contraction. In **Figure 6.3A** for example, assume that the entire bar is heated uniformly and the expansion per unit length (i.e., thermal strain) can be calculated:

$$\text{Thermal strain } \varepsilon = \alpha \cdot \Delta T$$

$$\text{Total expansion } \Delta L = L \cdot \varepsilon = L \cdot \alpha \cdot \Delta T$$

When expansion is prevented, the metal bar is shortened by the same strain. In other words, the metal must be under compression. From the stress and strain relation:

$$\text{Stress} = \sigma \text{ (MPa)} = -E\alpha \Delta T$$

where E = Young's modulus of elasticity, for steel E = 200,000 MPa

ΔT = Temperature increase (°C)

- Negative sign indicates a compressive state.

At room temperature (20°C) if the yield stress of the steel bar is 350 MPa, the temperature rise (ΔT) required to reach yielding in compression can be calculated:

$$\Delta T = \frac{\sigma}{E\alpha} = \frac{350}{200\,000 \times 11.8 \times 10^{-6}} = 148^\circ\text{C (above room temperature)}$$

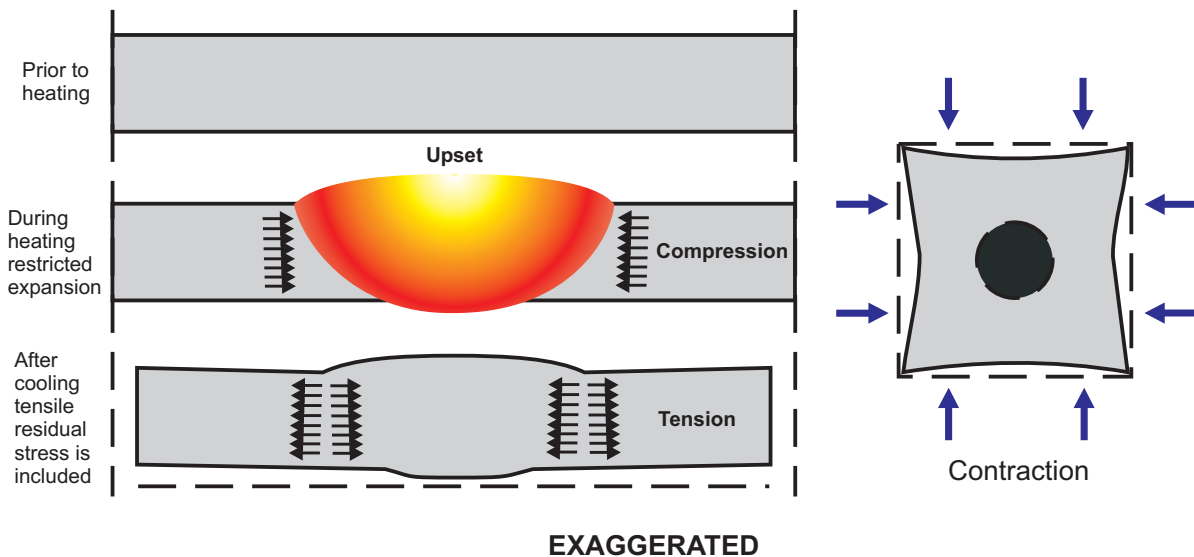
In this example, when temperature rises (ΔT) and is higher than 148°C, upset will occur. When the steel bar is cooled to room temperature, residual tensile stress will be induced if the bar is not allowed to contract.

6.4 Residual Stresses

The term residual stress means that some internal stress is created and stays inside the metal after the manufacturing processes are completed. These processes can include thermal cutting or heating, welding, mechanical forming or metallurgical changes such as heat treating. In this book, our discussion deals mainly with the first two processes.

6.4.1 Residual Stresses Induced by Thermal Process

We have discussed thermal effect on metals in the foregoing paragraphs. We also explained how stress may be set up when expansion and/or contraction is restricted. Previously we discussed heating a metal bar gripped at both ends (see **Figure 6.3**). To bring this analogy one step further, consider that a large square steel plate is spot heated (a small round area) at the centre of the plate as shown in **Figure 6.5**. At the heated area the metal becomes upset due to restricted expansion by the surrounding, relative cold, metal mass. After cooling, the upset remains and the contraction induces tension around the heated area. This tensile stress stays inside the plate if nothing else is done to the plate. This is why it is called “residual stress”, to distinguish it from other stresses created by external loading.



HEAT SPOT: The temperature is relatively the same throughout the thickness of the material but is localized.

Figure 6.5: Residual stress.

It may help the student to understand the practical meaning and effect of residual stresses as they are regarded as internal compression and tension in the metal. For example, tensile forces are developed across a butt weld when the weld metal is unable to contract freely. The residual stresses are static and balanced, i.e., the overall tensile stressed areas are balanced by the compressive stressed areas and no movement results once the balance is attained. But, in the process of balancing, while the metal cools movement may happen. Then, distortion occurs. This is another important subject which will be discussed.

6.4.2 Residual Stress Induced by Arc Welding

Next we shall investigate what happens when welding heat is applied to join two plates together as shown in **Figure 6.6**. Two large, thick, rectangular plates of same size are welded together along their long sides. During welding the long edges are under intensive heat (actually melted) and go through thermal expansion. But the areas a short distance from the edges are relatively cool, and do not expand at the same rate, or hardly expand because of the very steep thermal gradient. In other words, the expansion is restricted by the plates themselves. Following the same reasoning, when the weld is cooling down it goes through restricted contraction and sets up high tensile stresses along the weld line. This high tensile stress stays with the plates if nothing else is done to them. This is how residual stress is induced by welding. The residual stress in the longitudinal direction may be as high as the yield stress of the plate (see **Figure 6.6B**). As explained previously, the thermal expansion and contraction are in all directions (volumetric). Therefore, there is residual stress transverse to the weld line, as shown in **Figure 6.6A**.

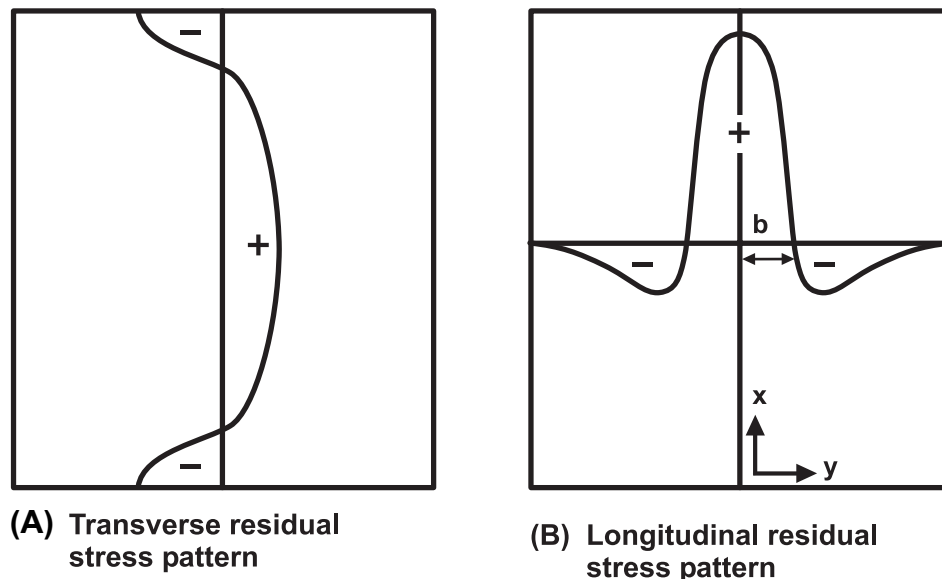


Figure 6.6: Typical residual stress pattern in a weld in a flat plate. Transverse stresses are not high except at the ends where they are compressive. The most important residual stresses are the high longitudinal stresses along the length of the weld and heat affected zone.

Further explanation of **Figure 6.6** is illustrated with the aid of **Figures 6.7 and 6.8**. **Figure 6.7** shows that the plate edges along the weld joint undergo expansion during welding and the plates tend to bow outwards. As the weld cools, shown in **Figure 6.8A**, the plates tend to bow in opposite direction because the plate edges contract with the weld. Since the weld holds the plates together, the middle part of the plates will be under tension perpendicular to the weld line. In the end regions compression is induced to balance the tension region in the middle part. This is the transverse residual stress pattern shown in **Figure 6.6A**.

Figure 6.8B illustrates the formation of longitudinal residual stresses that occur because the length of a welds undergoes changes. Imagine how the weld metal stretches longer to fit the plate edges as they expand outwards, and then contracts as the weld cools. This will result in tensile stress in the weld metal and part of the adjacent plate, for width **b** on either side of the weld (**Figure 6.6B**). This tension region must be balanced by compression regions outside width **b** on either side of the weld. These are the longitudinal residual stress patterns shown in **Figure 6.6B**.

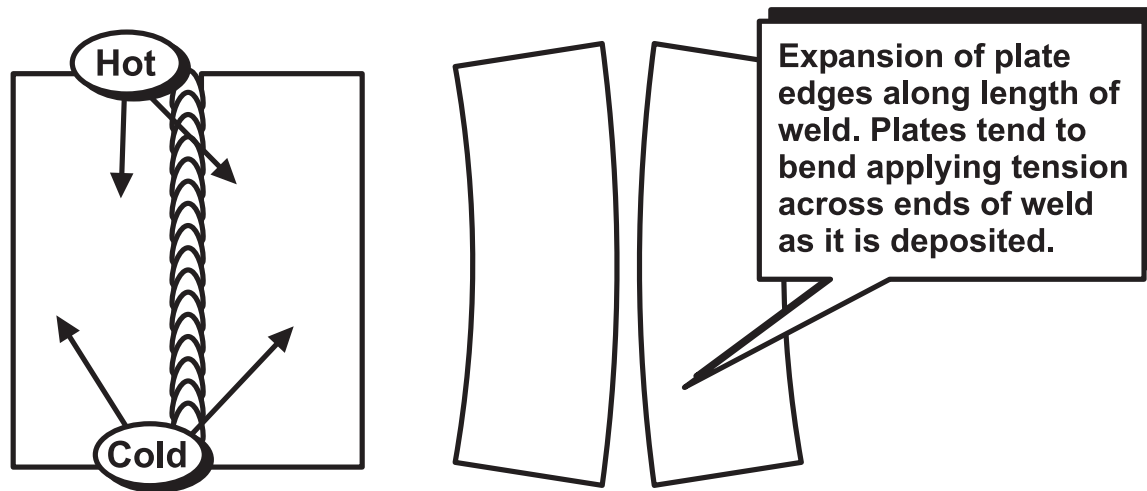


Figure 6.7: When the weld is deposited the edge of the plates get hot, expand, and tend to bow the plates. Yielding occurs along the edges of the plates.

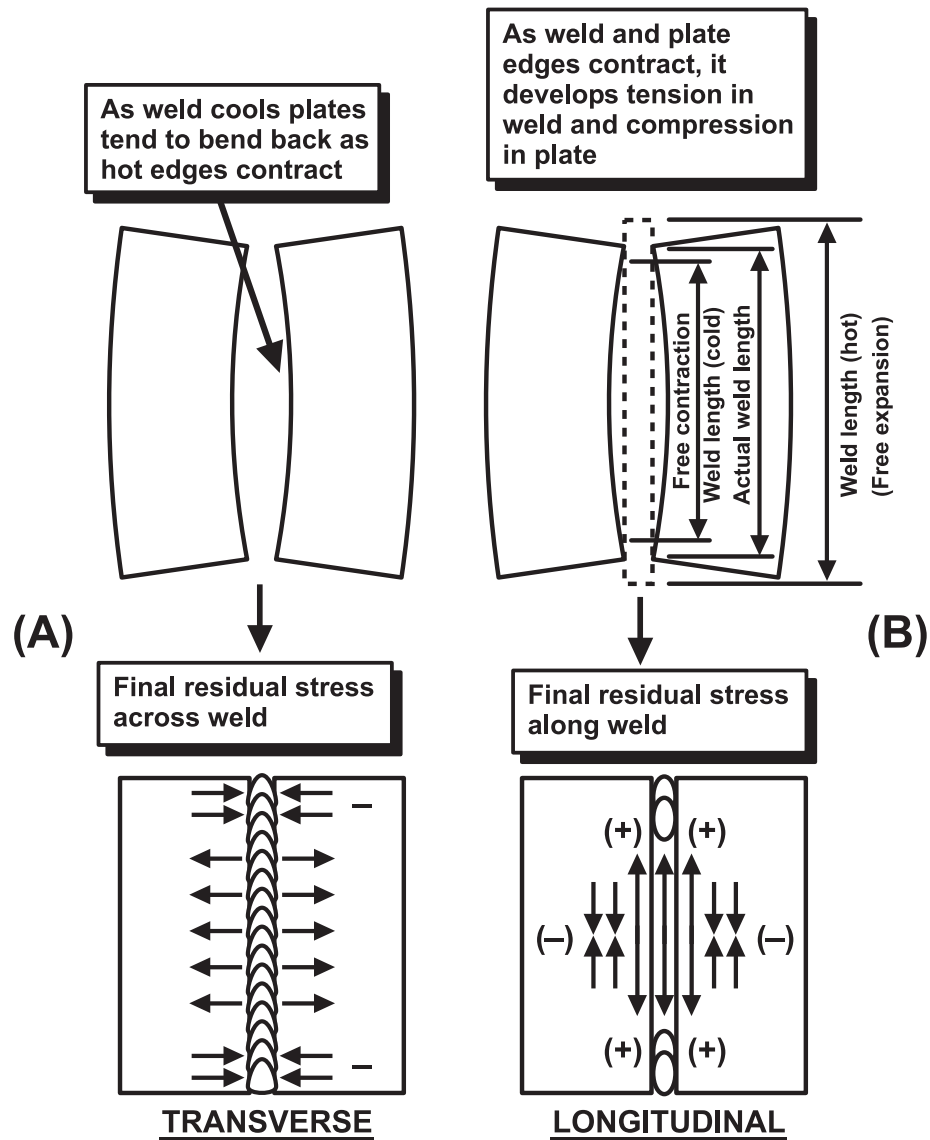


Figure 6.8: On cooling, the plates bow in the other direction but are held by the solidifying weld metal. Residual stresses, equivalent to a bending moment applied to the plate ends, result from the attempt to restrain the bow.

6.4.3 Residual Stress in Universal Mill Plates with As-Rolled Edges

Figure 6.9 shows the pattern of residual stresses in a universal mill plate with as-rolled edges. It shows compressive residual stress at the edges and tensile residual stress in the middle of the plate. A comparison of rolled edges with flame-cut edges (see **Figure 6.10**) shows a distinctive contrast. The flame-cut edges have tensile residual stress at the edges whereas at the as-rolled edges the residual stresses are compressive. From the discussion of the effect of heating and cooling we know that the rolled edges cool faster than the middle part of the plate. Therefore, when the whole plate is cooled to room temperature, the edges are under compression.

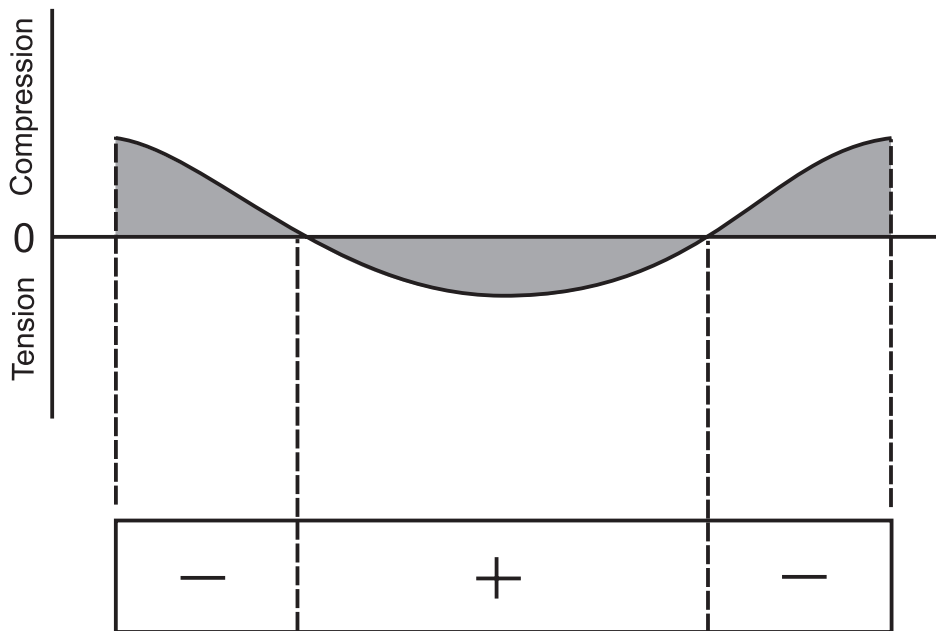


Figure 6.9: *Residual stress in plate with rolled edges.*

6.4.4 Residual Stress Induced by Flame Cutting

In oxyfuel gas cutting of steel, the temperature along the cutting surfaces can reach over 1000°C (1800°F). The rapid heating and subsequent cooling will induce residual stress. When a plate is cut with two torches simultaneously, the residual stress in the cutting edges is tensile. This is, of course, because of the restraining effect of the relatively cool areas adjacent to the cutting edges. As a result, the adjacent areas are in compression. The distribution of the longitudinal stresses across the width of the plate is shown in **Figure 6.10**.

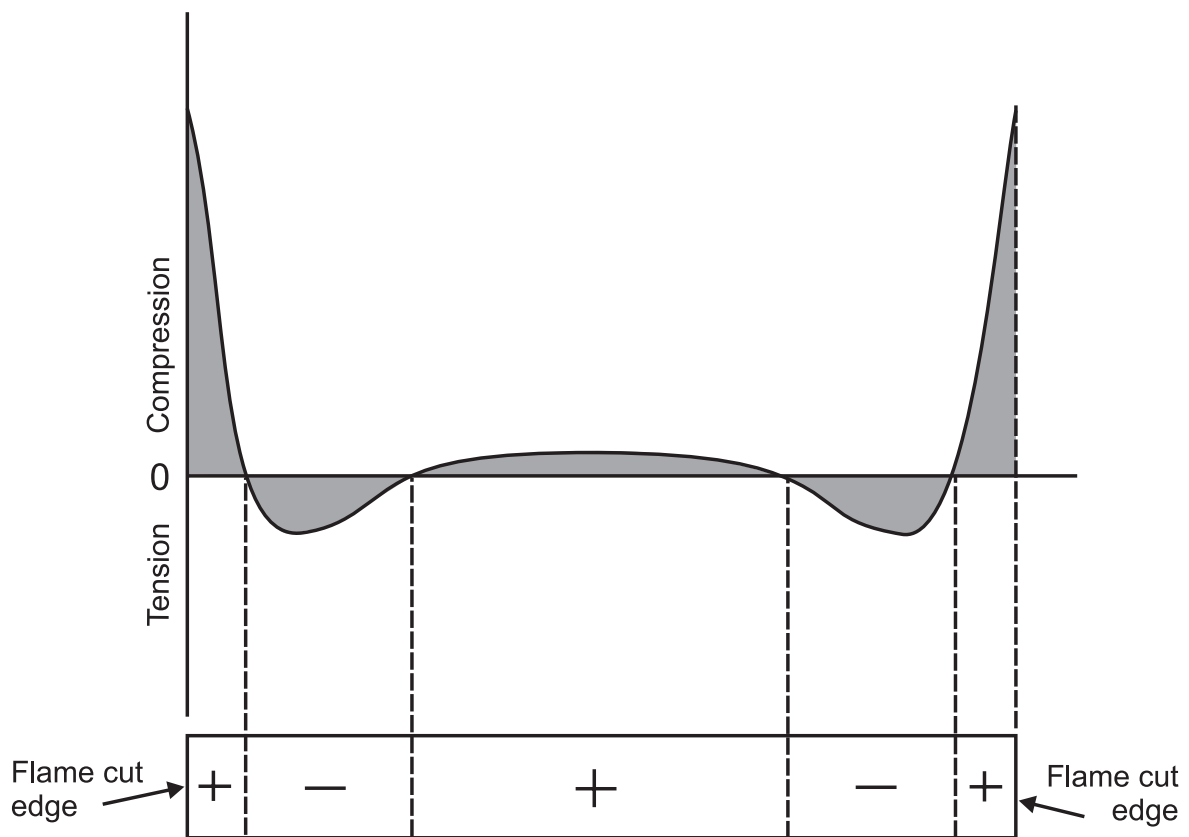


Figure 6.10: Residual stress in plate with flame cut edges.

6.4.5 Residual Stress in Welded Wide Flange Shapes

From the previous discussions on residual stresses in as-rolled universal plates, flame-cut plates and the influence of welding, we should be able to visualize the residual stress patterns in two welded wide flange shapes. **Figure 6.11** and **Figure 6.12** show the built-up shapes with as-rolled and flame-cut stress patterns.

The residual stress patterns of a welded wide flange with cover plates is shown in **Figure 6.13**. A large tensile residual stress is induced at the flange tips because of the high welding heat.

Residual stress in the welded box section is shown in **Figure 6.14**. Applying the same principles, the corner areas cool slower and are in tension.

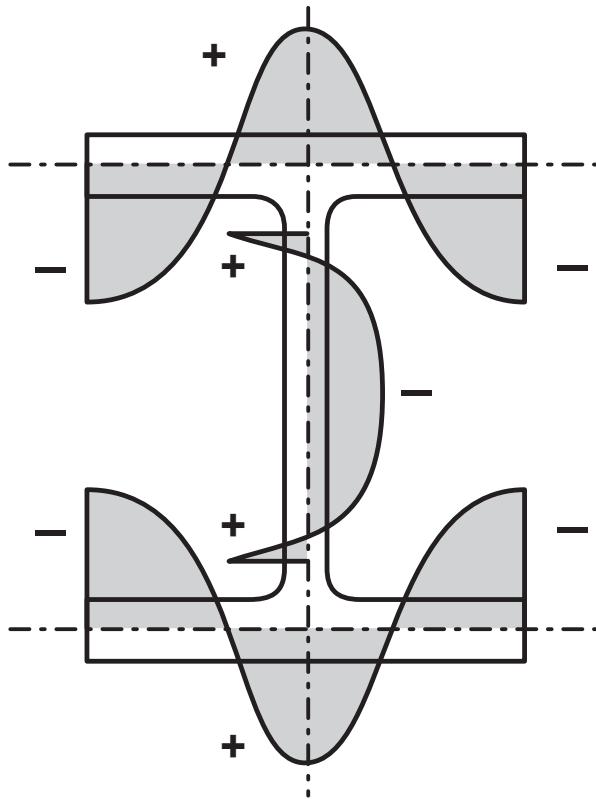


Figure 6.11: Longitudinal residual stresses in welded built-up column with as-rolled flange plates (Flange edges in compression).

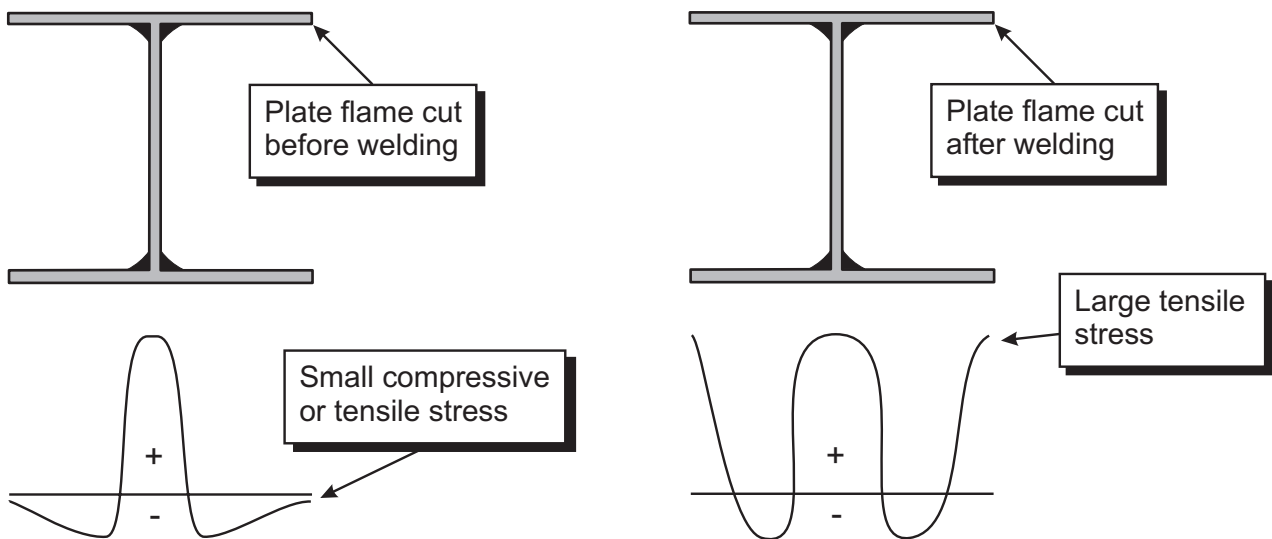


Figure 6.12: Welded wide flanges with flame cut edges.

Figure 6.13: Residual stress patterns in a welded wide flange with cover plate.

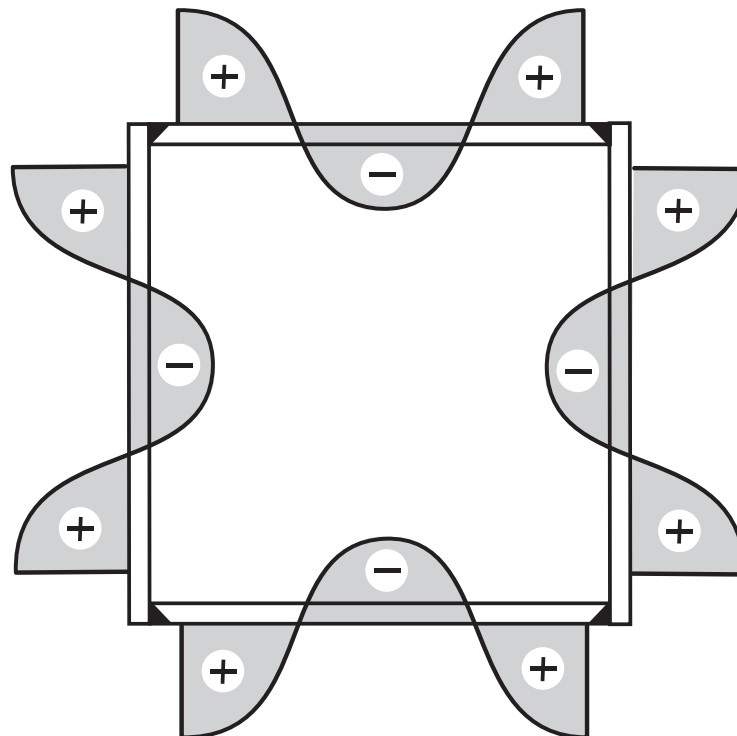
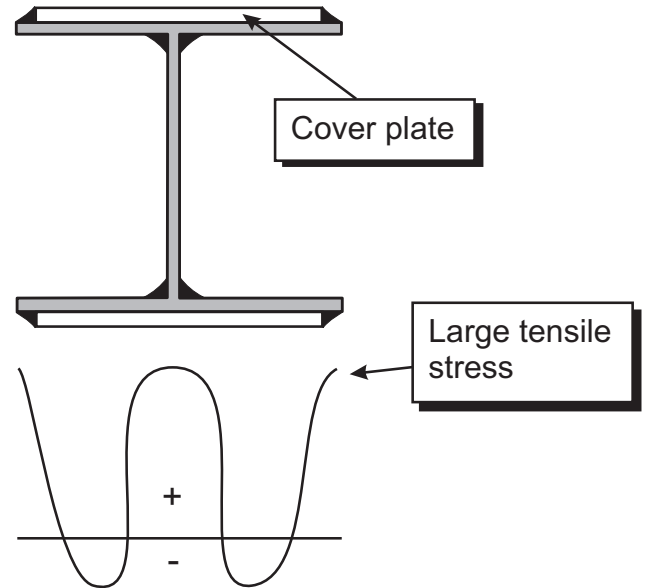


Figure 6.14: Longitudinal residual stresses in welded box column.

6.4.6 Residual Stress in Universal Mill Rolled Shapes

After the discussion of residual stresses in plates and welded wide flanges, you would expect these forces to be present in hot rolled shapes.

From the discussion earlier, we recognize that residual stress is induced due to uneven heating and cooling. Residual stresses are induced in hot-rolled I-shapes for the same reason. As shown in **Figure 6.15**, the parts that cool first (or faster) are the toes of flanges and the centre part of the web wherein compressive residual stress is formed. The parts that cool last (or slower) are the flange and web junctions, which are still contracting. The contraction is restrained by the parts that cooled first, and tensile residual stress is formed. Therefore, the pattern of residual stress is as shown in **Figure 6.15**.

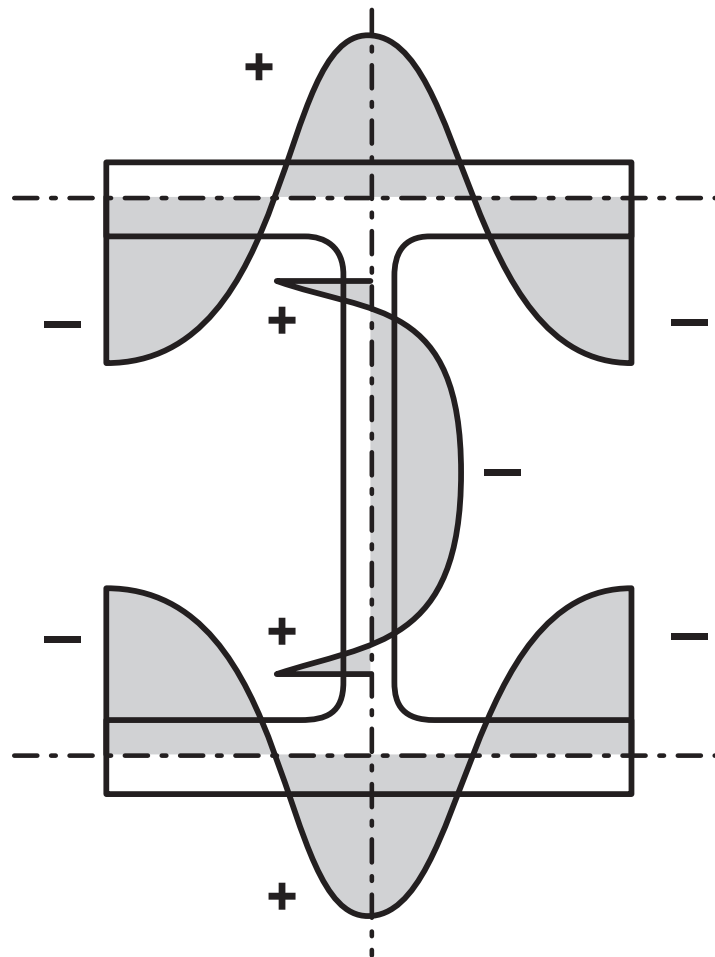


Figure 6.15: Residual stress in hot-rolled I-shape.

6.4.7 Estimation of Shrinkages

Formulas are available for calculating the amount of contraction or shrinkage of welds. The exact amount of shrinkage is not always calculable because all the variables cannot be exactly controlled, but these formulas do provide some indicators of which variable or variables exercise the most influence on shrinkage. In other words, use these formulas as a guide in practical shop fabrication and keep distortions within the code allowance.

1) Transverse Shrinkage of Butt Welds

The following formula is applicable to carbon and alloy steels

$$S = k \frac{A_w}{t} + 0.05 d$$

Where:

S	=	transverse shrinkage, mm or inch
A_w	=	cross-sectional area of weld metal, mm ² or square inch
t	=	thickness of plate, mm or inch
d	=	root opening between plates edges, mm or inch
k	=	0.18 for $6 \text{ mm} \leq t \leq 25 \text{ mm}$ ($1/4" \leq t \leq 1"$)
k	=	0.20 for $t > 25 \text{ mm}$ ($t > 1"$)

The graph in **Figure 6.16** shows the relationship between the plate thickness and transverse shrinkage of 60° groove angle, single and double V-groove joints. It can be observed that single V-groove contracts more than double V-groove of same thickness.

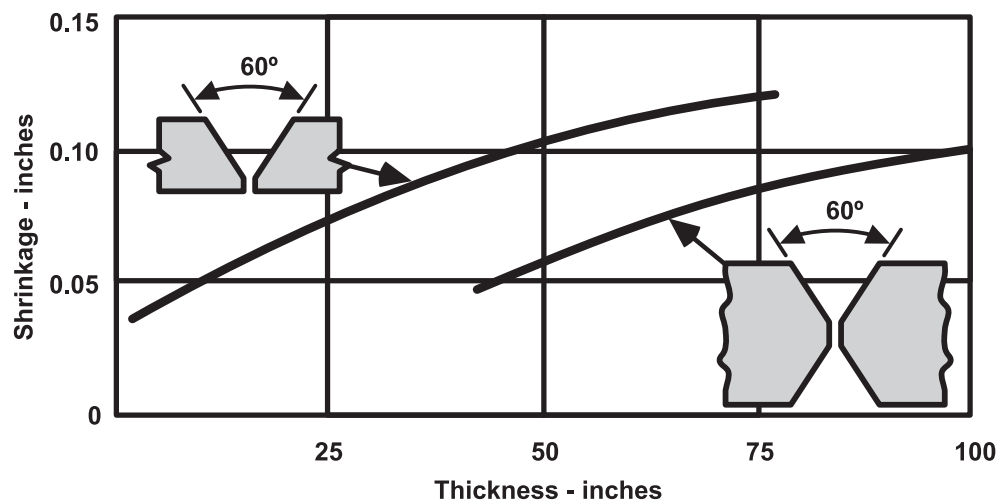


Figure 6.16: Transverse shrinkage of single and double vee welds.

Figure 6.17 shows that in joints with the same thickness of plates, the greater the weld metal area the greater the transverse shrinkage. This graph shows that to reduce transverse shrinkage a joint should be designed with double grooves of minimum groove angles as allowed by the welding standard for the applicable welding process.

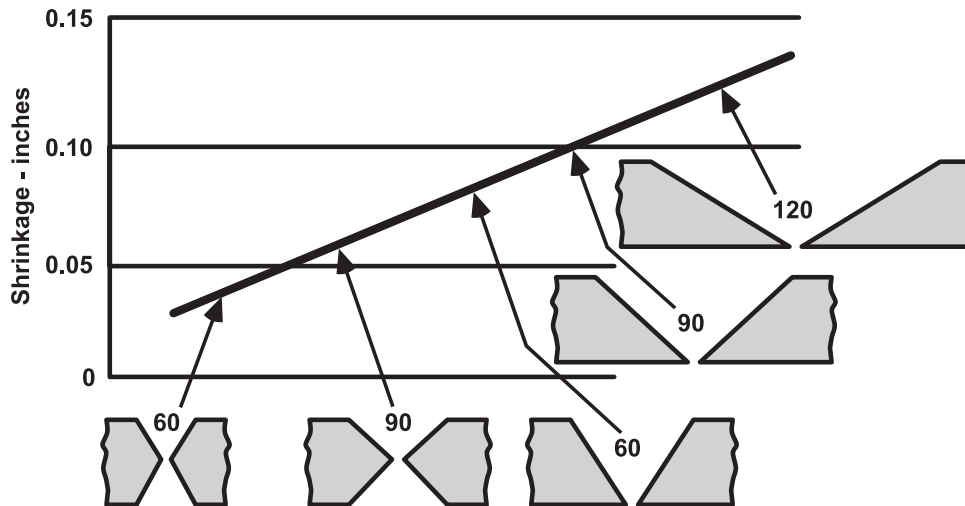


Figure 6.17: Proportion of transverse weld shrinkage produced by various types of butt joint preparations.

2) Longitudinal Shrinkage of Butt Joints

$$\Delta L = \frac{A_w}{A_r} \times 0.025 L$$

where: (see **Figure 6.18**)

- ΔL = Total longitudinal shrinkage, mm or inch
- L = Length of weld joint, mm or inch
- A_w = Cross-sectional area of weld metal, mm² or square inch
- A_r = Cross-sectional area of restraining plates, mm² or square inch

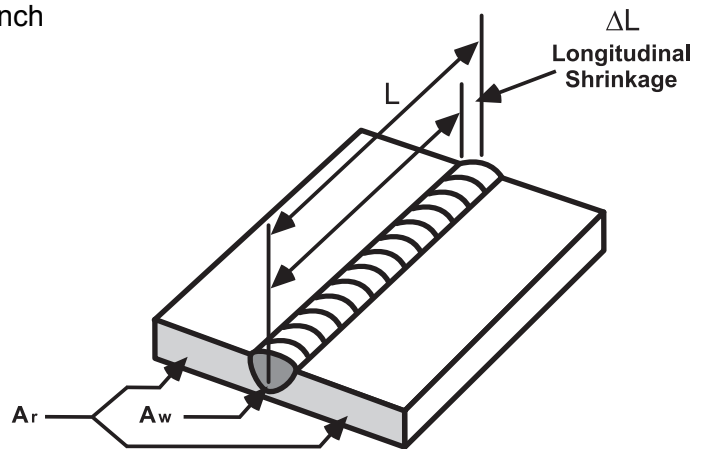
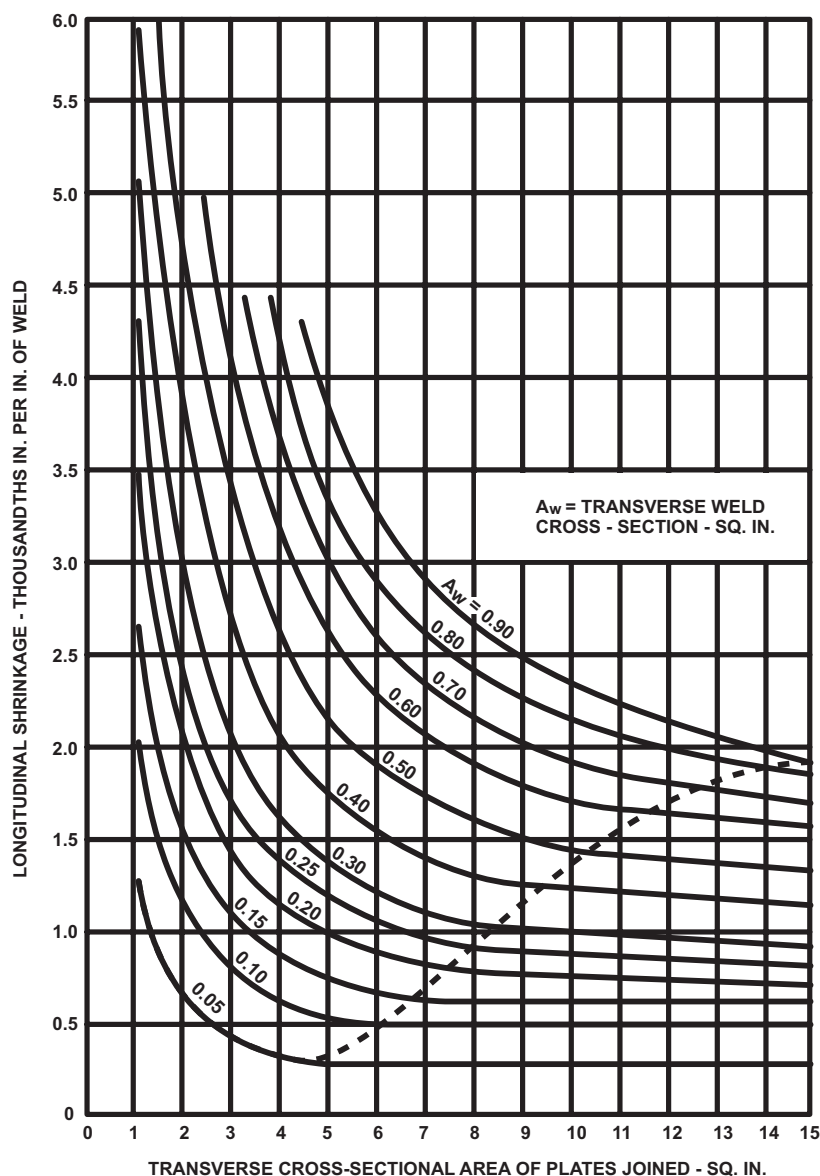


Figure 6.18: Longitudinal shrinkage of butt joints.

Due to restraint, this formula loses accuracy if the cross-sectional area of the plate is greater than 20 times that of the weld. In such cases the chart shown in **Figure 6.19** may be used. It should be observed that in the curves in **Figure 6.19** the shrinkage, which attains high values for small resisting sections, falls extremely rapidly as the section increases. The shrinkage tends to become constant when the resisting section exceeds a certain value. The form these curves take need not surprise us. In fact, the resistance to shrinkage offered by the resisting section increases very rapidly because the effect of shrinkage is a maximum in a relatively narrow band symmetrical with respect to the axis of the weld. Outside this band, only rather low temperatures are reached during welding and the metal offers a rapidly increasing resistance to the shrinkage arising from the hot parts. The resisting section, once it has exceeded slightly from the section corresponding to the hot parts of the assembly, exerts essentially its maximum resistance. Further increase in resisting section has scarcely any effect on shrinkage.



The following observation makes this phenomenon more significant. When the cross-sectional area of the weld is increased, the highly heated transverse portion, which is acted upon by shrinkage, is larger, and the resisting section necessary to completely prevent the effects of shrinkage also is larger. This is what the curves show. The dotted curve in **Figure 6.19** shows the resisting section at which shrinkage becomes practically constant.

Figure 6.19: Each curve represents the variation of unit longitudinal shrinkage as a function of the transverse cross-sectional area of the welded assembly for a given cross section. (The shrinkage tends to become stabilized when the sectional area of the assembly exceeds a certain value, which is indicated by the dotted line).

3) Transverse Shrinkage of Fillet Welds of Tee Joint

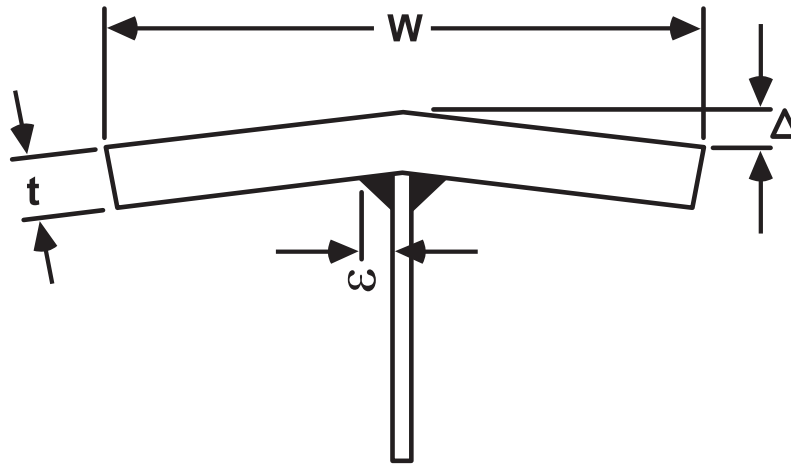


Figure 6.20: Angular distortion in a flange due to the two fillet welds.

A flange may suffer angular distortion as a result of the web-to-flange welds. The extent varies with the flange thickness, since a thicker flange bends less. A suggested formula for this distortion is:

$$\Delta = 0.193 W \omega^{1.3} / t^2$$

Where Δ is the displacement as defined in **Figure 6.20**, mm
 W is the width of the flange, mm
 ω is the fillet leg size, mm
 t is the plate thickness, mm

For the majority of practical cases, flange distortion predicted by this formula is within the tolerance specified in CSA W59 or AWS D1.1.

6.5 Distortion

What causes distortion? Stress. The stresses we are concerned with here are residual stresses caused by the thermal forces of the welding process. The reason a product distorts is due to the residual stresses induced during fabrication, which are somewhat reduced in the distorted state. In other words, a product distorts to reach an equilibrium state. For example, a distorted product, say a bowed welded tee-shape, is put in jig, supported at both ends and some force is applied in the middle to push back the bow and keep it straight (**Figure 6.21**). The tee is not in equilibrium by itself because as soon as the force is removed the bow comes back again. That is why we say the distorted state is an equilibrium state, the least energy state.

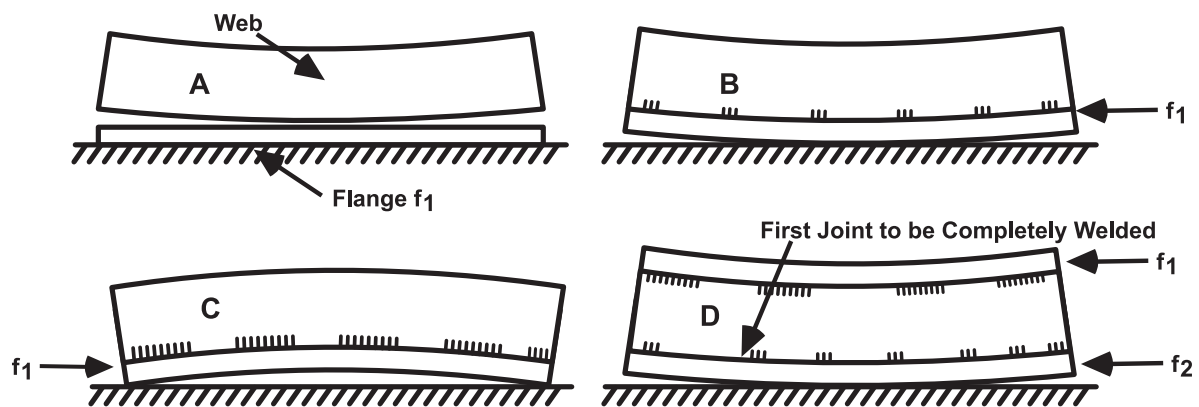


Figure 6.21: Bending distortion of welded tee-section.

The phenomena of distortion can only be fully understood with thorough knowledge of the behaviour of residual stresses. To complete the picture of the stress situation it is also necessary to point out that in the steel mill heating, rolling and cooling, some residual stresses are already present in plates and shapes before any welding or other work is attempted. Normally these stresses are also in equilibrium (otherwise, distortion occurs). For example, each flange of an I-beam processes residual rolling stresses (also from heating and cooling) but they are balanced by the equal stresses in the other flange.

However, when the balance of residual stresses is disturbed, distortion may occur. As an additional example, it may be mentioned that the application of heat to one flange of an I-beam may cause distortion solely because the residual stresses in that flange are reduced; i.e., the balance of stresses is upset.

This is one reason why distortion sometimes occurs in a welded structure despite the use of all the normal precautions.

6.5.1 Distortion Caused by Oxyfuel Gas Cutting

Oxyfuel gas cutting, commonly called flame cutting, is one of the major causes of distortion as the result of improper application of a thermal process. From the discussion of residual stresses, we know that flame-cutting induces residual stress and in turn causes distortion.

Figure 6.22 shows the mode of distortion that can happen in flame-cutting. By now you should be able to explain why the plate bows along its cutting edge. To avoid this type of bowing (bending) distortion, two torches must be used to cut simultaneously, as shown in **Figure 6.23**. When cutting a long strip of steel plate of any thickness, for example 3 mm to 300 mm, two torches should be used to apply heat along both edges to keep the plate straight.

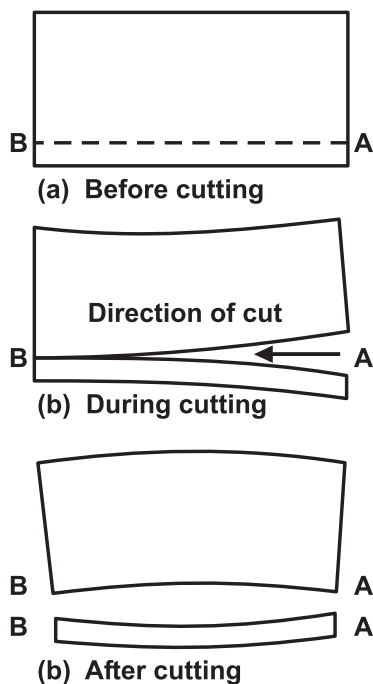


Figure 6.22: Effect of cutting a flat plate (with one torch).

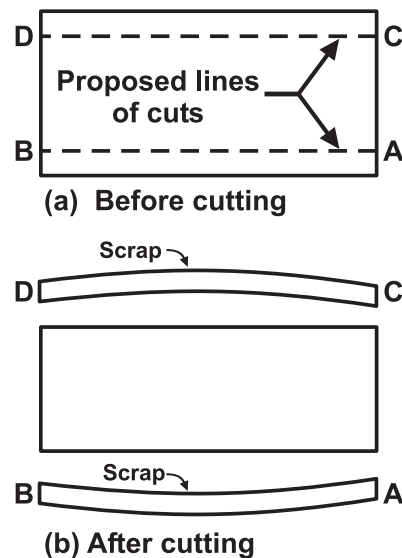


Figure 6.23: Effect of cutting a flat plate (with two torches).

In **Figure 6.22**, when one torch is used and heat is applied to one edge only, bowing is inevitable after cooling. Bowing is caused by the tensile residual stress which is induced by the heat of cutting. When two torches are used, as shown in **Figure 6.23**, the plate stays straight after cutting because the residual stresses along the edges are balanced to each other and the resultant residual stress is coincident along the centerline, or neutral axis of the plate.

In flame-cutting shapes from plate, the work piece must be kept with the remaining large plate until the last severance cut. This will prevent the work piece from moving away from the large plate due to the thermal expansion. A good example is shown in **Figure 6.24** in cutting a round plate out of a large plate. The cutting operation is controlled either numerically or by computer and the cutting torch traverses a perfect circle regardless of the expansion movement. Due to expansion, when the workpiece moves it will end up slightly oval, and the torch will not return to the starting point unless the starting point of the cut and sequence of cutting are preplanned. In **Figure 6.24**, the cut should be started at point A, never point B, when proceeding in counterclockwise direction. Similarly, you can start at point B and proceed in a clockwise direction.

Another practical example is shown in **Figure 6.25**. In cutting a ring flange plate from a large plate the first cut, second cut (removal of the centre piece), and the final (third) cut are shown. This is different from **Figure 6.24**, as the cut is initiated by piercing inside the plate, not the edge. Even so, the cutting directions must be followed. Remember that the width of the cutting kerf also provides room for expansion. It should be noted that the centre piece (scrap) should never be removed first or the inside diameter will change (pull inward) and the width of the ring will vary.

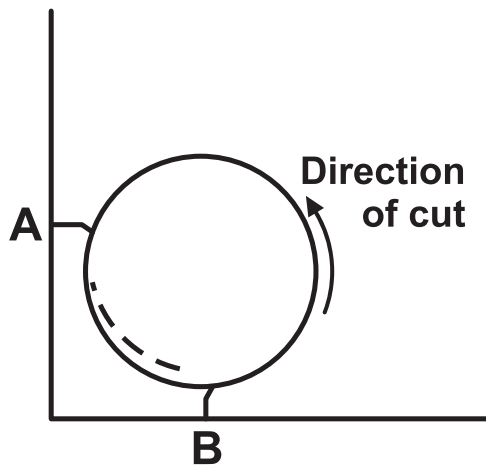


Figure 6.24: Method of cutting out a circle near the corner of plate.

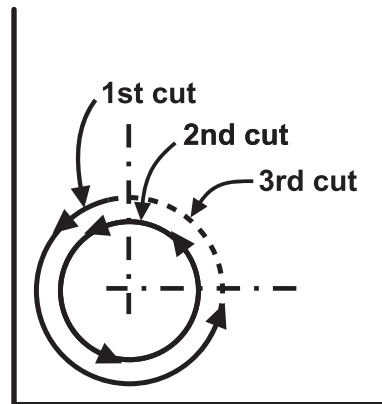


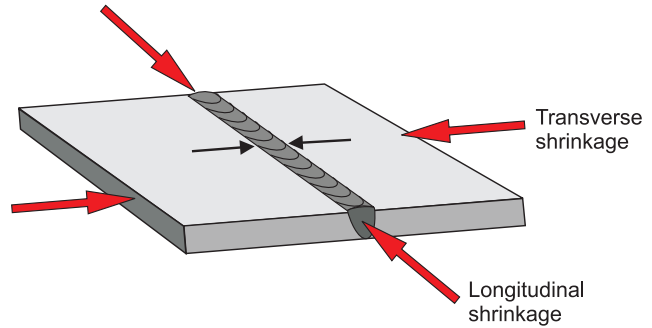
Figure 6.25: Method of cutting out ring flanges near edge of plate.

6.5.2 Distortions Caused by Welding

As shown in **Figure 6.6** and in the discussion of residual stress we have learned that welding heat causes residual stress and distortion. The frequently seen types of welding distortions are shown in **Figure 6.26**. It should be recognized that when distortion occurs it is not always in the simple form of distortion as shown. Quite often distortion occurs in compounded forms, such as bending and twisting or angular and bending and any combinations of the simple forms.

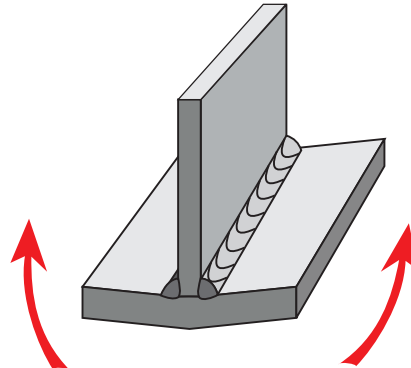
Shrinkage

- ♦ longitudinal shrinkage and transverse shrinkage



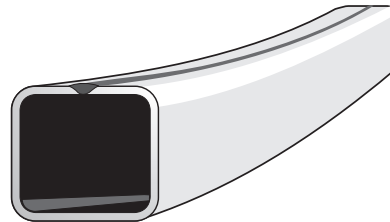
Angular Distortion

- ♦ caused by transverse shrinkage



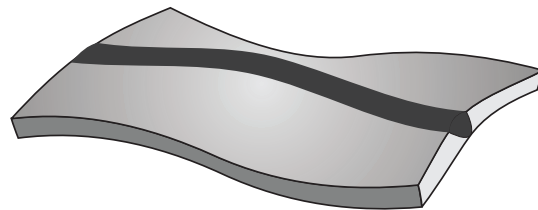
Bending Distortion

- ♦ caused by longitudinal shrinkage



Buckling

- ♦ Caused by longitudinal shrinkage (also to a minor degree, by transverse shrinkage); most often when welding large, thin plates or sheets



Twisting

- ♦ caused by high longitudinal shrinkage; more likely in thin metal

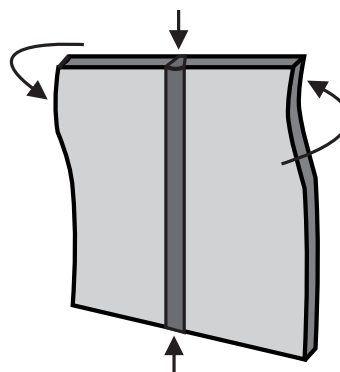


Figure 6.26: Types of distortion caused by welding.

6.5.3 Transverse Contraction (Shrinkage) - Angular Distortion

Consider a V groove joint as shown in **Figure 6.27A**, which is unrestricted, i.e., free to move as required by weld contraction. After welding, this joint will tend to assume the shape shown in **B**. The angular distortion results from the non-uniform contraction of weld metal due to the greater width of the top of the weld compared with the root of the Vee. If the weld metal could be deposited to form a more uniform section between the edges, as shown at C and D, there would (in theory) be no angular deformation, only uniform contraction across the joint.

Likewise it will be appreciated that in fillet welds the distortion resulting from contraction will be as shown in **Figure 6.27 F** and **G** for a joint initially set up as shown in **Figure 6.27E**.

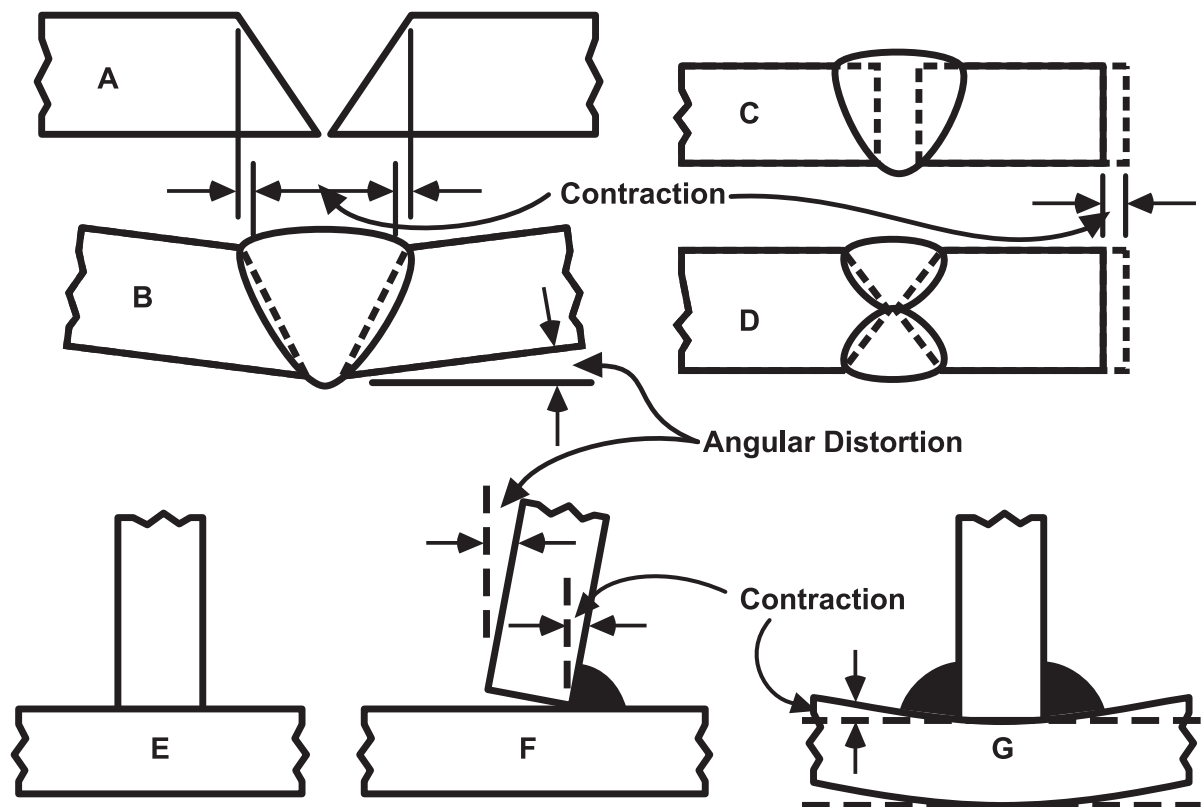


Figure 6.27: Distortion of butt and fillet joints due to weld metal contraction.

6.5.4 Longitudinal Expansion and Contraction (Shrinkage)

When we consider movements along this joint, the effect of expansion and contraction of the joint edges becomes important because these movements are resisted by the comparatively cool metal surrounding the weld point. Under this restraint considerable stress is set up in the metal.

This is illustrated in **Figure 6.28**. With reference to **Figure 6.28A**, if we assume that a portion of one edge has been rapidly heated, the result is the production of an effect similar to that described in conjunction with **Figure 6.28B**. In this case the expansion of the heated zone is prevented by the comparatively cool metal; the result is that the increased volume of metal in the heated zone is absorbed by a slight thickening or upsetting of the plate edge. Then, when cooling, contraction takes place, the edge shortens, producing the shape shown in **Figure 6.28B**. This is exactly what is happening to any joint edge or surface during welding, and the magnitude of the cooling effect depends upon the size of the heated zone in relation to the size of the plate.

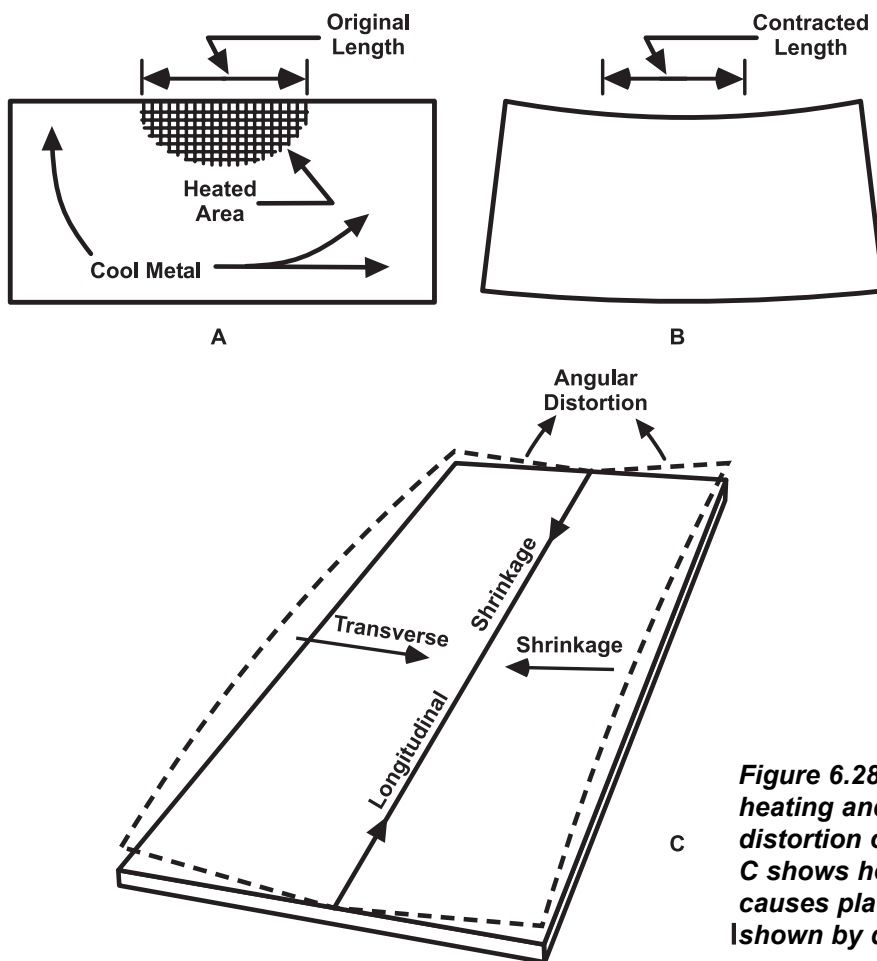


Figure 6.28: A and B show how heating and cooling cause distortion of plate edge. C shows how contraction causes plates to take the shape shown by dotted lines.

If the edges are restrained this effort to contract will, instead of causing distortion, set up stresses between the heated area (the weld) and the plate. This will happen if the parts being joined are massive and rigid, or if rigidly clamped or rigidly tacked in place, restricting movement.

The effect of both the transverse and longitudinal contraction (shrinkage) of a butt joint where the plate is not rigid is shown in **Figure 6.28C**. The important point, which should be very clearly understood, is that local heating always produces contraction during cooling of the base metal, which, with the additional contraction of the weld metal, causes concave bending, i.e., shortening of the weld side of the joint both transversely and longitudinally.

Another example shows the plate edge movement during welding in **Figure 6.29**. **Figure 6.29A** shows the far end of joint moving closer during welding with the shielded metal arc welding process (SMAW). This is the result of the low heat input and low travel speed, which allows the plate edges to contract. To prevent this from happening, a wedge block is inserted at the far end to keep a constant root opening. **Figure 6.29B** shows the far end of the joint moving apart during welding with the submerged arc welding process (SAW). Contrary to SMAW, submerged arc welding employs a high heat input and a fast travel speed, which keeps the plate edges in an expanding state ahead of the welding arc during the welding process. In this case, a heavy tack weld, or a tack-welded metal bar, at the far end must be used to maintain the constant root opening. Submerged arc welding can produce 3 times the heat input at 5 times the travel speed of SMAW.

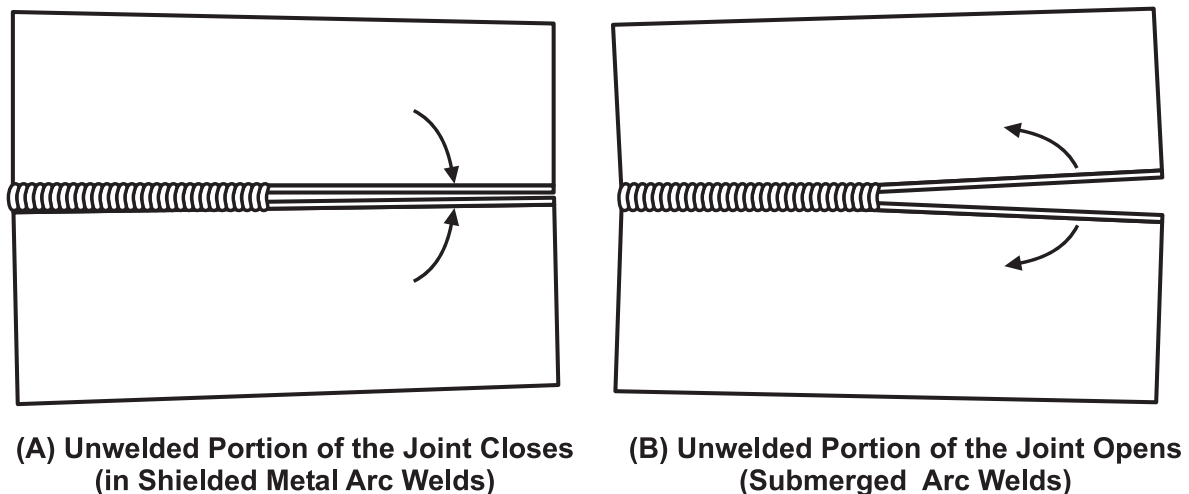


Figure 6.29: Contraction of two butt-welded plates - effect of travel speed.

6.5.5 Other Causes of Welding Distortion

We have discussed distortion caused by residual stress, but residual stress alone does not cause distortion, such as bending or angular distortions. When the distribution of residual stresses is symmetrical about the neutral axes of the shape, bending or angular distortion will not occur, although longitudinal shortening will always exist.

The neutral axis of some common section profiles are shown in **Figure 6.30**. The neutral axis is located through the centre of gravity of the cross-section of a shape. When residual stress is in symmetry about the neutral axis of a member it produces axial stress (tension or compression) only. When the residual stress is not in symmetry about the neutral axis, a moment is created (**Figures 6.31 and 6.32**), equal to force P times e (eccentricity, distance between the resultant of residual stress and the neutral axis). When the moment is large enough a visible or rejectable distortion will result.

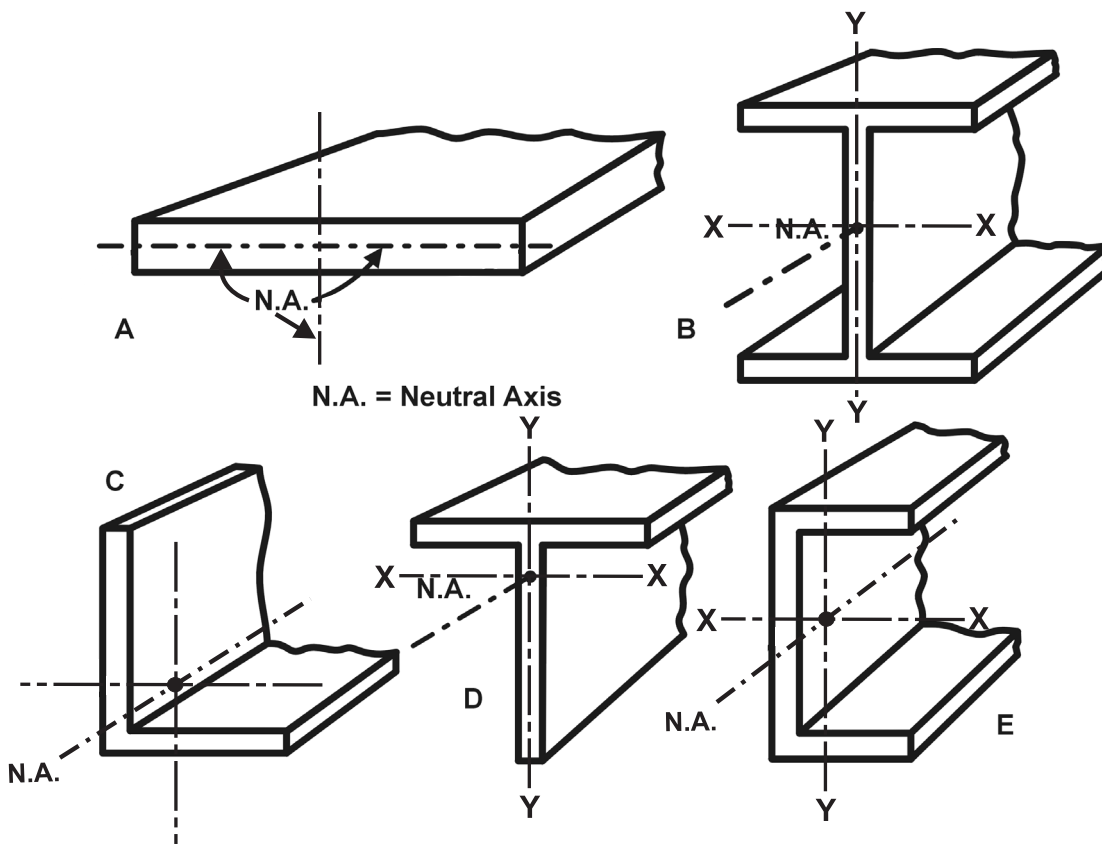


Figure 6.30: Neutral axis of various sections.

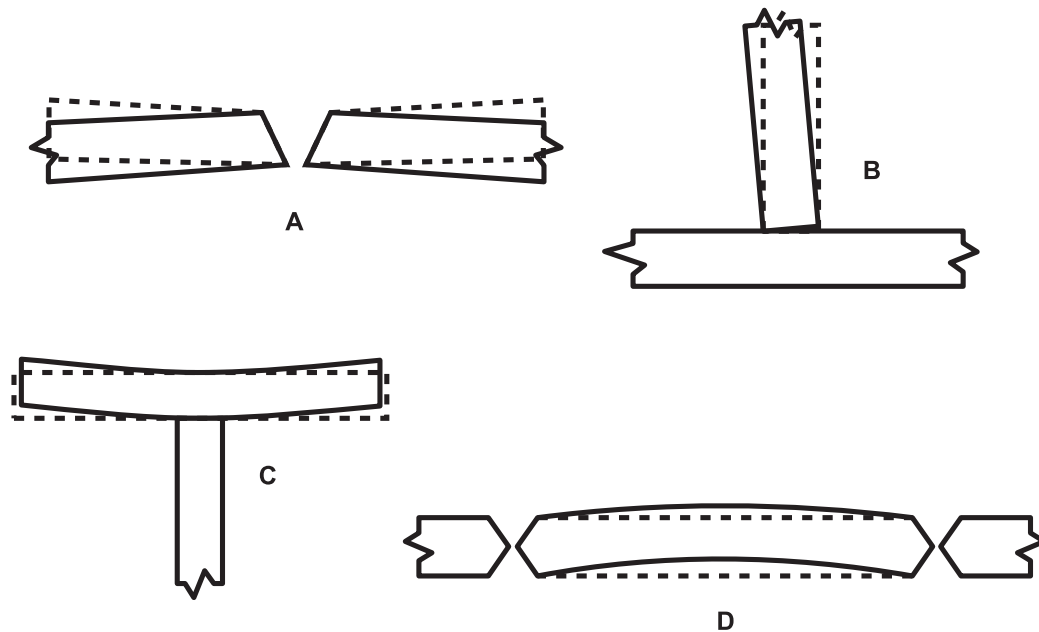
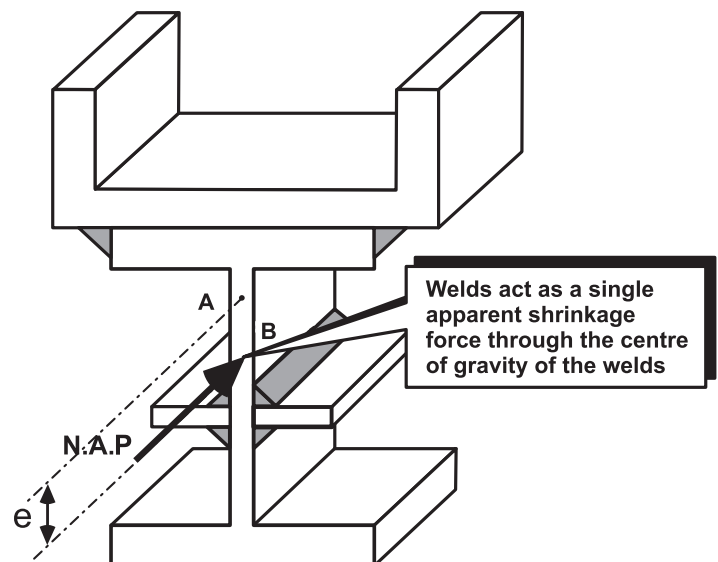


Figure 6.31: Bending distortion due to eccentricity.

For complicated built-up shape such as the one shown in **Figure 6.32**, point “A” indicates the centre of gravity of the built-up shape and point “B” is the centre of gravity of the weld areas, through which the apparent shrinkage force acts. The distance between A and B is the eccentricity.

Figure 6.32: Bending distortion results when the net longitudinal shrinkage force of the welds acts in a line displaced from the neutral axis of the assembly. The line of action of the net apparent shrinkage force is approximately at the centre of gravity of the welds.



From the previous discussion, we can conclude that there are five types of distortions:

1. Longitudinal distortion - shortening in length
2. Bending distortion - unbalanced residual stresses
3. Angular distortion - transverse contraction
4. Buckling distortion - longitudinal plus transverse
5. Twisting distortion - longitudinal contraction likely in thin plates or sheet metal

6.6 Welding Procedure and Distortion

When a welding arc is passing along the surface of a steel plate it creates a very drastic change in temperature variations, called a thermal gradient as shown in **Figure 6.33**. Observe that within a few millimetres of the welding arc the temperature may drop by 1000°C . The magnitude of the temperature drop in a given material is proportional to heat input and travel speed. In a large assembly, distortion occurs because of the uneven heating and rapid cooling of welding.

In previous paragraphs, we have already shown several modes of distortions caused by welding. To control welding distortion we must fully understand the relationship between distortion and welding procedures, joint design, preparation and fit-up.

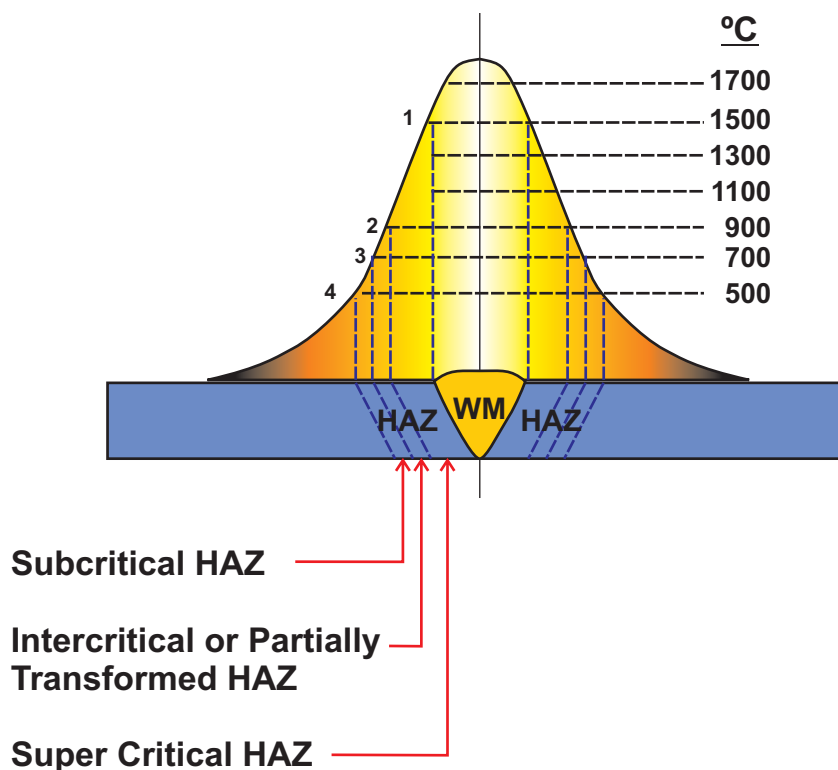


Figure 6.33: Thermal gradient of welding arc.

6.6.1 Welding Procedures

6.6.1.1 Weld Pass: Single Pass, Multipass or Small Pass

Generally speaking, multi-pass welding increases the angular distortion, i.e., a large number of small passes causes more distortion than a few large passes. The first pass forms a hinge point about which the contraction of subsequent passes takes place. Transverse shrinkage will also be greater because each pass will increase the number of upset areas along the plate edge. Therefore, the greater the number of passes the greater the distortion tendency.

In some cases, however, the number of passes should be increased rather than decreased. This occurs when the distortion in the longitudinal direction is more critical. In this case, the smaller the cross section of a bead the less contraction force it can exert against the rigidity of the plates and the more it will stretch. This apparently paradoxical relationship is a function of the thickness of the plate and its natural resistance to distortion. There is inherent rigidity against the longitudinal bending or shortening of a plate, providing the plate is thick enough. Light gauge sheets have little rigidity in this direction and, therefore, will buckle easily. Unless the two plates to be welded are restrained, there is virtually no lateral rigidity; since each of the two plates is free to move with relation to the other, out-of-plane distortion is more common.

6.6.1.2 Travel Speed of Welding Arc

The distortion of a joint will be affected by the rate of welding (travel speed). As the arc travels along the joint the heat fans out in all directions from the weld point, as indicated in **Figure 6.34**. Any heat that travels ahead of the weld point will distort the free joint edges and must, therefore, be kept to a minimum. The slower the rate of travel, the more time there is for the heat to spread ahead of the weld point, as shown in **Figure 6.34A**; the faster the travel the less heat spread that will occur ahead of the weld point as shown in **Figure 6.34B**.

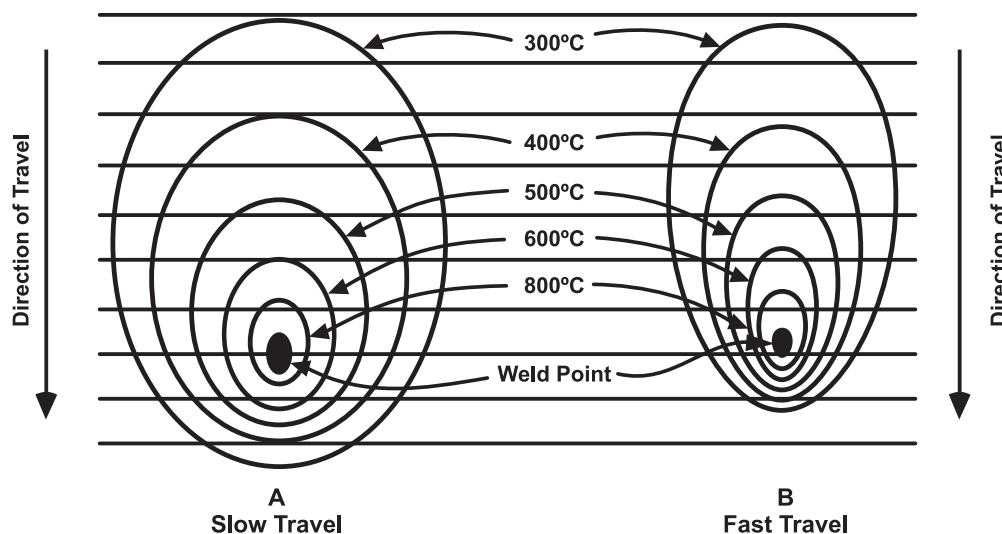


Figure 6.34: Arc travel speed and temperature distribution.

6.6.1.3 Uniformity of Heat Input

Expansion and contraction of the metal in the heat zone is further complicated by the fact that the heat input to the joint is not uniform, but, as shown in **Figure 6.6** is in the form of a concentrated zone (the weld point) which travels along the joint as the weld progresses. At the weld point the heated joint edge is expanding and upsetting (as previously described) and the weld metal is deposited in the fully expanded condition. Behind the weld point the joint edges and weld metal are cooling and contracting. In front of the weld point the joint edges are relatively cold and not yet subjected to expansion.

Obviously a better effect could be secured if the heat could be applied to the joint uniformly and simultaneously throughout the whole length. Although this is not practical in structural fabrication shops, preheat of work prior to welding does reduce the thermal gradient during cooling, in turn reducing distortion. By the same reasoning, postheat also reduces distortion.

6.6.1.4 Joint Design, Preparation and Fit-Up

It has already been noted in reference to **Figure 6.3** that the more symmetrical the weld section and the more balanced the transverse contraction movements, the less angular distortion will be. Joint design should, therefore, be as symmetrical as possible about the longitudinal centre line. Joint D of **Figure 6.27** is preferable from the viewpoint to Joint B. Similarly a U groove preparation is better than a V groove.

Since the weld metal shrinkage is proportional to the amount of weld metal, it follows that the smaller the weld the better. It is therefore the responsibility of the designer to detail weld sizes matching the calculated strength requirements, and for the operator to make welds no greater than shown by the drawings.

A large fillet will give more angular distortion than a smaller fillet and a wide Vee groove more than a narrow groove since the contraction at the top will be greater (see **Figure 6.27**).

Therefore Vee grooves should be designed for a minimum bevel, consistent with accessibility, and should be carefully prepared to see that this bevel is not exceeded.

6.6.1.5 Welding Sequence

Welding sequence is an essential part of any welding procedure. For example as shown in **Figures 6.35 and 6.36** for the same double V groove joint, the sequence of weld metal deposited affects the outcome of distortion.

1) Groove Welds

Figure 6.35 shows a symmetrical double-V butt joint preparation. In **Figure 6.35A** one side is welded completely and the joint is distorted as shown in **Figure 6.35 A2**. Then, when the other side is welded, the final joint geometry is distorted as shown in **Figure 6.35 A4**. This welding sequence cannot eliminate the distortion that occurred in step A2 because the joint is locked rigidly. **Figure 6.35B** shows an alternate sequence. The numbering of the weld passes shows that at step B2 the distortion caused by pass 1 is partially eliminated. At step B3 the joint bends slightly upward. At step B4 the joint is recovered to straight position. This is a satisfactory welding sequence. Notice that the plate assembly has to be turned over and back a few times to achieve the final weld.

Figure 6.36 shows a double-V groove joint with unequal depths. **Figure 6.36A** shows welding without root gouge and **Figure 6.36B** with root gouge. The one without a root gouge shows angular distortion. The one with a root gouge ends up straight. It should be noted that root gouge is always done on the shallow groove side for reduction of angular distortion. Again, in the example the work has to be turned over once for downhand welding.

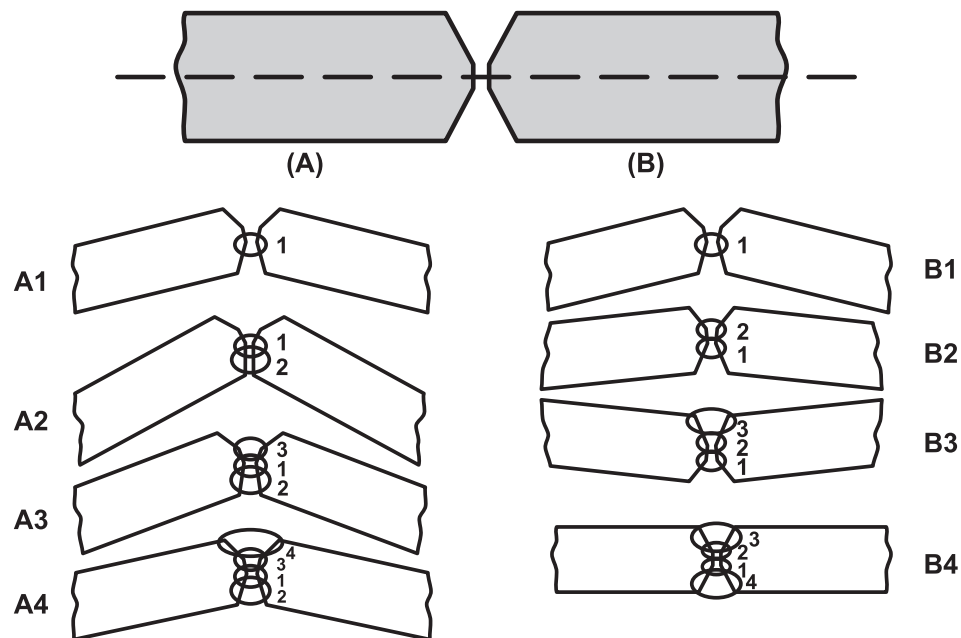


Figure 6.35: Symmetrical double-V butt joint preparation showing effect of welding procedure: balanced welding (right) prevents distortion.

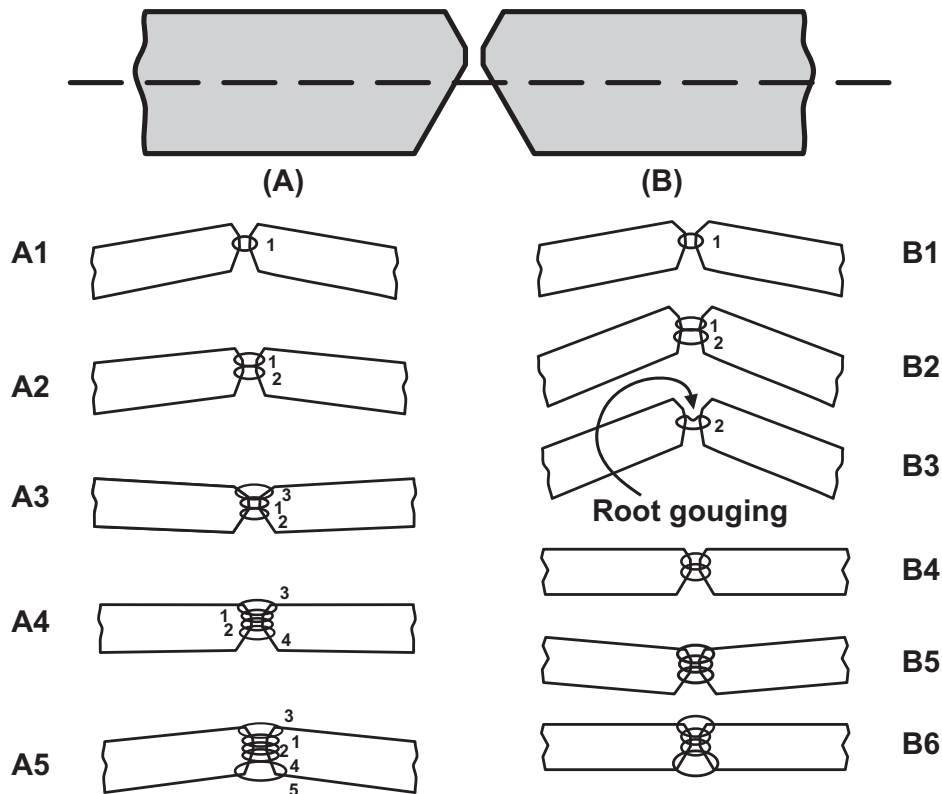


Figure 6.36: Asymmetrical double-V butt joint preparation showing how gouging prevents distortion.

It should be noted that these two figures (**Figures 6.35 and 6.36**) do not show the welding position, although the positions of the weld passes are shown. All the weld passes are deposited in a flat position.

The sequence in which welds are carried out should be studied from the viewpoint of avoiding complete restraint, which will inevitably introduce residual stresses in joints and, when severe, result in distortion or cracking.

Figure 6.37 illustrates the welding sequence necessary to avoid restraint when welding structures consisting of plates and stiffeners. The welding sequence is given as follows:

- 1) weld transverse fillets; this allows plate A to shrink without restraint
- 2) weld butts in plate A; plate is free to move.
- 3) butts in stiffener may now be welded while it is free to move
- 4) stiffener may now be welded to vertical plate;
- 5) brackets may be welded to vertical plate; bracket plate is free to move along stiffener.
- 6) bracket may now be welded to stiffener.

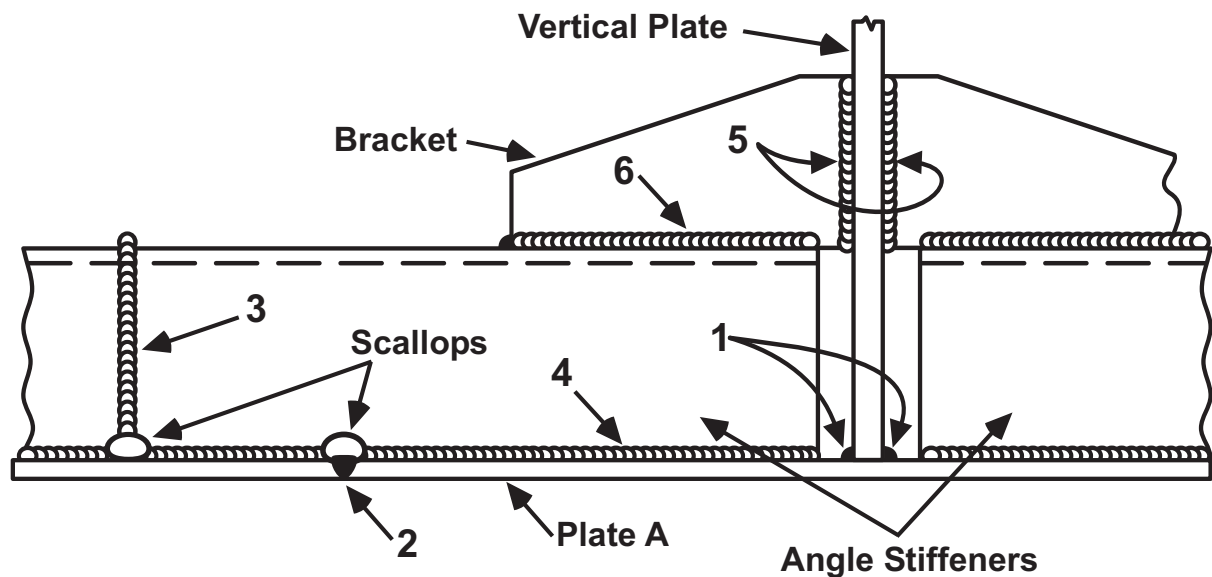


Figure 6.37: An example of welding sequence in a structure combining plating and stiffeners.

6.6.1.6 Seam Welding

Seam welding is normally required when building ships or large fuel tanks where multiple plates are welded along the seams (horizontal and vertical seams) to form the hull or tank wall. Correct welding procedures or sequence is necessary if smooth surfaces and joint geometry are to be maintained.

The simplest form of distortion control is exemplified by the well-known method for welding a longitudinal seam of starting the weld some distance in from the end of the joint and making a short weld first, as shown in **Figure 6.38**. In this way the first weld pre-sets the joint edges and prevents the closing in of the joint as the main weld proceeds (compare **Figure 6.29**).

It has already been mentioned that distortion control involves applying the proper pattern of heat distribution. We have seen how this principle may be applied by welding equal and opposite welds. Also it has been noted that it would be desirable to apply heat uniformly and simultaneously throughout the entire length of a joint. As this is obviously not possible in arc welding, the next best thing is to weld at spaced intervals along the joint.

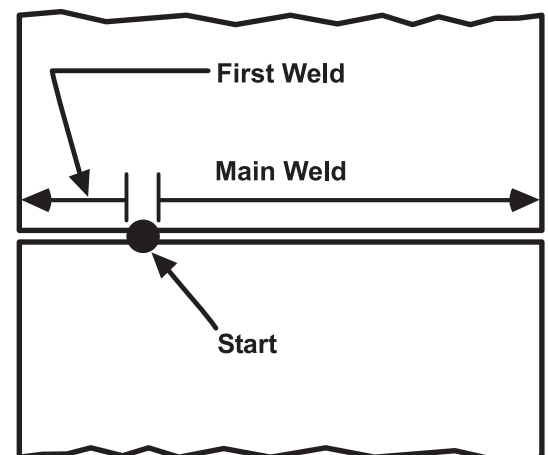


Figure 6.38: Simple welding sequence.

Figure 6.39 shows several sequences that apply this principle. A simple back-stepping method is shown at A. This consists of starting a weld a short distance from the end of a seam - the distance being the length of bead deposited by one electrode (SMAW). The next weld is then started a similar distance from the first weld and is fused in to the previous starting point, and so on, until the joint is completed. B is a minor variation of A, leaving one unwelded space in consecutive steps, called back-step and skip welding. On long joints the welder works outwards from a central point as shown in C and E. This is an important principle to follow.

Still more elaborate variations of this procedure are the “staggered” or “wandering” sequence shown in D and E. These procedures consist of leaving spaces between each weld bead, progressing along the seam in this manner and then completing the unwelded spaces.

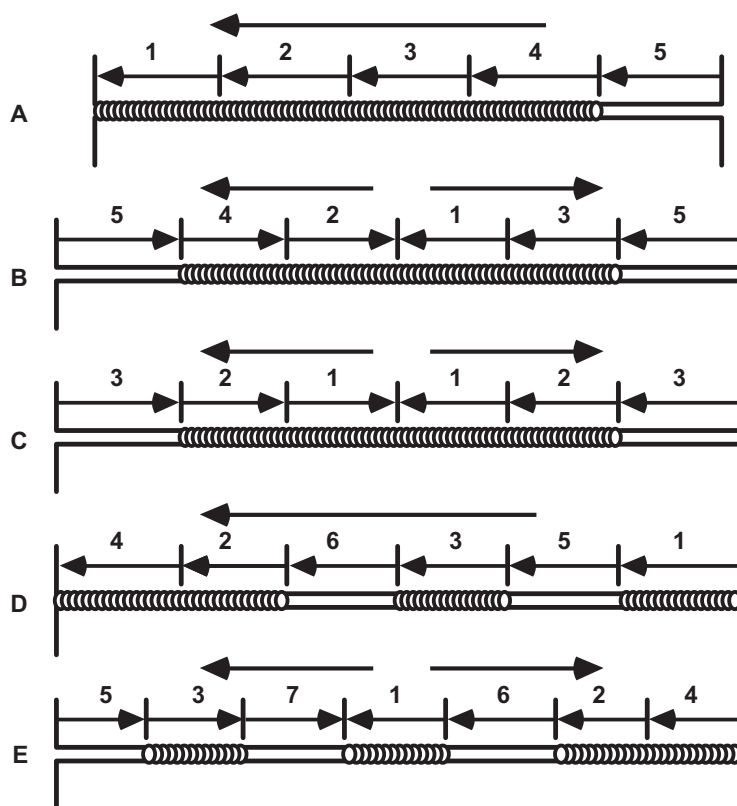


Figure 6.39: Seam welding techniques.

With a large area of plating, as shown in **Figure 6.40**, the welding should start at a central point and proceed outwards, keeping the progress of welding as symmetrical about the centre as possible as shown by the numerical order. The principle is to arrange in a way to allow for each joint to have freedom of movement for the maximum time interval.

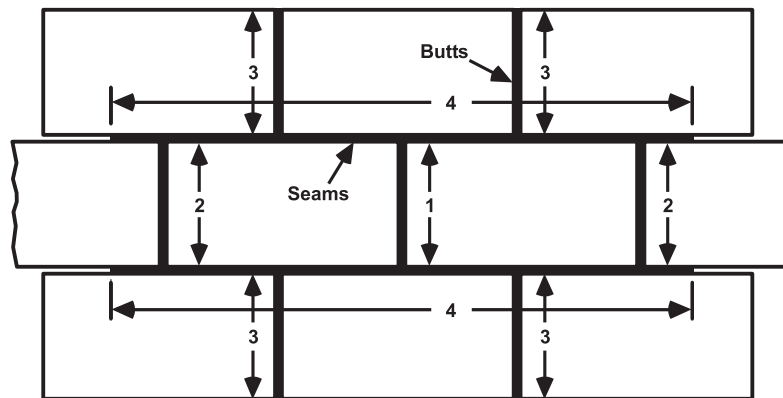


Figure 6.40: Suggested sequence for plate welding.

At the junction of seam weld (horizontal) and butt weld (vertical) the welding sequence is shown in **Figure 6.41**. The seam weld adjacent to the butt weld should be left unwelded for a length of 300 to 380 mm on each side and then completed after the vertical butt is welded. This sequence allows contraction of the butt weld and avoids high rigidity.

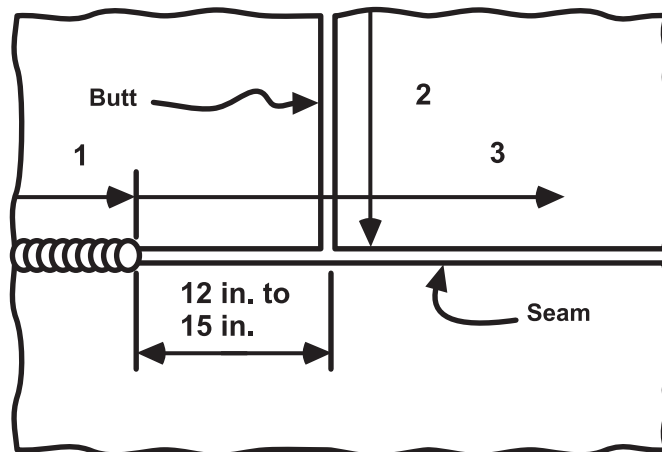


Figure 6.41: Sequence for seams and butts.

6.6.1.7 Non-Continuous Fillet Welds

The seam welding technique as shown in **Figure 6.39** may be used for both butt and tee joints, but in the latter case the welds may be staggered on both sides of the joint as shown in **Figure 6.42**. The main advantage of non-continuous fillet welds (or intermittent fillet welds) is that the heat input to the joint is considerably less and thereby distortion and shrinkage stress are reduced.

It will, of course, be essential to make sure that a non-continuous weld will give the required joint strength. Quite often the minimum practice size of the fillet provides more strength than that required by design calculations; in such cases non-continuous welds may very well be used. On the other hand, if a complete joint seal is required, non-continuous welding cannot be adopted.

Another advantage is that the heat is more uniformly distributed than it would be in the case of a continuous weld. Moreover, the longitudinal weld shrinkage and, therefore, overall distortion, is only a small fraction of that produced by continuous welding. It has, in fact, been found that the reduction in these factors is far greater than would appear to be represented by the proportion of intermittent to continuous weld.

6.6.1.8 Built-up Structures - Neutral Axis

The advantage of equal and opposite welding about neutral axis has already been noted in **Figure 6.27**, B and D and is also shown in **Figure 6.43**. The neutral axis always passes through the centre of gravity and is usually defined as the line on which there will be neither tension nor compression when the piece is flexed or bent.

In the case of a piece of plate, the neutral axis coincides with the centre plane of the plate (see A in **Figure 6.30**); similarly, in the case of an I beam of channel the neutral axis coincides with the centre of the web, see B and E. In the case of a Tee or single section member, arranged as shown at C and D, the neutral axis is not in the centre of the depth, but is near the flange.

A clear understanding of the position and function of the neutral axis is necessary if the effects of welding either a plate or section, or a complete weldment, are to be visualized.

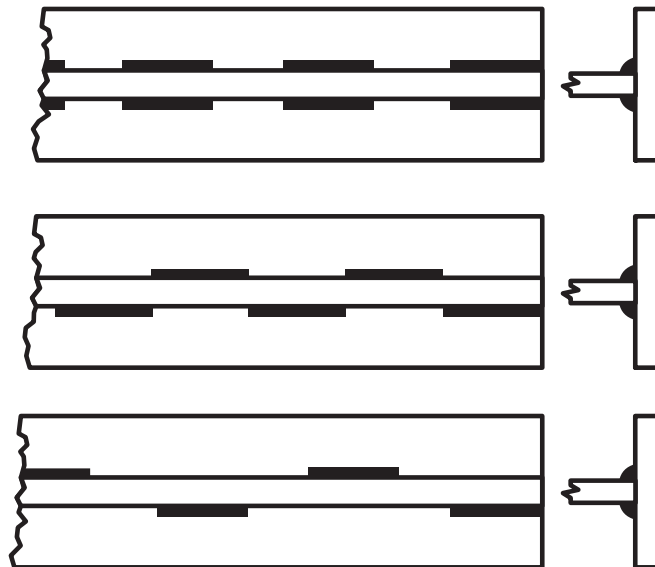


Figure 6.42: Intermittent fillet welds.

As previously mentioned, the simple deposition of a bead of weld metal on the surface of a plate will cause that plate to bend with concavity on the welded side. This is simply due to the fact that the contraction of the weld metal exercises a shrinkage force that is offset from the neutral axis of the plate. If, on the other hand, beads were deposited simultaneously on opposite sides of the plate, the contractions of the two welds would be balanced about the neutral axis and there would be no bending or distortion.

This balancing of welds about the neutral axis of a built-up section or structure is the most important fundamental point in reducing distortion. A further example is shown in **Figure 6.43** where various welds are arranged around the neutral axis of a built-up section, the sequence in which the welds should be made being indicated by numbers.

Emphasis so far has been laid on the importance of welding equally about the neutral axis to maintain alignment. This assumes that the structure is true to begin with. In some cases this may not be so and welding unequally about the axis may be used as a means of straightening.

A case in point is the construction of a beam from plate sections where the web plate has a curvature as received from the mill. This might be as much as 10 mm in 1500 mm. The following procedure may then be used to produce a straight beam. (See **Figure 6.44**).

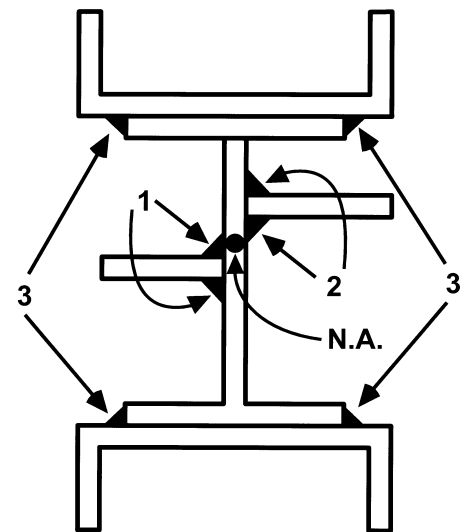


Figure 6.43: Balancing the sequences of welds about the neutral axis of a section.

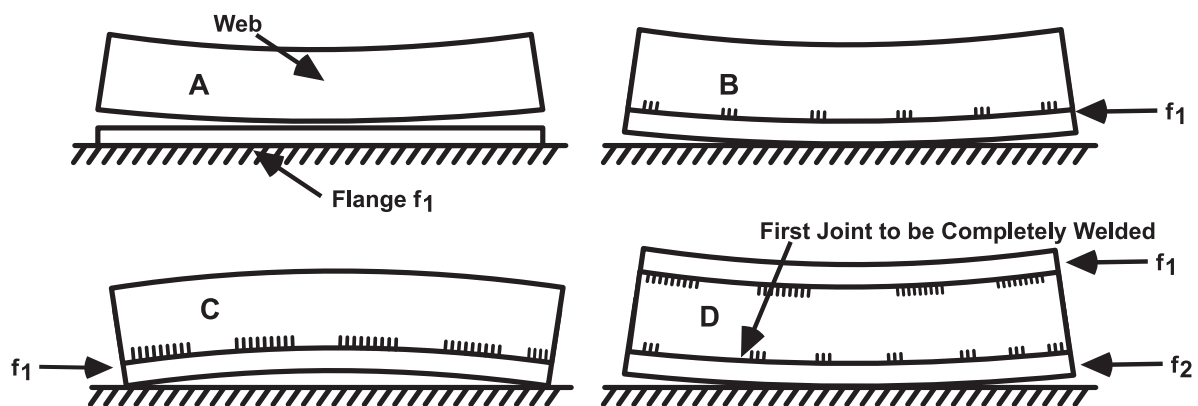


Figure 6.44: Operations in welding a built-up I beam with curved web.

The flange plate f_1 is laid down on a slab and the web plate (with convex side down) is set up vertically on it as in A. The flange is then pulled up to the web plate and strongly tacked as in B. The welding of this flange and the web is then carried out until the web is not only straightened but slightly bent in the opposite direction as shown in C. The second flange f_2 is now fitted to the web and tacked securely as in D. The welding is then completed, preferably using two welders on opposite sides of the web and working in the same direction. With such a sequence the beam should be reasonably straight on completion. Welding the first flange to the web before the second flange has been tacked to the latter results in a considerable bending effect due to the shortening of the weld in as much as the beam is not strong or stable without the second flange. If in doing such welding the beam is slightly 'over bent', the welding on the second flange, when completed, ought to be just sufficient to pull the beam back to the straight position, since due to greater rigidity the shrinkage effect will not be as great as under the conditions in which the first flange was welded.

6.6.1.9 Complicated Weldments - Accurate Assembly

In the case of complicated assemblies, the accuracy of preparing the various components requires careful consideration to enable dimensional tolerances to be kept to a minimum. An accumulation of tolerances over a number of components may create costly post-welding difficulties. Obviously the more generous the tolerances, the greater the fit-up gaps, and an excessive amount of weld metal will be necessitated, resulting in greater distortion than would otherwise be involved.

To avoid this, it may be desirable to machine components to size to obtain close tolerances and increase the accuracy of the final weldment. It is also often possible to arrange the assembly of components in such a way that cumulative tolerances can be controlled and prevented from adversely affecting the final accuracy of the structure. (See **Figure 6.45**).

Where accurate location points are essential, the assembly arrangement of the structure should provide for some allowance in case the various sub-assembly allowances do not work out to the degree of accuracy expected. For example, in the case of built-up I-beams, the accumulated longitudinal contraction of the flange to web welds and the transverse contraction of the stiffener welds, will result in appreciable shortening of the beam, and it is usual to leave the flange and web plates overlength so that they may be finished to size after welding.

Similarly, for machine structures such as bedplates, engine frames, etc., those points that must be located to close tolerances should be fixed only by the last weld that affects their location.

With tolerance of ± 1.6 mm on plates X and Y, assembly A would necessitate a tolerance of ± 3 mm whereas the accuracy of B could be ± 0.8 mm.

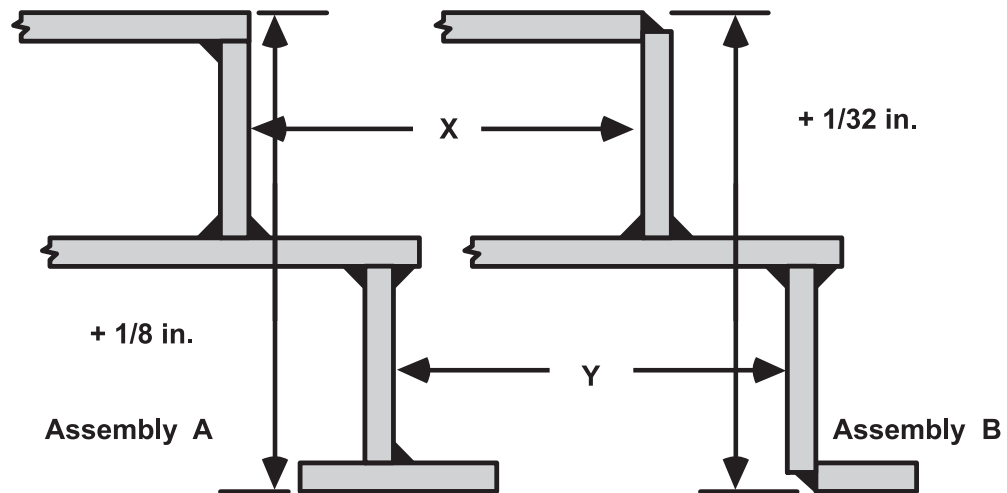


Figure 6.45: Arranging components to ensure finished accuracy.

6.7 Control and Correction of Distortions

We have discussed the causes and types of distortions. What happens when the weldment is distorted beyond the allowance referenced by the applicable codes or standards? What are the common measures used by the welding fabrication shops to prevent distortions? What corrective actions can be taken to eliminate distortions once occurred? A brief discussion will be given in the following paragraphs.

6.7.1 Control of Distortion

In previous discussions of welding and distortion, several ways of preventing distortion have already been mentioned. The following is a summary of control of distortion by welding procedure control:

1. Accurate joint preparation and fit-up. This is one way to maintain minimum weld metal for the joint.
2. The use of back-stopping or a skip technique.
3. Welding progresses outwards from a central point.
4. Balancing welds on either side of a centre line, central point or about the neutral axis of a section.
5. Welding butts (groove joints) before fillets to allow large contraction to take place first.
6. Using intermittent fillets instead of continuous fillets when code allows.
7. Arranging the weld sequence so that each joint has the maximum freedom of movement for the longest possible period.
8. Dividing a weldment into sub-assemblies to reduce cumulative distortions or shrinkage, especially lengthwise.

In addition to the above procedures, which are aimed at reducing distortion, the following points should be given attention since they are particularly concerned with the production of an accurate weldment:

- (a) Applying the welding so as to counteract plate edge curvature if any
- (b) Arrange components so as to avoid accumulation of errors due to tolerances on plate width
- (c) Where a high degree of overall accuracy is required, prepare components accurately to reduce fit-up tolerances
- (d) Arrange the sequence of welding so that location points necessitating a high degree of accuracy are assembled and welded last
- (e) Allow for weld metal shrinkage
- (f) Arrange for some latitude in assembly dimensions so that a weldment can be machined to size if shrinkage and other allowances do not work out as expected

Other means of distortion control besides the welding procedures are:

1. Preheating - reduces shrinkage because it provides more uniform heating and cooling
2. Peening - reduces shrinkage because it stretches the weld metal
3. Restraint - any degree of restraint, external or self weight, may be expected to reduce the amount of shrinkage and such restraint may be applied in any of the following ways:
 - a) clamping
 - b) rigid tacking
 - c) maintain minimum or zero root opening (reduce transverse shrinkage)
 - d) cooling between weld passes (reduce the restraining required)

Mechanical Control

- a) Presetting to allow recovery of angle or longitudinal distortion (see **Figure 6.46**)
- b) Use of temporary stiffeners
- c) Use of strongbacks or special jigs or fixtures
- d) Artificial cooling

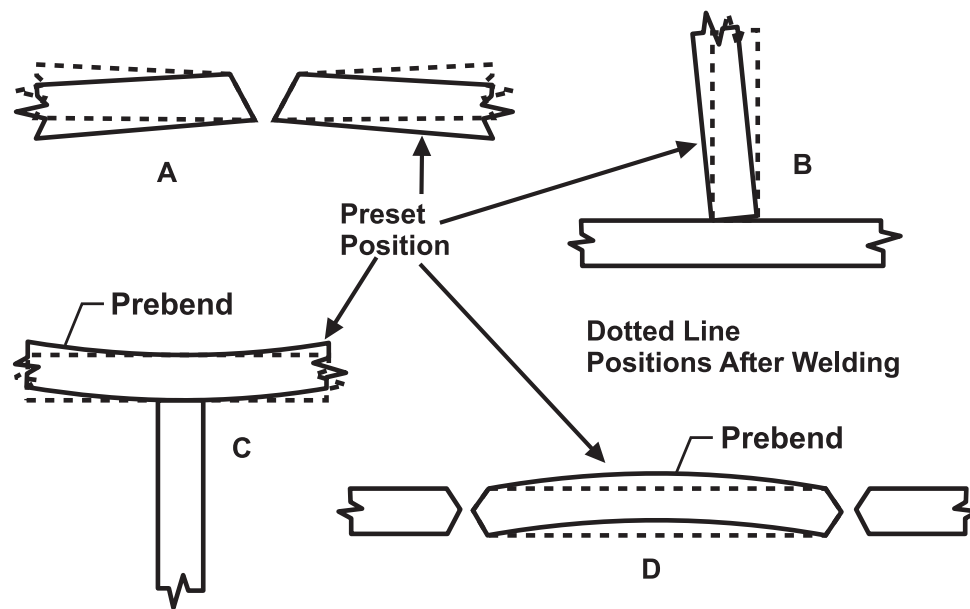


Figure 6.46: Presetting of joint members to allow for contraction of weld metal.

It has been already noted that distortion may be reduced by fixing components either by tacking, clamping, or by assembling in jigs. Complete rigidity in this respect is however, contrary to the above-mentioned principle of minimizing stresses. Therefore, unless the weld metal can be permitted to contract freely (e.g., as in a preset joint), a balance must be found between the extremes of free movement and complete rigidity so that both distortion and stresses may be kept to a minimum.

Accurate edge preparation and joint fit-up has considerable influence on the production of stress-free joints. A variable and unnecessarily wide joint causes considerable heat concentrations at the wide places, thus creating excessive lock-up, that is, residual stresses in the assembly.

Another preparation fault is excessive root face, particularly if accompanied by a tight fitting joint. Not only is complete fusion of the joint difficult (if not impossible) to achieve but shrinkage of the deposited metal will be prevented. The result will be high shrinkage stresses that are very likely to cause cracking in service if the weld does not crack before it is completed.

Rigid alignment and complete restraint of joints by strongbacks, clamps and such devices should be avoided. **Figure 6.47** shows several methods commonly used to align joints. In A the joint is made rigid and the method is entirely incorrect. In B and C the joint is free to contract and the methods are suitable, while D is correct if the jack is removed after tacking and before final welding.

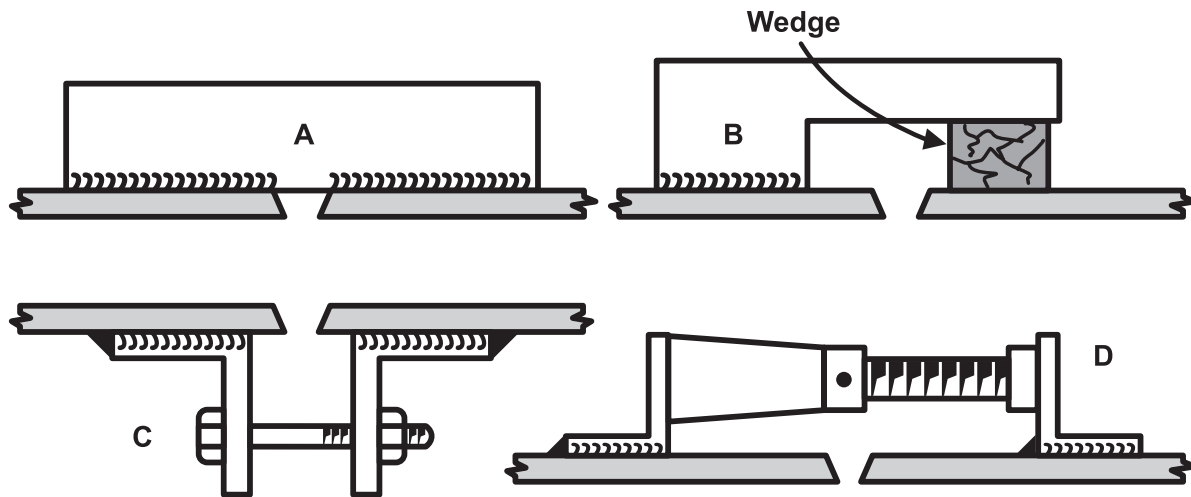


Figure 6.47: Methods of joint alignment.

Alternatively, weldments may be rigidly clamped to heavy slabs or bases during the period of welding; also they may be mounted in rigid fixtures or assembled and rigidly tacked for welding. Strongbacks and temporary stiffeners may be used to align and rigidly maintain edges and joints.

Heavy slabs and fixtures will not only hold assemblies rigidly, but will withdraw the heat of welding from the weldments, further reducing distortion. A similar effect can be obtained by immersing assemblies in water, or by spraying.

However, none of the methods of restraint can be expected to fully retain alignment. Some springing and distortion will usually follow release from such superimposed control.

Further, the greater the restraint against contraction the greater will be the residual stresses induced and the more likelihood that cracking will result as in **Figure 6.47C**.

Heavy weldments of heavy plate may in themselves offer great rigidity and restraint to welds.

Figure 6.48 shows cover plates welded to H sections. The fillet welds will have a tendency to shorten due to their longitudinal contraction. This contraction will cause bending and a shortening of the sections. If they are tacked or clamped together as shown, this bending tendency in each will be counteracted by the other. The procedure should be to start welding in short increments outward from the centre, alternating from one section to the other so that equal and opposite welds are made alternatively and thus counterbalance each other.

It is understandable that distortion will be increased in large assemblies where the welds are long. It therefore follows that if the job is broken down into a number of smaller weldments or sub-assemblies, the distortion in each will be less and can more easily be controlled and corrected. If necessary, each sub-assembly can be straightened or machined before final fitting and welding. Therefore final fabrication from sub-assemblies is to be recommended and the designer should bear this requisite in mind. Sub-assemblies further make for easier and more efficient handling and reduce the accumulation of additive residual stresses.

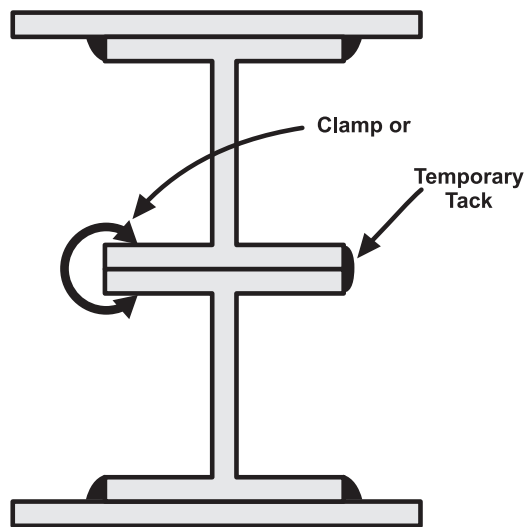


Figure 6.48: Eliminating distortion by balancing weld contractions of two similar weldments clamped or tacked back to back.

Experience has shown that control of distortion and reduction of welded-in-stresses can be achieved by carefully planning the welding procedure.

6.7.2 Correction of Distortion

Although the foregoing suggestions for control or minimizing distortion provide some assurance of final products, it should be appreciated that, despite the observance of all reasonable precautions, distortion may still occur. Any such distortion will, however, be much less severe than it would have been had no precautions been taken. When the distortion is greater than the code allowance corrective measures are necessary. There are two common methods which are available to the fabrication shops:

1. Mechanical straightening
Use mechanical device, such as jacks, presses or specially designed straightener as shown in **Figure 6.49**.



Figure 6.49: Specially designed straightener. (Courtesy of Canon Inc.)

2. Application of heat

Use the principle of resisted expansion during heating and subsequent contraction on cooling.

Several examples are given later to illustrate how the principle is applied.

It should be pointed out that each method is suited for certain applications. Most mechanical straighteners are suited for minor straightening. Heavy components require specially built straighteners, which are not available in small fabrication shops.

By far, flame straightening or flame forming is more common and readily available in all fabrication shops, and is especially suited for large assemblies that cannot be corrected by mechanical straighteners.

For example, a piece of Tee section bent as shown in **Figure 6.50A** may be straightened by heating and cooling the area XYZ. The basic principle, which has already been studied, is that the expansion of the metal in the heated zone is resisted by the cool surrounding metal. It therefore upsets and remains so on cooling (**Figure 6.50B**) resulting in a reduction in the distance XY, straightening the member as shown at right.

For the successful application of this principle both heating and cooling should be as rapid as possible and the dimensions of the heated area should be at a maximum where most contraction is desired. In the example shown at A, B and C in **Figure 6.50** rectangular areas are heated. Even large, built-up I-beams can be straightened by successively heating and cooling along the convex side of the beam as shown at D. This principle can be applied also to the correction of distortion or buckling on plates or a combination of plating and stiffeners.

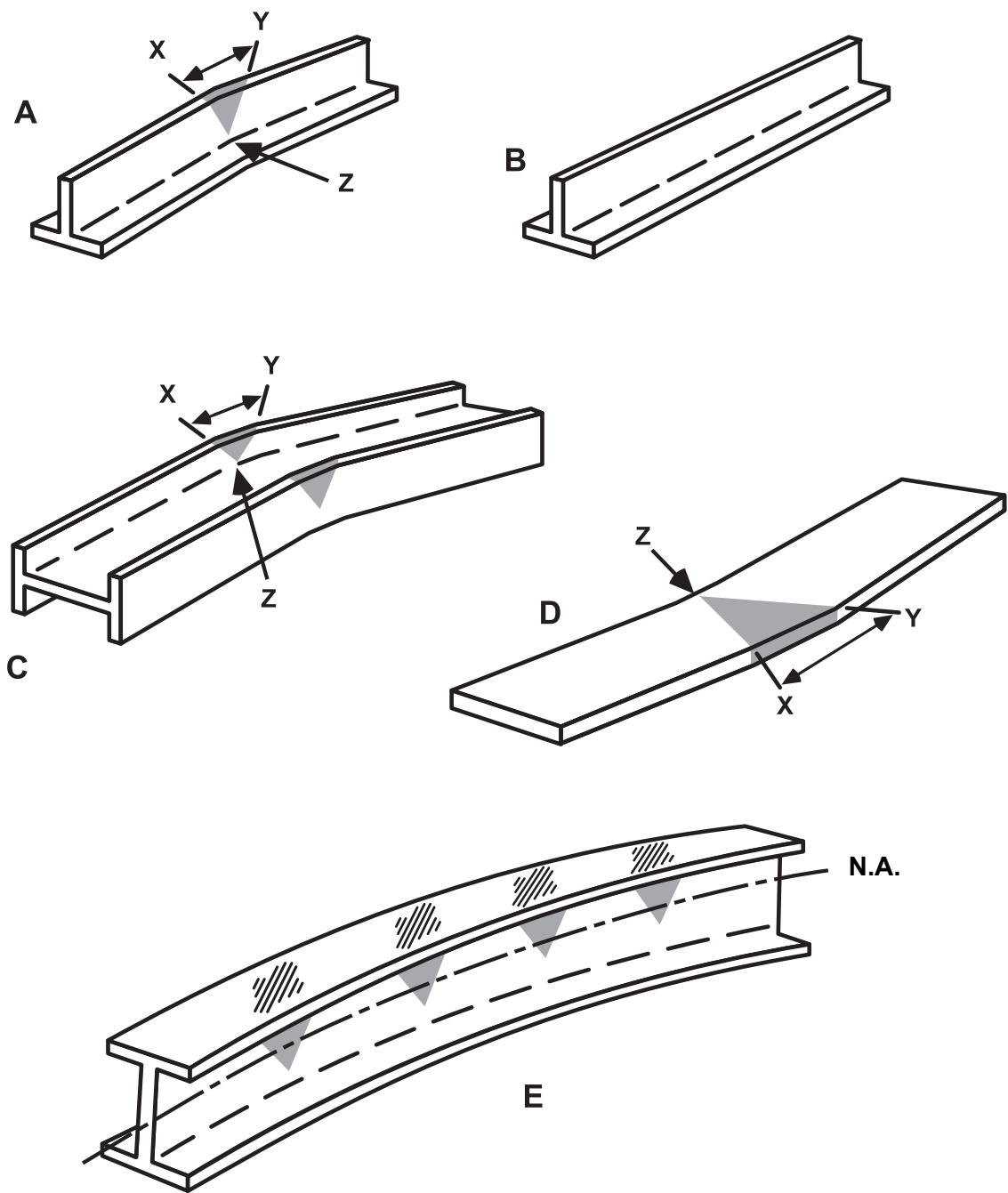
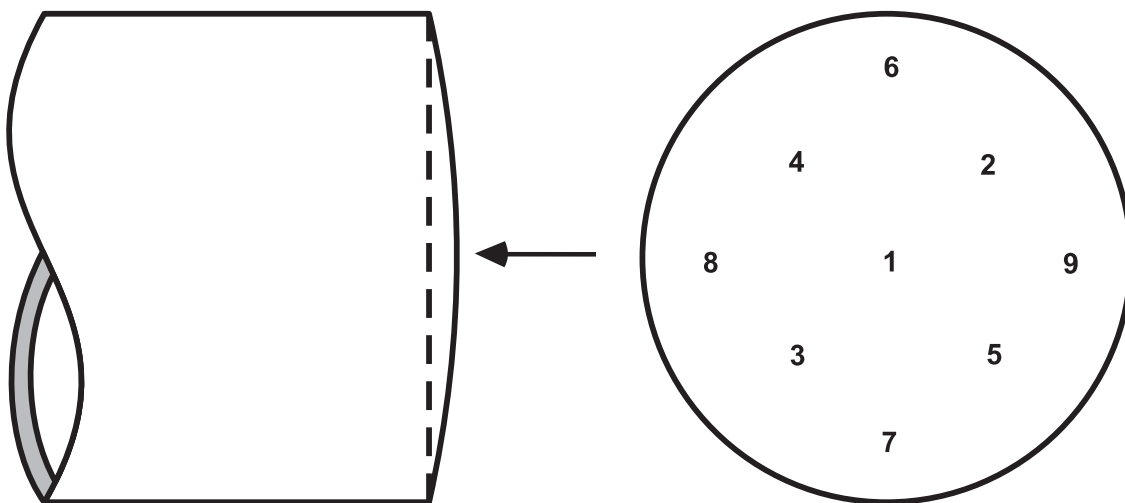


Figure 6.50: Eliminating distortion by heating and cooling.

The first example (**Figure 6.51**) shows a simple cylindrical vessel with a flat welded end or bottom plate, which may be in any thickness of plate usually encountered in what is called the light or medium tank work field. The weld is a corner weld inside and out round of the flat end plate, thus causing a bulge in the centre. This condition can easily be corrected by application of heat in local spots as shown. To achieve the best result, the spots should be evenly spaced and symmetrical over the bottom. It must be noted that it is possible to overdo the application of local heat and undo much of the good that may have been done. Overheating can produce buckles as bad as those it is desired to eliminate. Therefore, in the first place, spots 1 to 5 should be tried, spots 6, 7, 8 and 9 being tried if the first prove inadequate. The heat should be applied in the form of spots about 2 inches in diameter and the plate brought to a cherry red colour. Care should be taken not to overheat or the effect can be nullified.

The heat, of course, is applied by means of an oxy-acetylene flame. In this connection a word or two about nozzle sizes may be helpful. A nozzle or tip for approximately 9 cubic feet per hour gas flow in a standard torch is the best for use for anything up to 16 mm thick plates. For thicker plates, a nozzle for approximately 23 cubic feet per hour gas flow in a heavy duty welding torch should be used.



Heated spots should be as evenly spaced and symmetrical as possible, and in sequence shown by numbers. More or less spots may be required.

Figure 6.51: Application of heat in local spots, evenly spaced and symmetrical.

The next example illustrates how considerable trouble can be experienced with rectangular tanks. **Figure 6.52** shows diagrammatically the top flange of a rectangular tank, indicating how the welding contractions have pulled it out of square. A simple way of correcting this is to apply heat to the corners of the flange as shown by the arrows. Evenly heat the area a few inches round the corners of the flange on the outside at the extremities of the long diagonal and round the inside of the flange at the extremities of the short diagonal. Correction can be assisted by inserting a prop, with a jack at one end, across the short diagonal and applying pressure to stretch. Alternatively, bars attached to either end of the long diagonal can be used with a turn buckle to draw in the tank in this direction. In some cases it may be necessary to torch cut the flange at each end of the long diagonal and possibly remove a triangular section to permit the necessary movement. Further assistance can be given in stretching the material by peening the metal adjacent to the welds down each corner of the tank. Care should be taken not to cause excessive indentations on the plate surface.

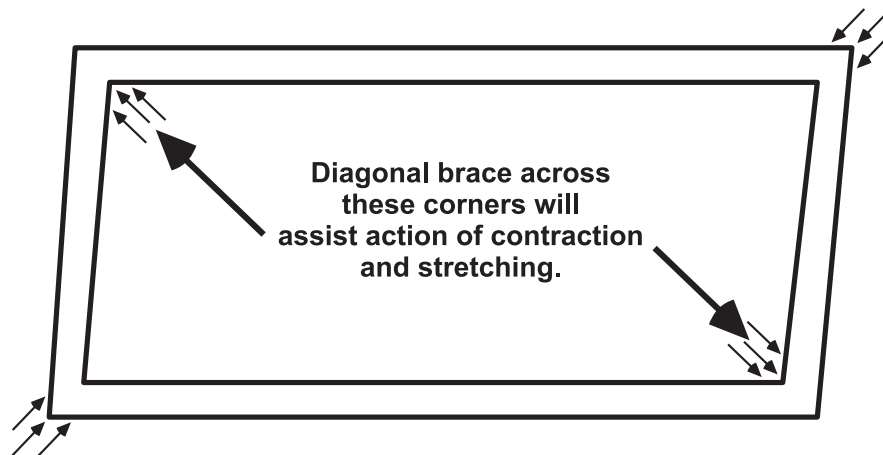


Figure 6.52: *Distorted top flange of rectangular tanks. Apply heat to the corners of the flange.*

Another example (**Figure 6.53**) of a large rectangular tank shows how the heavy type flange or curb can be distorted by the weld that joins it to the top of the tank body. Again the cure is comparatively simple; it consists of the local application of heat to the spots indicated by the arrows, and the heat in this case is applied across the face of the flange in a V shape, the wider part of the V matching the side that is being shrunk. This is particularly necessary if the flange is a heavy one.

Finally, large rectangular tanks with heavy stiffeners can bulge appreciably in the panels made by positioning of the stiffeners; this bulging can be eliminated by heat applied to spots in the middle of the panels as described previously. The sketch (**Figure 6.54**) indicates the manner in which this can be done, and a tank in a comparatively bad state can be brought into good shape, with almost complete flatness in the panels.

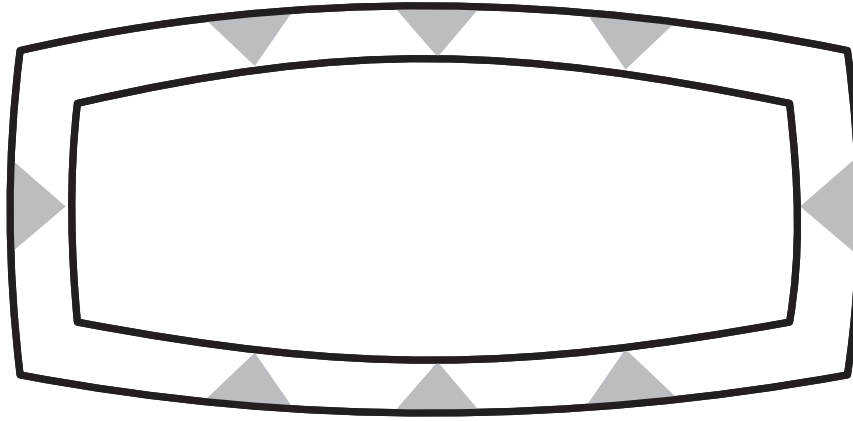


Figure 6.53: Another example of distorted flange of a large rectangular tank.
Local application of heat as shown.

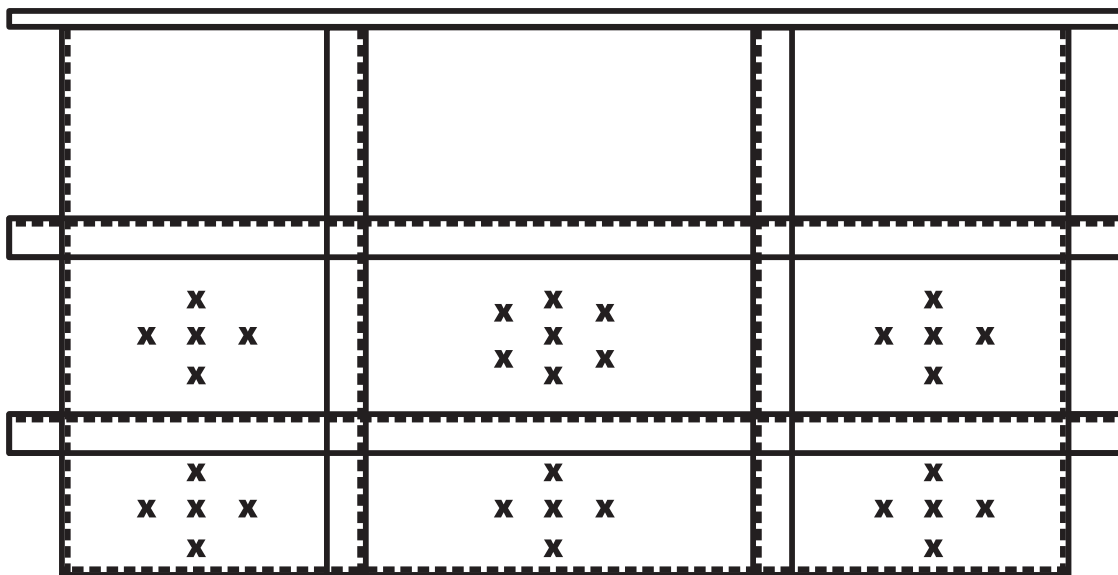


Figure 6.54: Bulged panels of a rectangular tank. Apply heat to spots in the middle of the panels.

Chapter 7

Fracture and Fatigue of Welded Structures

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7.1 Introduction

To engineers who design mechanical components, crane runways, highway bridges and seismic resistant structures, fractures and fatigue of structural members and connections are not strange subjects. Because these structures carry moving and variable loads, the stresses in the members fluctuate and sometimes reverse. The strength of the member and connection under these conditions are much lower than those under static loads. It is a rather complex process to predict the member strength because it involves load magnitude, range of fluctuation and frequency, member configuration, service temperature, manufacturing process and metallurgical compositions. Therefore, the breaking strength cannot be simply formulated as in the case under static loads.

Another factor that complicates the problem is fatigue of metals. To fracture in fatigue a crack must be first initiated. The crack may be initiated under fluctuating loads, or are existing, such as inclusions or porosities due to welding. It may be superficial or internal. It is difficult to decide when a crack is initiated. There is always a time lag between the initiation of the crack and the detection of the crack. The time required for a crack to grow (propagate) under each loading cycle until fracture is always an educated guess (statistical). Therefore, the study of fatigue and fracture relies heavily on experiment results and statistical interpretation. A lot of documented data is available to aid the design engineer. For instance, various welded structural joints are grouped and categorized. The fatigue resistance of a member or a detail can be calculated accordingly.

It should be pointed out that fracture and fatigue are two different subjects. Fracture can happen under static loads alone, such as in laboratory tensile tests without cyclic loads (fatigue). The result of fatigue always leads to fracture.

Fracture mechanics is an important tool in analysing and designing welded joints. It is also used to predict fracture behaviour and fatigue life. Only brief outlines will be discussed to assist the understanding of the fracture phenomena. The students are encouraged to study the following CWB Modules to get further insight on this subject:

Module 35	Fracture Fundamentals
Module 36	Fracture Applications
Module 37	Fatigue Fundamentals
Module 38	Fatigue Applications
Module 39	Weld Mechanics

7.2 Stress-Strain Relationship

We are all familiar with the stress-strain relationship curves of steels as shown in **Figure 7.1**. The steep, straight portion of the line shows the steel before it reaches the yielding point. The curve to the right of the straight line shows the steel passing the yielding point into plastic deformation, before breaking. This is a typical ductile structural steel property that designers depend on. The striking characteristics of the tensile test sample is shown in **Figure 7.2B** showing necking and a large amount of strain before breaking.

It should be noted that the curves shown in **Figure 7.1** and breaking feature in **Figure 7.2B** are generated under certain extrinsic conditions, such as monotonic loading and room temperature. Some metals with ductile behaviour under a given set of extrinsic conditions appear to lose their ductility under another set of conditions and become brittle as shown in **Figure 7.2A**.

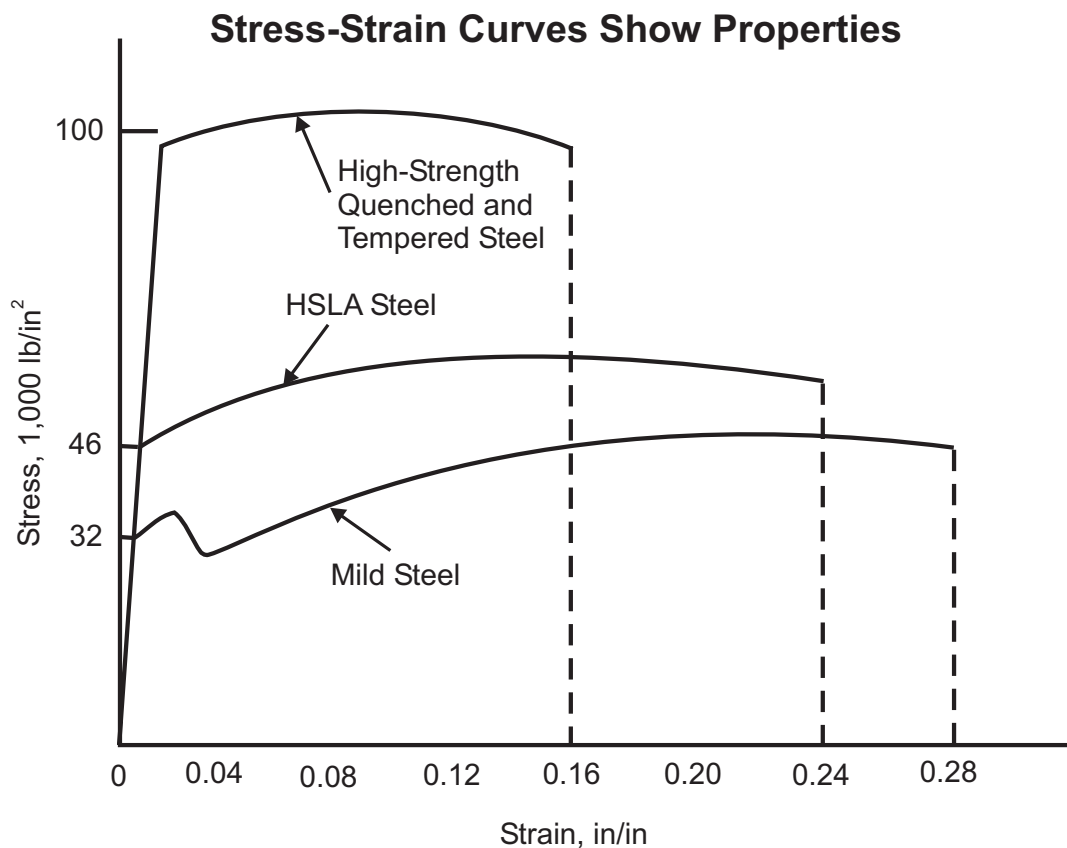


Figure 7.1: Ductility is the mainstay of structural steels that designers depend upon.

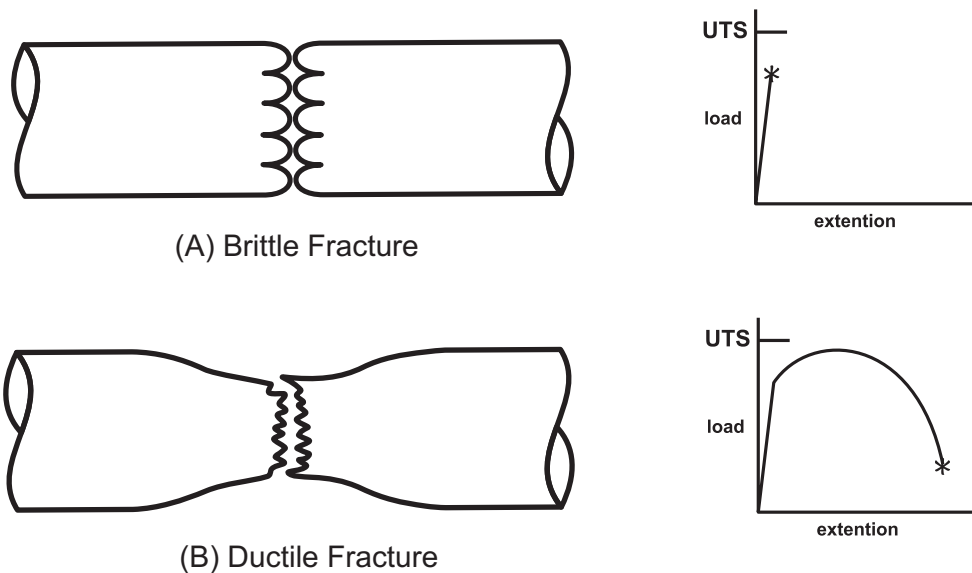
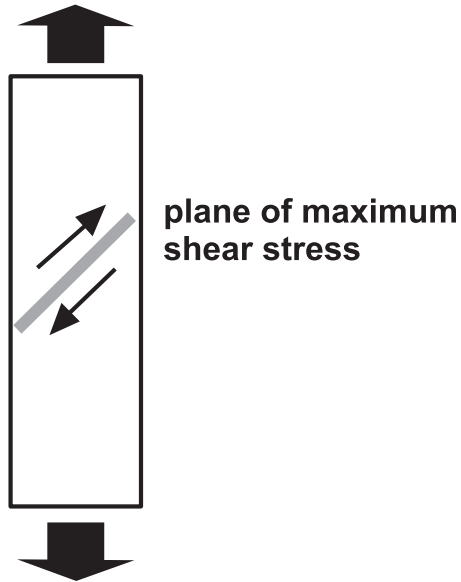


Figure 7.2: (A) Brittle fracture occurs with negligible deformation or elongation, (B) ductile failures act in an opposite manner.

7.3 Fracture of Steel Components

Numerous studies and analysis of fractured steel components conclude that there are generally two modes of fracture: ductile fracture and brittle fracture. Ductile fracture surfaces show large deformation (strain) and shearing characteristics, which are inclined to loading (See **Figure 7.3 & 7.4**). Brittle fracture surfaces, on the other hand, show little deformation (strain) and a flat surface which is perpendicular to loading (**Figure 7.4**). In between these two extremes, there is a range of mixed modes of fractures.

Although brittle fractures seldom occur in everyday structures, when designing for low temperatures under fluctuating loads, engineers must consider this possibility. We all know through study or experience that steel is a ductile metal, but the service temperature and the state of stresses can change the ductility. For instance, when the ambient temperature is low and/or the shearing stress is restricted by biaxial or triaxial stresses, the ductility will be reduced, as at stress concentrations of a member with sharp changes in the cross-sectional areas. A combination of low service temperatures and restricted stresses can actually reduce the ductility to near zero. The member can fracture in a brittle manner, like cast iron.



7.4 Fracture Surface

The first obvious clue as to the type of fracture that has occurred is the angle and shape of the fracture surface. Consider a thin plate (strip) loaded in tension until it breaks (**Figure 7.3**). Plastic deformation occurs in a plane at an angle to the direction of loading because that is where the shear stresses causing slip are highest. After the material has necked down and failed, the fracture surface shows a characteristic slant.

Figure 7.3: Plastic deformation occurs on planes of high shear stress, at an angle to the principal stress. Ductile failures show characteristic slant fracture surface.

A brittle fracture, on the other hand, runs more or less normal to the maximum tensile stress and shows a characteristic flat, normal surface (**Figure 7.4**).

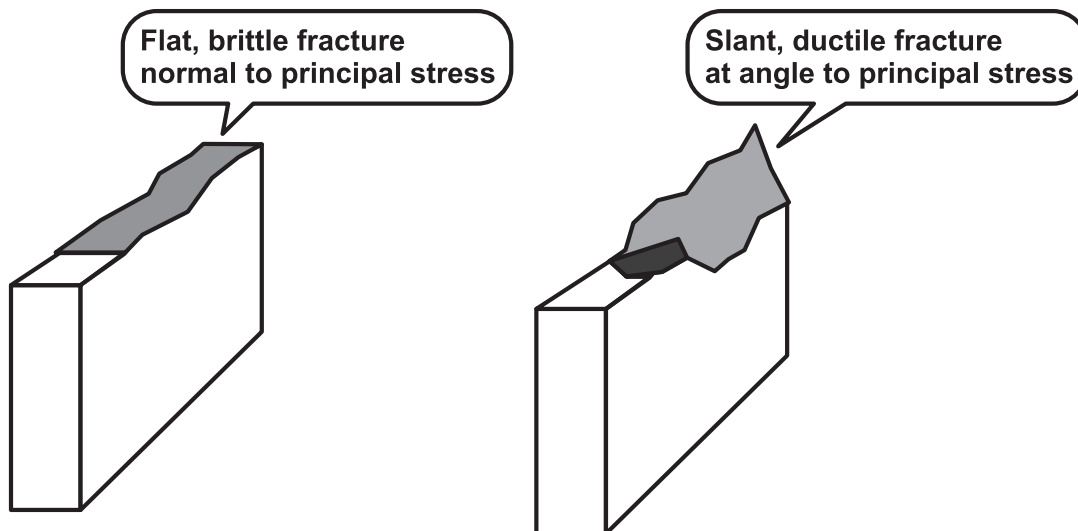


Figure 7.4: Brittle fracture (left) shows flat surface, normal to principal stress. Ductile fracture (right) shows slant.

From the study of previous chapters, we have learned that the atomic structure of steel in room temperature is body-centered cubic, due to the presence of an atom at the centre of the cube. Shear failure of steel crystals occurs by sliding on a plane along the diagonal of the cube that contains the centre atom. Brittle failure of steel crystals occurs by cleavage, separation between the faces of the cube. **Figure 7.5** shows a brittle fracture by cleavage.



Figure 7.5: Surface of brittle fracture.
The shiny facets result from the cleavage of the individual grains giving a crystalline appearance.



Figure 7.6: Characteristic river pattern on the surface of a cleavage fracture observed under high magnification.

7.5 Cleavage

In some metals, notably iron and steel at low temperatures, fracture may occur by cleavage, as individual grains crack along specific crystallographic planes, with negligible plastic deformation. The cleavage of grains appears as shiny facets on the fracture surface as **Figure 7.5** illustrates. The energy required for cleavage fracture is very small. A fast-running brittle fracture can continue to run under a stress as small as 35 MPa (5 ksi).

As a cleavage crack advances, the stress field at the tip of the crack causes cleavage to occur in the grains just ahead of the main crack. These may cleave on different planes, which may be at slightly differing angles. The cracks subsequently link up. Under a high power microscope (**Figure 7.6**) the cleavage surface is flat but not completely smooth, showing instead characteristic “river patterns”, where the crack jumps from one to another parallel crystallographic plane. The small cleavage cracks on separate planes may be linked by tearing i.e., a plastic deformation process. The energy associated with such crack propagation is increased because of the energy required in plastic tearing, and it is higher for a smaller grain size metal where many more tears must form. This fracture surface is referred to as ‘quasi-cleavage’.

7.6 Grain Size Effect

One of the most important microstructural features affecting brittle fracture is grain size. A grain boundary provides an obstacle to cleavage crack propagation since adjacent grains will have their cleavage planes at varying angles. A metal with a small grain size, and hence a large number of grain boundaries, has a greater resistance to cleavage fracture. A small grain also means that a cleavage crack in a single grain is shorter and less likely to initiate a crack in an adjacent grain (**Figure 7.7**).

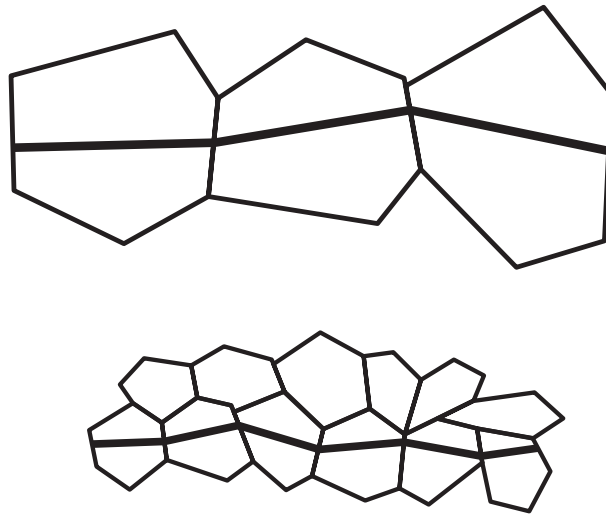


Figure 7.7: Cleavage crack propagation through polycrystalline metal. Small grain size increases the resistance to cleavage.

7.7 Transition Temperature and Brittle Fracture

Brittle fracture is not common in most structures, occurring far less frequently than fatigue. If brittle fracture does occur, it can be catastrophic. A brittle crack propagates through the material at the speed of sound.

A brittle fracture starts with little warning: it fails suddenly with extremely little deformation (**Figure 7.2A**), in direct contrast to the ductile failure shown in **Figure 7.2B**.

Above a certain temperature, a given steel behaves in a ductile manner, while below this temperature, the same steel behaves in a brittle manner. This transition occurs at the transition temperature (**Figure 7.8**). Steels having good resistance to fracture are said to be “tough”.

The most common method used to establish the transition temperature is the Charpy V-notch impact test (**Figure 7.9**). Standard-sized specimens are subject to an impact load over a range of temperatures. The absorbed energy is then plotted against temperature, the results being represented in a typical curve.

The transition temperature is often defined in design specifications as the temperature that corresponds to an energy level of 15 ft-lb. However, the whole process of impact testing is somewhat arbitrary, as the Charpy V-notch test does not produce a definite value that can be directly included in design calculations. Rather, impact values are primarily used to facilitate material selection or verify contract specifications.

Charpy values indicate which of two grades of steel is the tougher, however, the values will not, of themselves, predict if the grade is adequate. The impact tests are done on small, standardized specimens, which do not correlate well to the much larger sections of a given engineered structure.

When the Charpy test was first introduced, most steels had a ferritic microstructure. Modern steels, being very clean and thus very ductile, may give extraordinary high energy absorption values. There are several other tests that were developed to gauge the material toughness. See CWB Modules 35 to 38 for detailed descriptions of testing set-up and procedures.

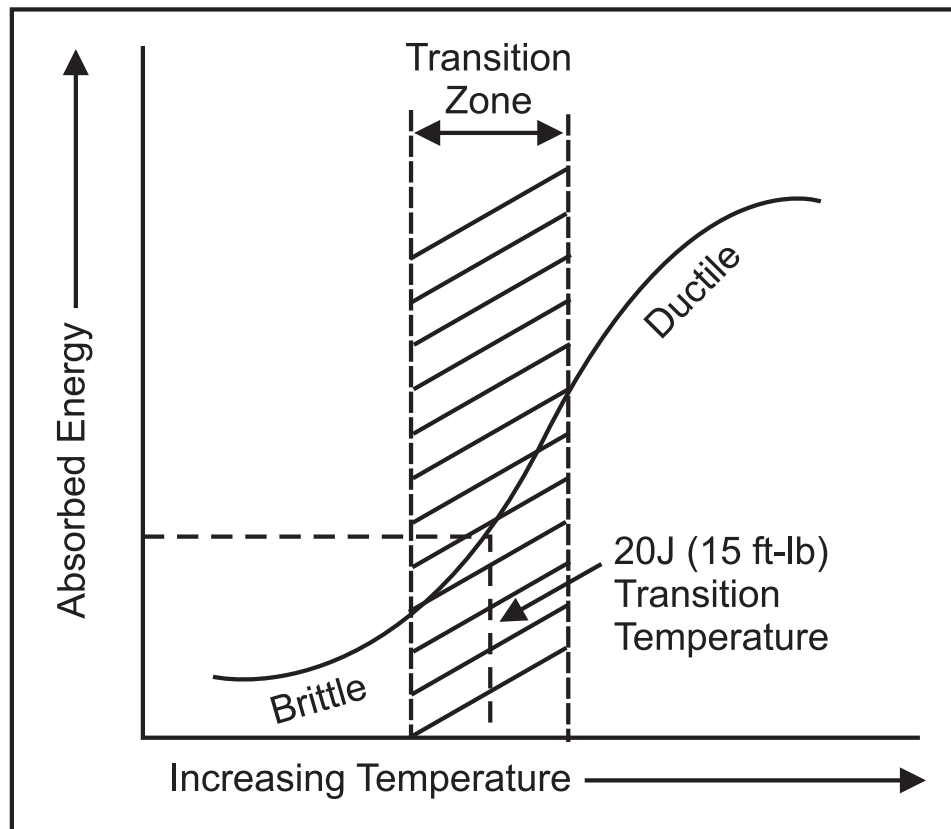


Figure 7.8: A given grade of steel will behave in a ductile manner if above its transition temperature, but becomes brittle if below this value.

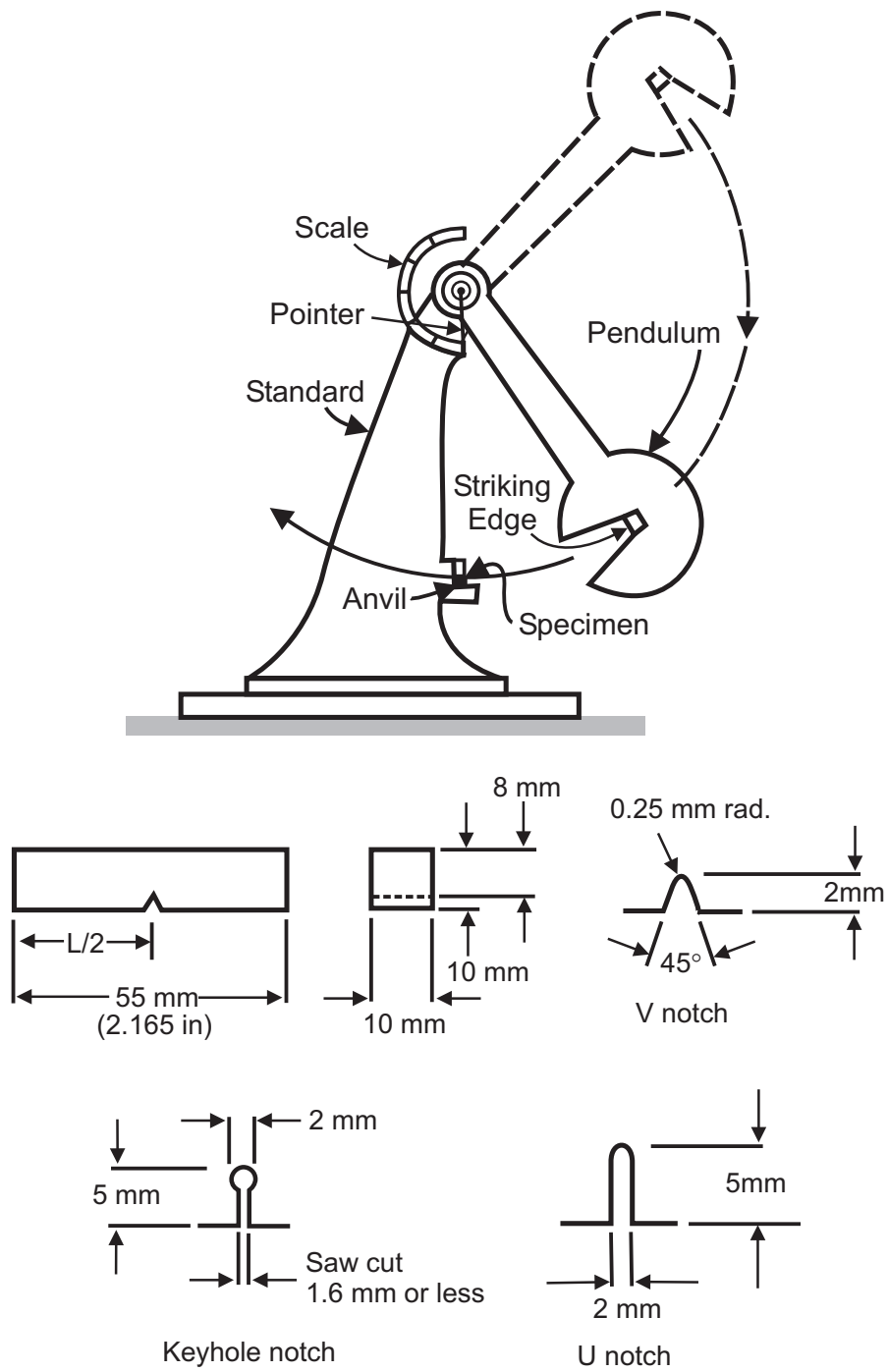


Figure 7.9: Charpy V-notch testing.

Where there is a history of past performance, the Charpy impact test can be used to establish a meaningful value for inclusion in the engineering specification. The first and somewhat classic example was the investigation into the large number of brittle fractures associated with welded ships during World War II (**Figure 7.10**).

Extensive research established that those vessels with Charpy values over 15 ft-lb at the normal operating temperature were almost totally free of brittle fractures.

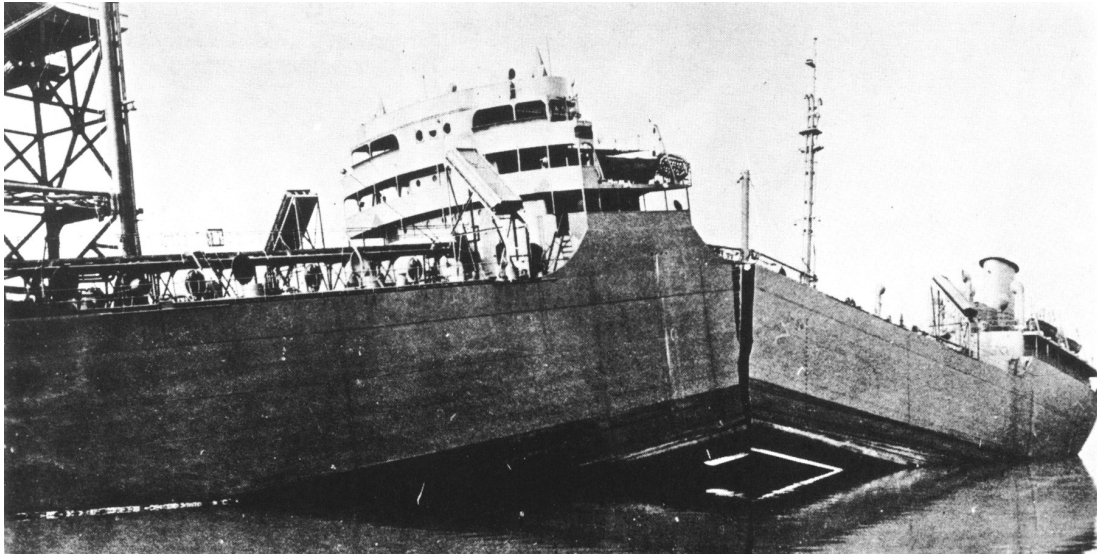


Figure 7.10: Fracture of Liberty ships during World War II.

7.7.1 Design Considerations

Let us look at the critical factors associated with brittle fracture. It is important to recognize that *no fracture can occur* unless the following *three* conditions exist simultaneously:

1. Temperature is below the transition point, indicating that the material is in a brittle state.
2. Presence of a notch or severe stress concentration, often a welding defect.
3. Presence of tensile stress. (The residual tensile stresses from welding are generally at the yield point.)

If a notch, or weld defect, is subject to a high tensile stress while the steel is in a brittle state, a running crack will propagate from the notch. Thus, the designer must assess the probability of these three factors occurring during operation. If the factors will likely occur, the structure should be designed with no obvious “stress raisers” and the material selection should be reviewed.

7.7.2 Material Selection

Special material considerations are not normally necessary, since only where there exists the likelihood that all three of the above-noted conditions will occur simultaneously will brittle fracture occur. A number of other factors should also be noted:

- ◆ A high rate of strain will have the effect of raising the transition temperature. This fact also points out one weakness of the Charpy test: the actual rate of strain imposed on the test specimen greatly exceeds what a structure can be expected to resist in practice.
- ◆ Thicker sections are more susceptible to brittle fracture (**Figure 7.11**), as plane strain rather than plane stress governs the fracture mechanism. Triaxial stresses have a similar effect (see Fracture Mechanics later in the Chapter).

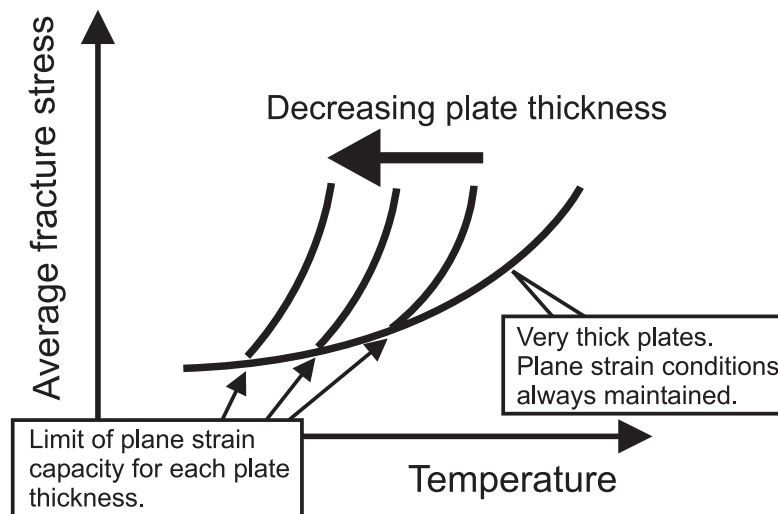


Figure 7.11: Material toughness decreases as the material thickness is increased.

- ◆ A material having a fine grain size is most beneficial (**Figure 7.12**): such grades are usually controlled rolled and fully killed (deoxidized). These two manufacturing features represent the only methods currently available that result in greater toughness without lowering the strength. Normalizing and cross rolling are also effective.

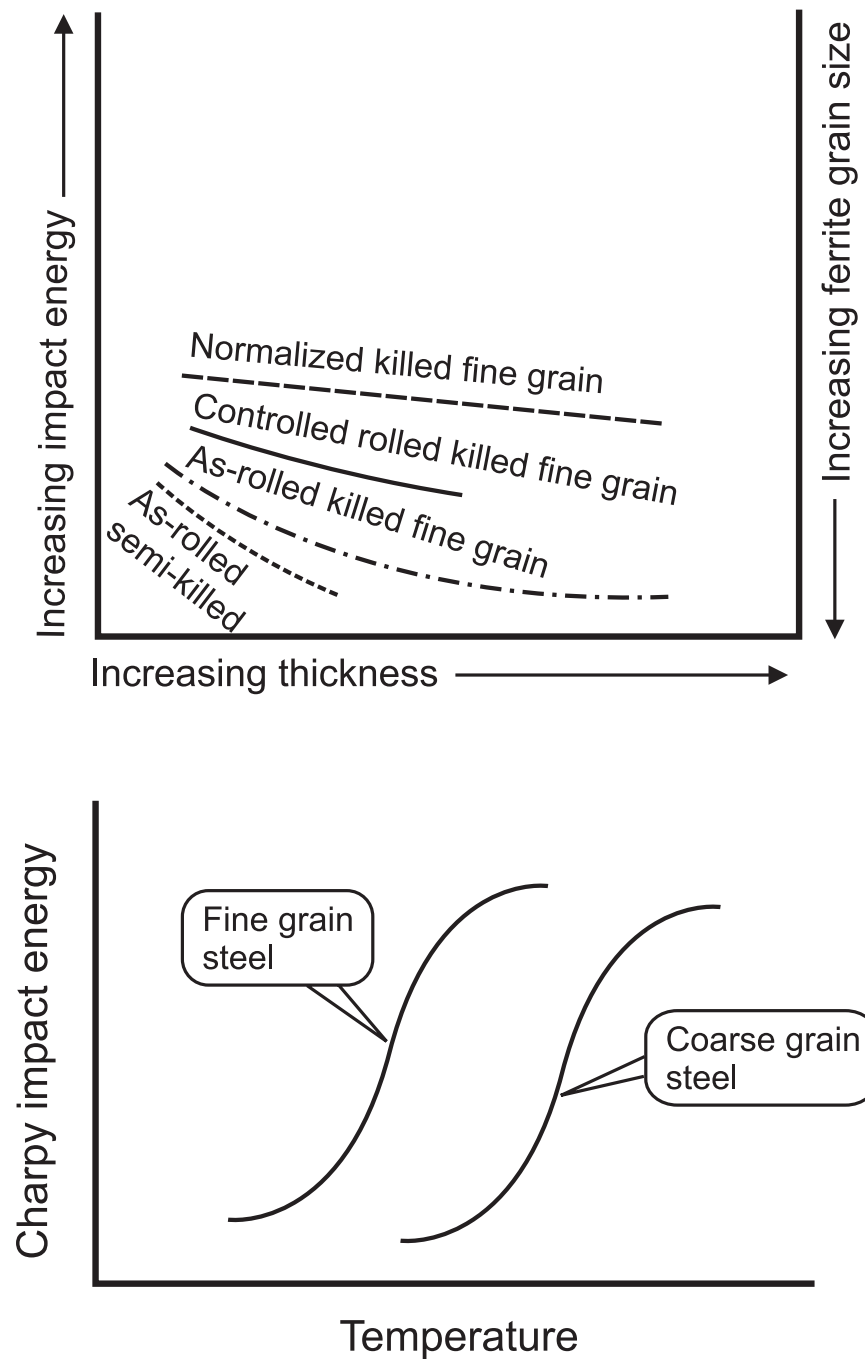


Figure 7.12: Modern steels (CSA G40.21 Series) that are fine grain and/or controlled rolled, and fully killed, offer excellent toughness.

7.7.3 CSA G40.21 Steels

General Structural steel should be ordered to the CSA G40.21 Specification. All grades ending in “WT” (44WT or 350WT) are weldable, with improved impact properties. The “WT” steels are available in five impact categories, one of which must be set by the customer. All grades are fine grained, fully killed.

(a) *Fine Grain Practice*

A *fine grain practice* simply means that elements such as aluminum or silicon have been added in sufficient quantity to raise the coarsening temperature. This results in a critical range that makes it easy to obtain a fine grain with controlled heating and/or controlled hot working. Since neither the austenitic grain size test nor an aluminum analysis is necessarily performed, the actual grain size or aluminum content is not certified or reported. Regular rolling practices apply.

(b) *Fine Grain Steel*

The term fine grain steel indicates that the steel has a carburized austenitic grain size of 5 or finer when subjected to the McQuaid-EHN test (ASTM Standard E112). If aluminum is used for grain size control, a product analysis showing a minimum of 0.010% acid soluble aluminum is acceptable as an alternative to a McQuaid-EHN test result. In this case, the controlled rolling practice is used, forcing recrystallization.

Thin plates may achieve a fine grain structure when only “semi-killed”, or partially deoxidized. Thick plates, being subject to plane strain, must be “fully killed”.

(c) *Static Strength*

The overwhelming tonnage of steel used is the common carbon or HSLA grades. Those specified under CSA G40.21 have three common features that make them particularly suited to structures:

- (1) Strength, yields of 44 and 50 ksi
- (2) Ductility, approximately 22% standard elongation
- (3) Good weldability

Structural steels are often locally stressed beyond the yield point; grades with good ductility (**Figure 7.1**) can readily redistribute the stresses and maintain equilibrium without fracture. Higher strength steels sacrifice ductility.

(d) *Weldability*

Weldability is used to describe the ease with which a steel may be joined by the arc welding process. A convenient approach in assessing weldability, and the effect of carbon and the alloying elements, is the “carbon equivalent (CE) formula”. This formula expresses the relative influence of the various elements in terms of carbon. **Table 7.1** shows the CE values for G40.21 steels. Note the rating index at the bottom.

Carbon Equivalent (CE) Values and Weldability Ratings ⁽¹⁾⁽²⁾⁽³⁾					
Standard	Grade	Thickness (mm)	CE Values		Weldability rating based on carbon equivalent values
			Mean	Max	
CAN3-G40.21M	230G	25	0.33	0.36	excellent
	260W	25	0.40	0.44	excellent to good
	300W	25	0.41	0.44	good
	350W	25	0.40	0.44	excellent to good
	400W	20	0.40	0.43	excellent to good
	480W	10	0.38	0.40	excellent
	260WT	25	0.39	0.43	excellent to good
	300WT	25	0.41	0.44	good
	350WT	25	0.43	0.46	good to fair
	400WT	20	0.39	0.42	excellent to good
	480WT	10	0.38	0.40	excellent
	350R	14	0.40	0.46	good to fair
	350A	25	0.44	0.50	good to fair
	400A	25	0.45	0.51	good to fair
	480A	19	0.48	0.54	fair to poor
	350AT	25	0.44	0.50	good to fair
	400AT	25	0.45	0.52	good to fair
	480AT	19	0.48	0.54	fair to poor
ASTM A283	A	25	0.19	0.23	excellent
	B	25	0.22	0.26	excellent
	C	25	0.29	0.33	excellent
	D	25	0.34	0.38	excellent
ASTM A36		25	0.31	0.35	excellent
ASTM A572	42	25	0.40	0.44	excellent to good
	50	25	0.40	0.44	excellent to good
	60	25	0.38	0.40	excellent
	65	12.7	0.40	0.44	excellent to good
ASTM A588	C	25	0.44	0.50	good to fair
ASTM A242	1	12.7	0.40	0.46	excellent to fair
	2	25	0.44	0.50	good to fair
ASTM A441		25	0.40	0.44	excellent to good
Stelco Wearwell		25	0.59	0.65	poor

(1) Carbon equivalent is calculated using the formula in CAN3-G40.21-M81:

$$CE = C + 1/6 Mn + 1/5 (Cr + Mo + V) - 1/15 (Ni + Cu)$$

Weldability rating: CE to 0.40 incl. - excellent
CE 0.41 to 0.45 incl. - good
CE 0.46 to 0.52 incl. - fair
CE over 0.52 - poor

(2) The mean and maximum carbon equivalent (CE) values were determined using the average and maximum chemistries normally applied by Stelco for plate in the thicknesses shown.

(3) Lower carbon equivalent values are normally applicable for light thicknesses while higher carbon equivalent values may be applicable for heavier thicknesses.

Table 7.1: Carbon equivalent (CE) values provide an index to weldability.

7.7.4 Stress Concentration

To illustrate the effect of stress concentration, suppose a plate contains a circular hole (**Figure 7.13**). The cross section area in the plane containing the hole is less than the gross section but must still carry the same load. Since no load can be transmitted across the hole, the stresses in some parts are therefore increased. It is sometimes useful to think of stress in terms of continuous lines of force within the material. In a reduced section the lines must bunch up, representing an increase in stress. The presence of the hole consequently produces a stress concentration, which for a round hole raises the stress by a factor of three. It does not matter how large the hole is, the stress concentration factor for a round hole is never larger than three.

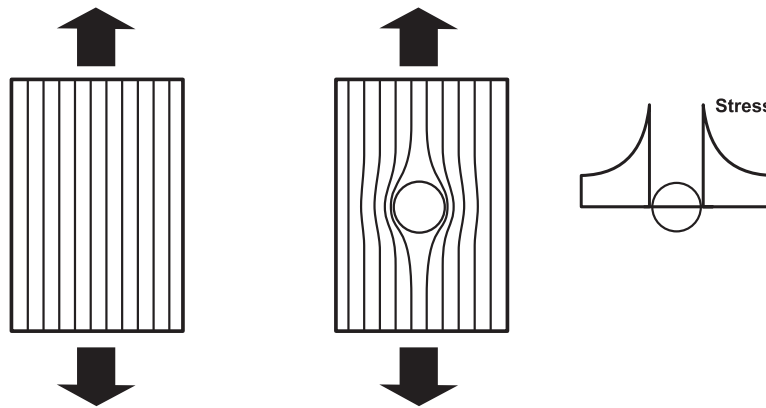


Figure 7.13: Stress concentration due to the presence of a round hole in the plate. In the vicinity of the hole the stress is raised by a factor of three, regardless of the diameter of the hole.

7.7.5 Net Section Yielding

As the load on the plate increases (illustrated in **Figure 7.14**) the material at the edge of the hole reaches the yield point and starts to yield while the average stress across the specimen is only one third of yield. With the load continuing to increase, the yielded region cannot support stresses higher than yield, so the load redistributes itself with higher stresses being supported in the elastic region away from the hole. The plastic yielded zone spreads across the specimen until the entire specimen has yielded. This is termed net section yielding.

If, instead of being elastic/perfectly plastic the material work hardens, stresses higher than yield could be supported in the yielded region. If, in addition, the hole is small, stresses in the net section will rise above the yield stress until yielding in the gross section occurs.

You can see from this example that, in a ductile material, general yield in the presence of a small hole occurs at a load equal to the general yield load of a plain specimen. The presence of small defects or stress concentrations has essentially no effect on the overall yield strength of a ductile material.

It is for this reason that a designer traditionally determines the load-carrying capacity of a member on the basis of *average* stresses across a section and does not take into account the effects of section changes, surface imperfections and other stress concentrations that affect the stress locally.

7.7.6 Effect on Brittle Fracture

Stress concentrations, however, have a significant effect on brittle fracture. We may illustrate this by considering the fracture of steel specimens at various temperatures. Steel is brittle at very low temperatures but is ductile at higher temperatures, so a specimen may be made to fracture in a certain manner simply by changing the test temperature.

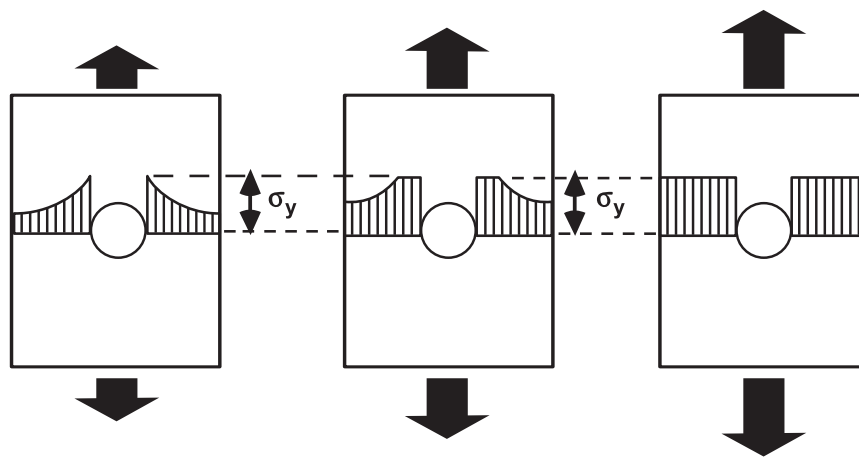


Figure 7.14: Yielding in a plate containing a round hole. Yielding starts first at the edge of the hole, then spreads out. A small amount of yielding at the edge of the hole does not affect the overall linear behaviour of the specimen. Eventually the net section yields.

7.7.7 Effect of Temperature

Let us consider the behaviour of a smooth steel specimen subject to tension tests over a range of temperatures. At room temperature the specimen shows considerable plastic deformation after passing the yield stress, finally reaching the ultimate tensile strength (UTS) before necking down and breaking. As the temperature is lowered, this behaviour is retained, except that the yield and ultimate strengths increase. **Figure 7.15** illustrates this behaviour.

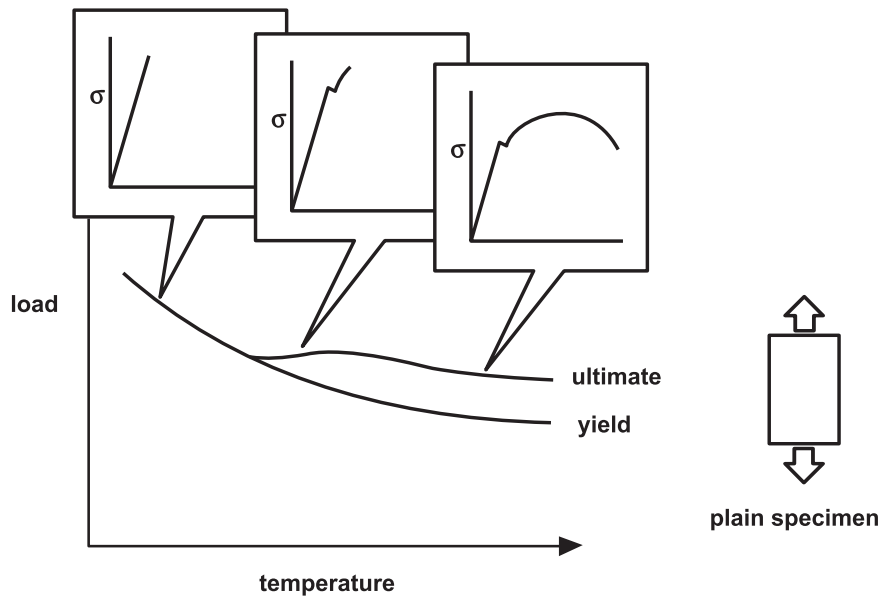


Figure 7.15: Behaviour of plain specimens of steel tested in tension over a range of temperature.

7.7.8 Plain Specimen

At a sufficiently low temperature the behaviour changes. Failure now occurs with little plastic deformation, and at very low temperatures fracture occurs as soon as the yield stress is reached. Note that with a smooth, defect-free specimen fracture does not occur below the yield stress even at very low temperatures. This has been verified by measuring the yield stress in compression. It is the same as the fracture stress in tension at very low temperatures. We may conclude from this that at least *some* plastic deformation is required even for a completely brittle fracture.

7.7.9 Notched Specimen

Now imagine the same tests on specimens containing a small notch. At room temperature there is very little difference in behaviour. As we have seen, the load at yield is about the same as for the smooth specimen, and there is substantial deformation before failure. At lower temperatures, however, the behaviour is markedly different. Fracture now occurs at an average stress well below the yield strength of the material (**Figure 7.16**). The reason, is of course, that the notch provides a stress-concentrating effect, raising the stress at the tip of the notch beyond the yield stress, while the average stress is still well below the yield. The specimen fails by fracturing from the notch.

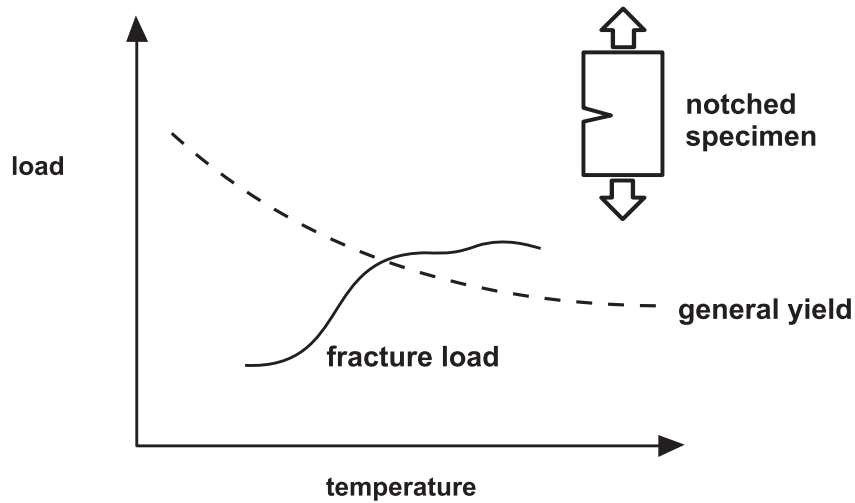


Figure 7.16: Notched steel specimen shows a transition in fracture load with decreasing temperature. Above the transition range the specimen behaves in a similar manner to a plain specimen, showing similar strength. Below the transition the fracture load is well below the general yield load.

When the tests are conducted on specimens containing sharp cracks rather than notches, the fracture stresses at low temperatures are further reduced while behaviour at higher temperatures does not change very much (**Figure 7.17**).

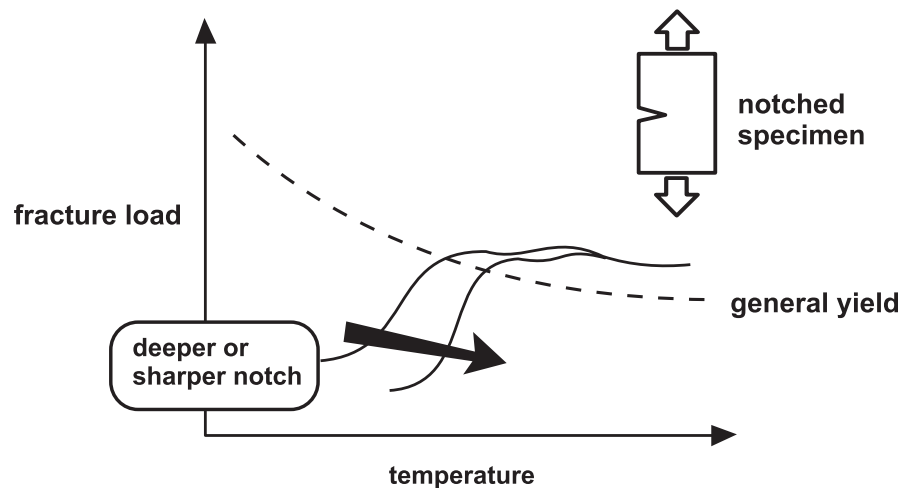


Figure 7.17: Increasing the sharpness or size of the notch lowers the fracture stress at low temperatures but has little effect at high temperatures.

The three important conclusions from these observations are:

- ◆ for brittle fractures to occur at average stresses less than yield, defects (stress concentrations) must be present
- ◆ the yield strength is not very sensitive to the presence of defects when the material is ductile
- ◆ the fracture stress is very sensitive to the size and sharpness of defects when the material is brittle

7.7.10 Transition Behaviour

Let us explore more fully the transition in fracture of steel with changing temperature. In **Figure 7.18** we consider the fracture stress and the yield stress independently, but both as functions of temperature. We see that at high temperatures the yield stress is reached before the fracture stress, and the specimen deforms plastically. In effect, yielding intervenes to prevent fracture. At low temperatures the fracture stress is reached before general yield takes place, the specimen failing by fracture without much deformation. We can conclude that the temperature dependence of the yield stress in steel is a basic cause of transition behaviour.

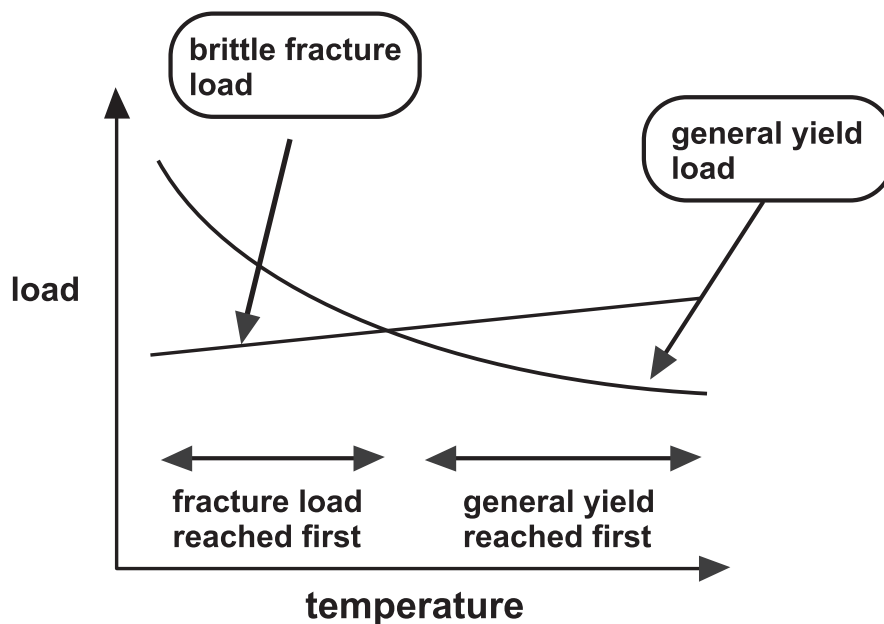


Figure 7.18: Fracture transition behaviour in steel. At low temperatures the brittle fracture load is reached before general yielding occurs. At high temperatures yielding occurs first.

Anything that raises the effective yield stress, without similarly raising the fracture stress, results in an increase in the transition temperature (**Figure 7.19**) Yield stress can be raised in many ways. As we have seen, a deep notch in thick material raises the effective yield stress because yielding is constrained by the triaxial stress state.

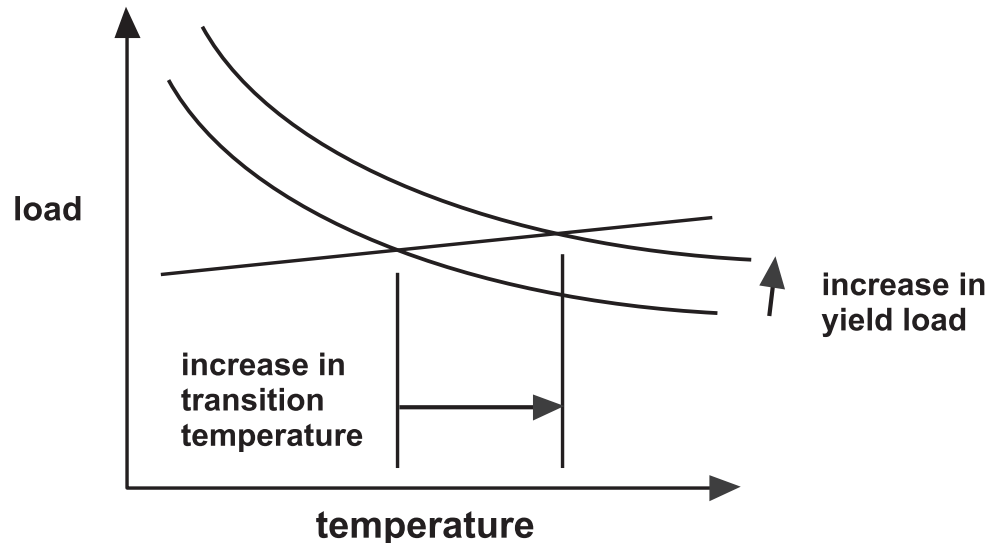


Figure 7.19: Factors that increase the yield stress have the effect of increasing the transition temperature.

7.8 Effect of Strain Rate

A second factor that raises the yield strength, particularly in low- and medium-strength steels, is the strain rate. High strain rates experienced, for example during impact loading, increase the yield stress and cause a corresponding shift in the transition temperature. In fact, one reason for performing the Charpy test under impact loading is to artificially raise the temperature to reveal brittle behaviour.

Figure 7.20 shows the effect of strain on yield stress for a typical mild steel, and **Figure 7.21** shows the approximate shift in transition temperature of a structural steel that follows from this effect. The effect of strain rate diminishes as the strength of the steel gets higher, virtually disappearing for steels of more than 1000 MPa (150 ksi) yield strength. The shift in transition temperature, therefore, decreases roughly linearly with yield strength (**Figure 7.22**).

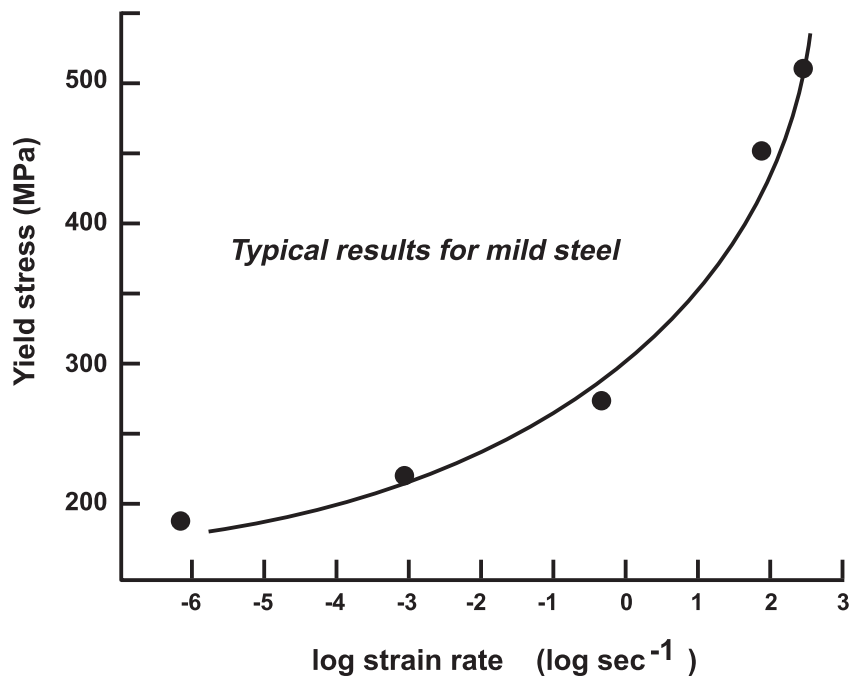
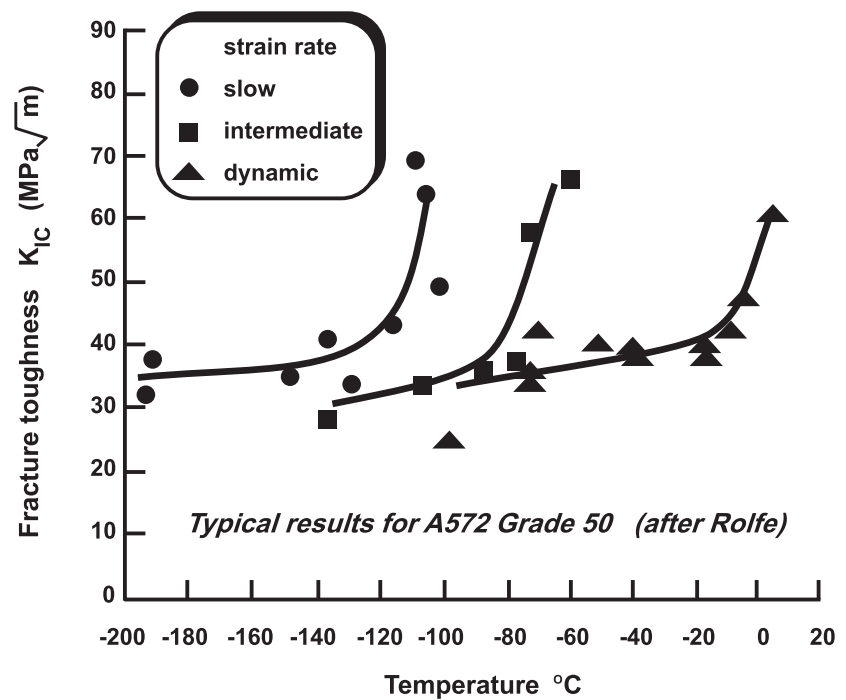


Figure 7.20: Effect of strain rate on the yield stress for a typical mild steel.

Figure 7.21: Effect of temperature on the fracture toughness of a structural steel. Note the increase in the transition temperature with increasing strain rate.



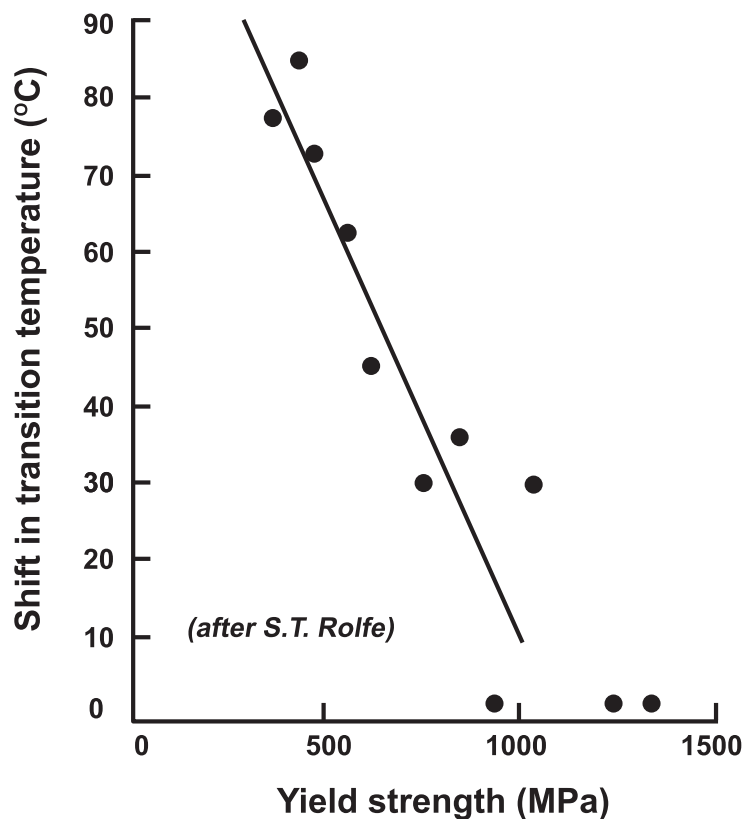


Figure 7.22: The shift in transition temperature on increasing the strain rate from slow to fast (impact) progressively decreases with an increase in steel strength. For steels with a strength greater than about 1000 MPa (150 ksi) there is no effect of strain rate on fracture behaviour.

7.9 Fracture Mechanics

Fracture mechanics is the science of fracture behaviour quantitatively in relation between applied loads and crack sizes, and defines the toughness of materials against brittle cracking. **Figure 7.23** shows the possible modes of crack tip deformation. In this chapter, we concentrate our attention on Mode I, which is the most relevant to our interest.

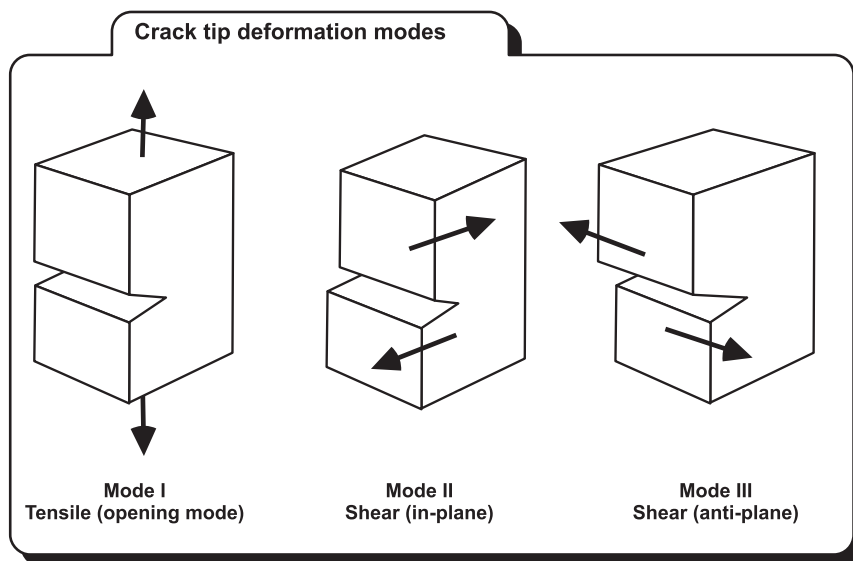


Figure 7.23: Crack tip deformation modes.

7.10 Stress State of Crack Tips

Figure 7.24 illustrates the different behaviours of thin and thick plates with cracks. It explains the physical meaning of plain strain and plain stress.

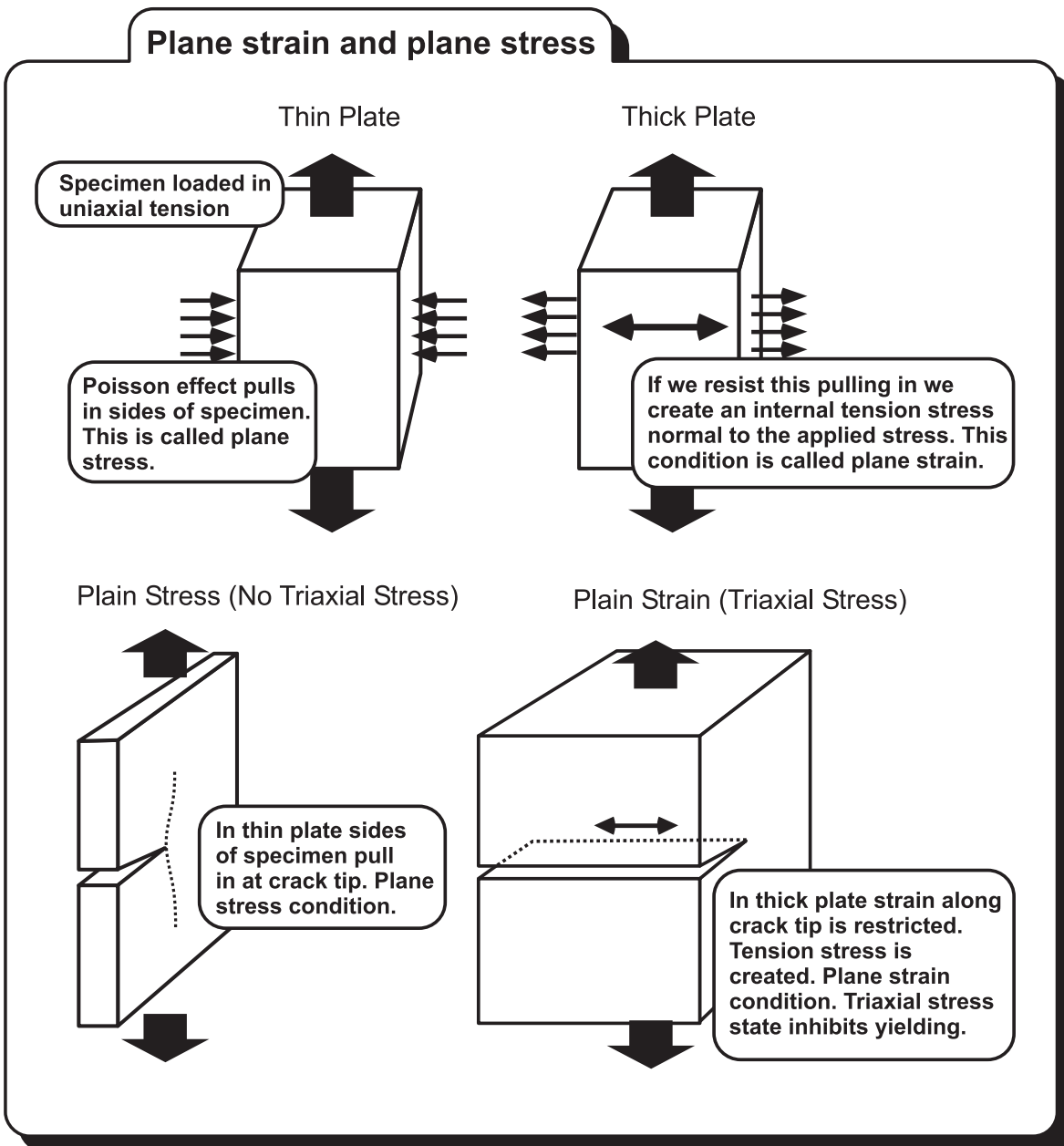


Figure 7.24: Plain strain and plain stress.

Figure 7.25 shows the different stress states of crack tips of thin and thick steel plates. In thin plates, the Z-direction restraint is negligible and therefore no stress is induced. The stress is two dimensional (plain stress). In thick plates, high restraint in the Z-direction prevents contraction (plain strain, Poisson's effect) from taking place and consequently tensile stress is induced in that direction. **Figure 7.25 (b)** illustrates the triaxial stress state at the tip of the thick plate.

The stress in the Y-direction, σ_y , near the crack tip is very high because of the stress concentration effect due to shape change in the cross section. The stress in the X-direction, σ_x , is zero at the crack surface and rises to a maximum and then drops flat at that distance away from the crack tip. The stress in the Z-direction is, obviously, zero on the plate surface. The stress curve of σ_z is shown at the centre of the plate thickness. The biaxial stress state near the crack tip is shown in the thin plate and the triaxial stress state is shown in the thicker plate. This explains why fractures occur even when the average stress is low. Also, the brittle cleavage fracture occurs because the triaxial stress state prevents fracture in shear.

It should be noted that in the triaxial stress state, yielding in the Y-direction is inhibited and σ_y continues to rise. The maximum σ_y may reach three times the uniaxial yielding stress.

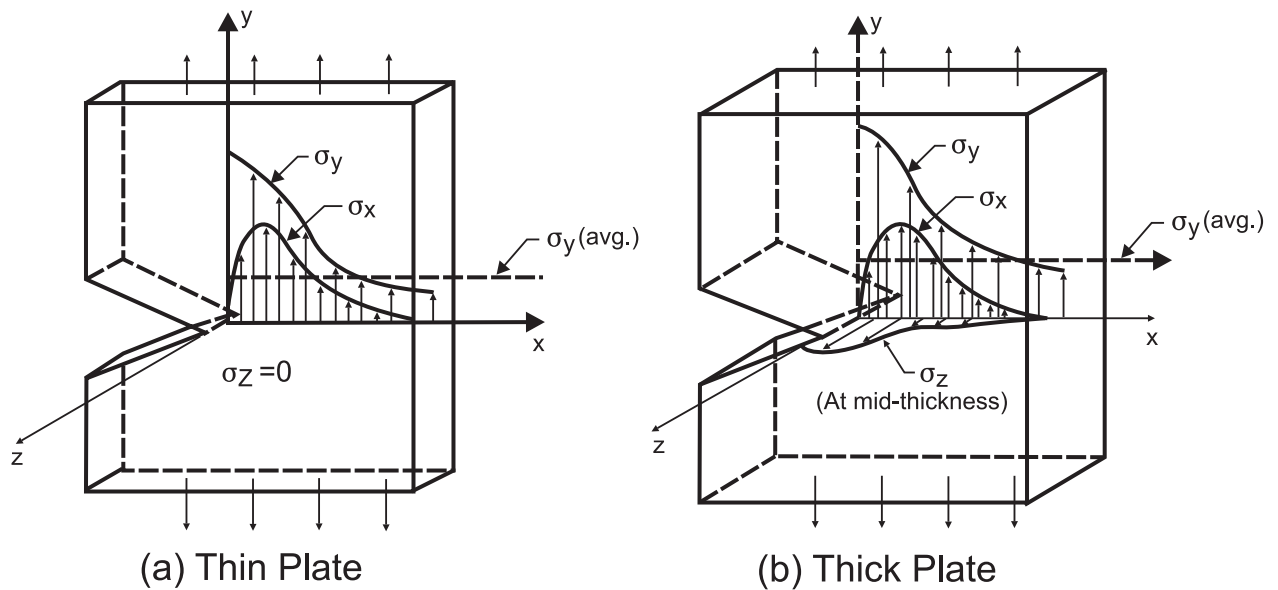


Figure 7.25: State of stress at the root of a notch under uniaxial load.

7.11 Stress Intensity Factor

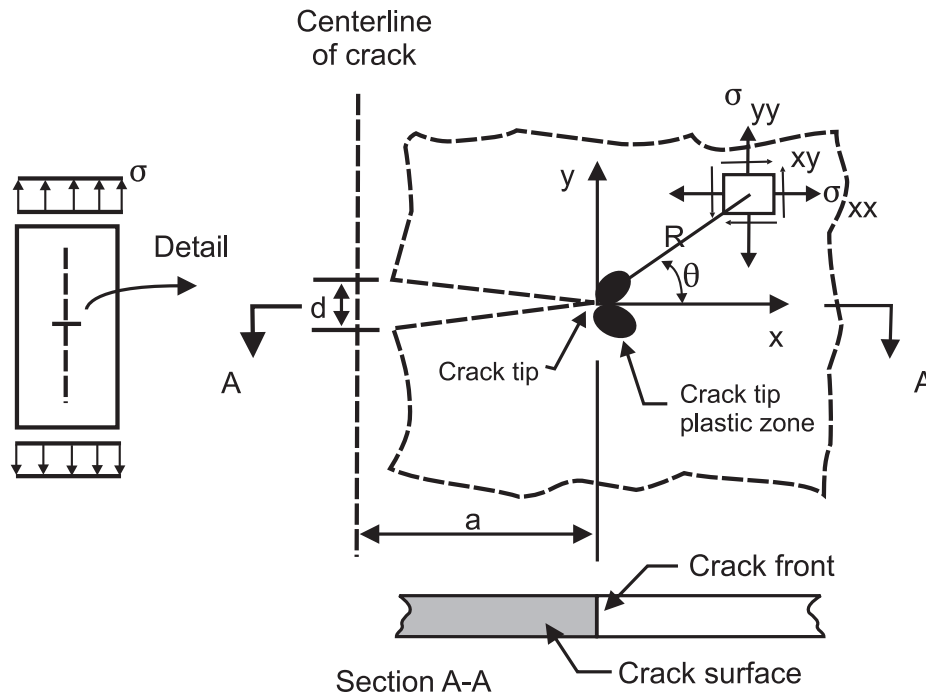


Figure 7.26: A crack in an infinitely wide plate.

The stress equation using polar coordinates with $\theta=0$ (see **Figure 7.26**) is:

$$\sigma_{yy} = \frac{\sigma \sqrt{\pi a}}{\sqrt{2\pi r}} = \frac{K_I}{\sqrt{2\pi r}}$$

K_I is called the stress intensity factor, which determines the stress gradient near the crack tip. For practical application, K_I is expressed in the following equation for tensile loading:

$$K_I^2 = Q \sigma^2 \pi a$$

Q - Shape Factor

crack through an infinite plate

$$Q = 1$$

internal circular crack

$$Q = 4 / \pi^2$$

internal elliptical crack

$$Q = 1 / \phi^2$$

long surface crack (shallow)

$$Q = 1.2$$

elliptical surface crack

$$Q = 1.2 / \phi^2$$

$$\phi = \int_0^{\pi} \left[1 - \left(\frac{b^2 - a^2}{b^2} \right) \sin^2 \theta \right]^{1/2} d\theta$$

where θ is the angular coordinate

a = crack radius for circular cracks

a = semi-minor axis for elliptical cracks

b = semi-major axis

K_I is affected by the same factors that effect fractures, such as:

- ◆ service temperature
- ◆ loading rate
- ◆ component thickness and geometry
- ◆ fabrication and material composition

The stress equation is often expressed in the following form:

$$K_I = \sigma \sqrt{2\pi a}$$

and the unit of K_I is $\text{MPa} \sqrt{m}$, (m is metre in metric units), and $\text{kip} \sqrt{\text{in}}$ in imperial units. So, when “ a ” is expressed in millimetres it must be divided by 1000 to convert it to metres. Also note that “ a ” is half the length of internal through-cracks, and is the crack length for edge cracks. For surface cracks other correction factors are used to convert “ a ” to equivalent through-crack lengths. See **Figure 7.27**.

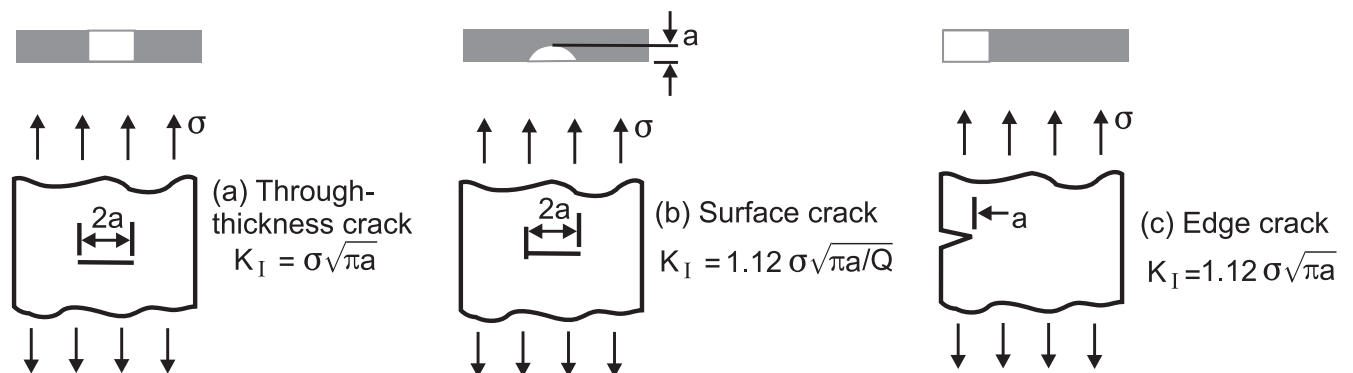


Figure 7.27: K_I values for various crack geometries (infinitely wide plates).

The above equation shows that there is a critical crack size (or flaw size) for each nominal stress (σ). When $\sigma\sqrt{Q\pi a}$ exceeds the K_I of the member, crack size will grow.

It should be noted that the general equation is only applicable to certain crack sizes with negligible plasticity at the crack tip. See CWB Modules 35 and 36 for practical examples.

7.12 Fatigue and Fatigue Cracks

As mentioned in the introduction, fatigue is caused under fluctuating loads. For fatigue cracks to happen, there are usually locations with stress concentrations or intrinsic flaws. Fatigue crack growth originating from welded details are observed in structures and laboratory experiments. Fracture mechanics is applied to account for the behaviour of cracks in structural components.

Figure 7.28 shows that the fatigue crack surface is striated, corresponding to loading cycles. Fatigue cracks originate from an initiation point that can be clearly seen in **Figure 7.29**. The initiating point can be internal (internal flaw) or external.

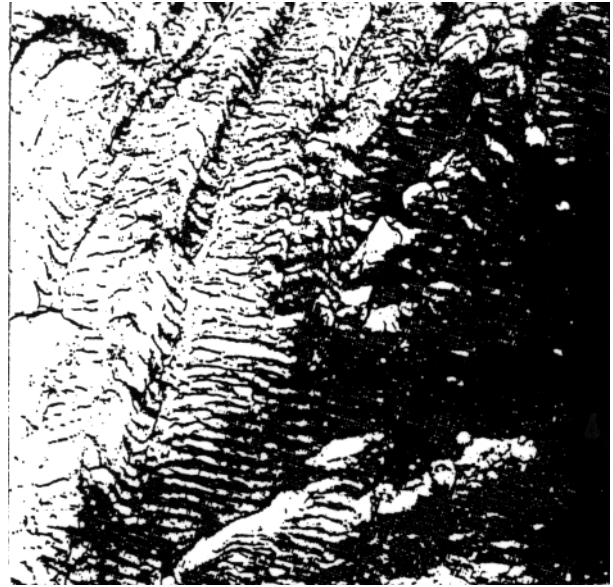
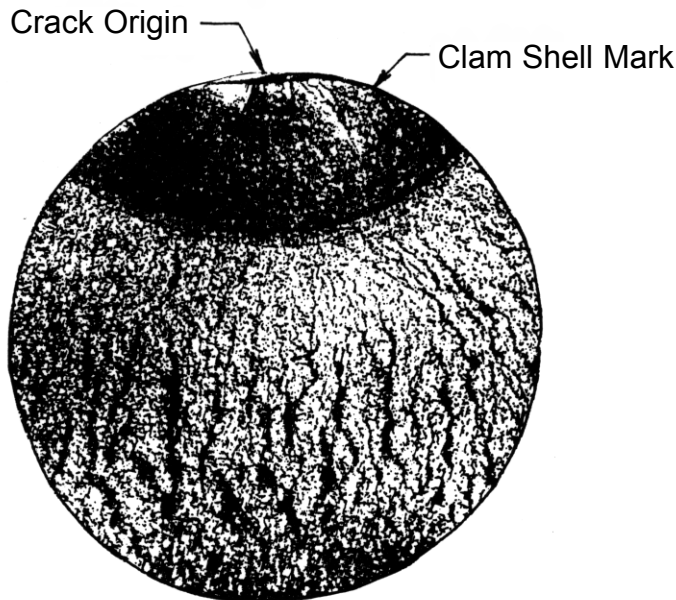


Figure 7.28: Microscopic fatigue striations electron microscopy. (6500X)



The crack growth always shows clam-shell markings, which indicates the initiating point. As the crack grows or propagates the net section area is gradually reduced, and finally fractures when it cannot support the internal stress.

Striation changes directions at grain boundaries to suit crystalline orientation.

Figure 7.29: Microscopic view of fatigue fracture surface.

7.12.1 Stress Range Categories and S/N Criteria

Through numerous experiments and observations it is found that the stress range is the most dominant factor affecting the fatigue life of a component. The stress range is defined as the algebraic difference between maximum and minimum nominal stresses as shown in **Figure 7.30**. From **Figure 7.30** it can be seen that under static loading the stress range is zero. Stress range should not be confused with maximum stress. **Figure 7.31** shows the same stress range but with different $S_{\max}$ and $S_{\min}$.

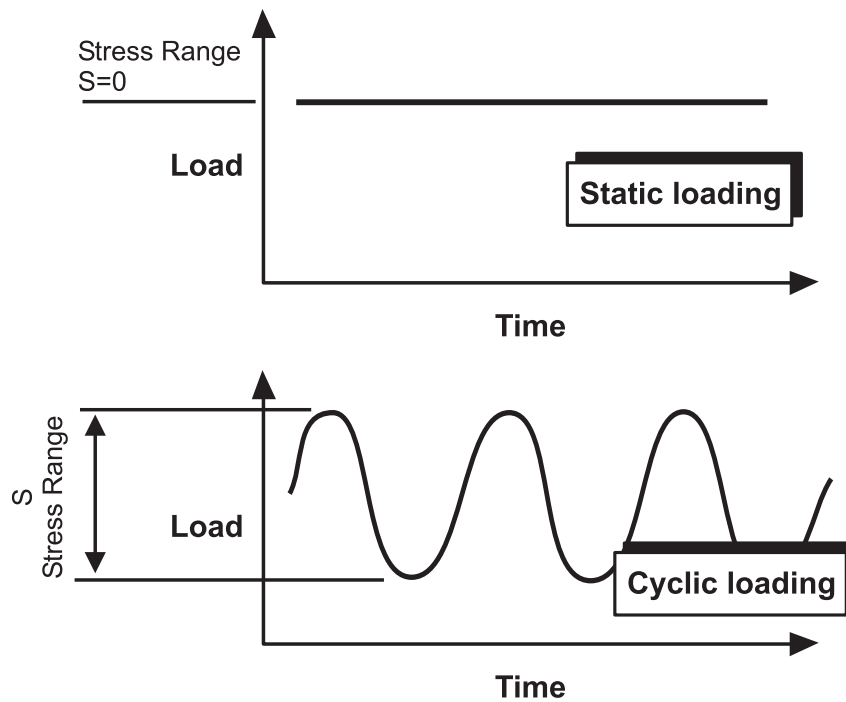


Figure 7.30: Stress range.

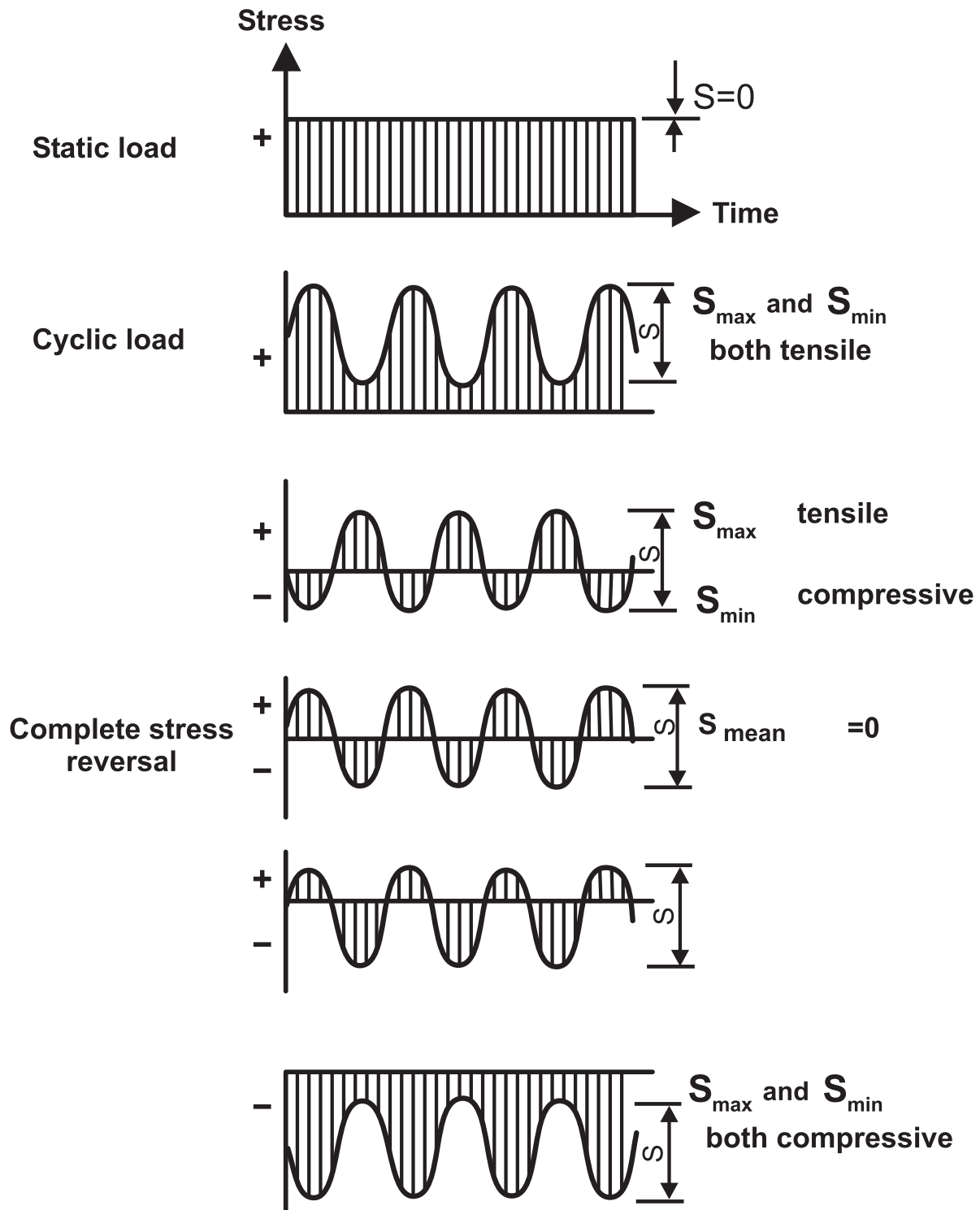


Figure 7.31: These stress ranges, while looking different, are equal.

The relationship between stress range (S) and number of loading cycles (N) can be used as an indicator of fatigue characteristics of a member or a welded joint. **Figure 7.32** shows the S/N curves plotted to log-log scale. It covers the variables of stress range, number of cycles and design categories. The stress range of the horizontal portion of each curve represents the endurance limit of that category. It means that if the component is in or under that stress range, no fatigue will occur.

Figure 7.33 illustrates a butt joint and a fillet weld Tee-joint. Under the same stress range the fatigue life (N_f) of the CJPG butt joint is much longer than the fillet Tee-joint (N).

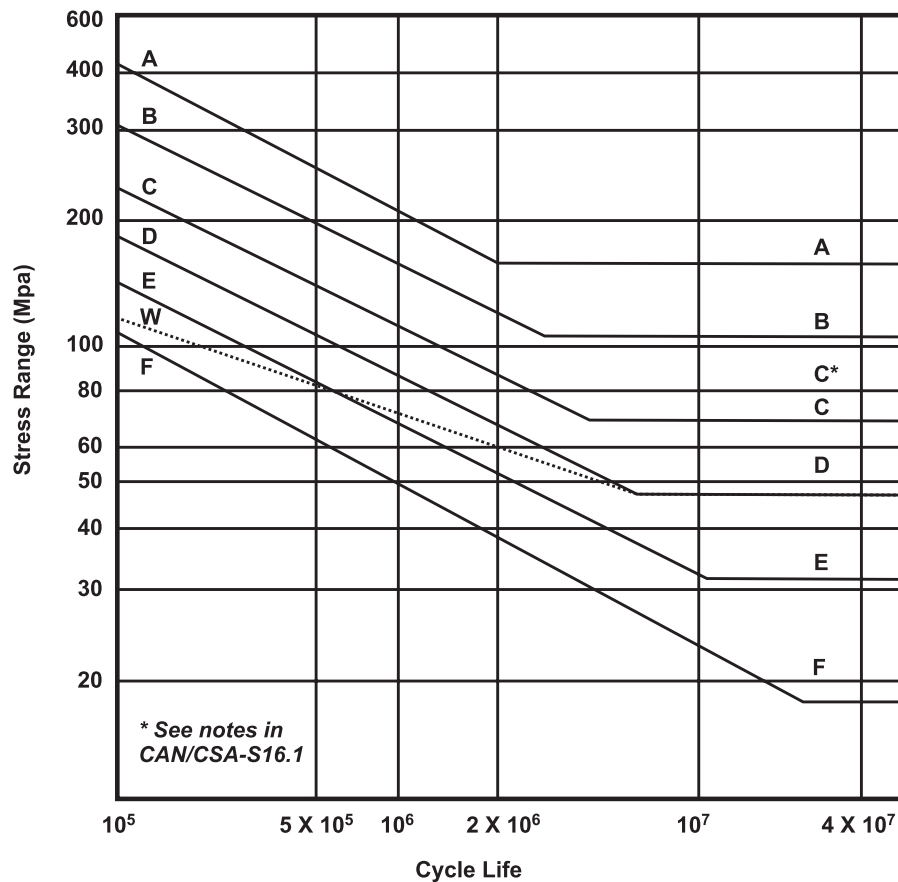


Figure 7.32: CSA W59 and S16-01 base fatigue life calculations on S-N Diagrams.
Laboratory data is plotted to log-log scale.
Stress range, number of cycles, and design category make up the variables.

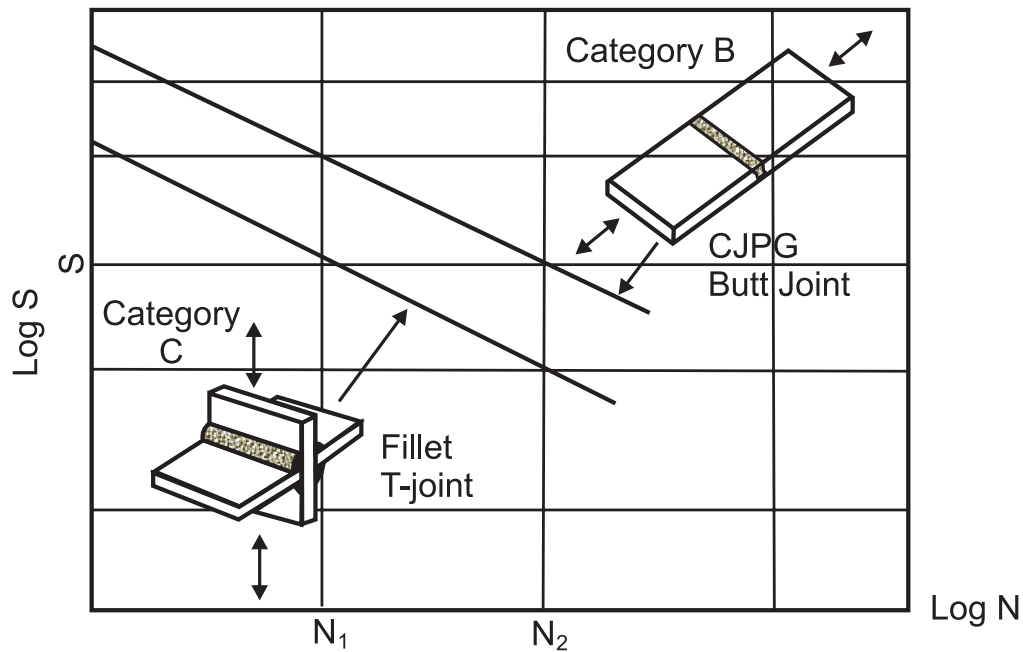


Figure 7.33: Different welded connections produce different stress concentrations, and thus have different fatigue life profiles.

The stress range of each category is given in **Table 7.2** (Table 12-4 of CSA W59) for different fatigue lives (N). For detailed illustrations of stress range categories, see **Table 7.3** (Table 12-4 of CSA W59).

Category	Allowable Range of Stress, F (MPa)			
	For 100,000 Cycles	For 500,000 Cycles	For 2,000,000 Cycles	Over 2,000,000 Cycles
A	120	95	75	65
B	110	85	65	50
C	97	70	52	40
D	76	50	35	25
E	55	35	25	15
F	40	27	20	12
W	40	27	20	12

Table 7.2 CSA W59 provides design values for various categories.

General Condition	Situation		Kind of Stress	Stress Range Category (See Table 12-3)	Illustrative Example (See Figure 12-1)
	S-No.	Description			
Plain Material	S1	Base metal with rolled or cleaned surfaces. Flame-cut edges with a surface roughness not exceeding 1000 as defined by CSA Standard B95, Surface Texture (Roughness, Waviness and Lay).	Tension or Reversal	A	1,2
Built-Up Members	S2	Base metal and weld metal in members without attachments, built-up of plates of shapes connected by continuous complete or partial penetration groove welds or by continuous fillet welds parallel to the direction of applied stress.		B	3,4,5
	S3	Base metal and weld metal along the length of horizontal stiffeners and cover plates connected by continuous complete or partial penetration groove welds or by continuous fillet welds parallel to the direction of applied stress.		B	7
	S4	Base metal at toe of transverse stiffener welds on girder webs or flanges subjected to calculated flexural stress.		C	6
	S5	Base metal at end of longitudinal stiffeners.		E	7
	S6	Base metal at end of partial length welded cover plates narrower than the flange, having square or tapered ends, with or without welds across the ends. Flange thickness $\leq \frac{3}{4}$ inch Flange thickness $> \frac{3}{4}$ inch		E F	7
	S7	Base metal at end of partial length cover plates wider than the flange having square ends with welds across the ends. Flange thickness $\leq \frac{3}{4}$ inch Flange thickness $> \frac{3}{4}$ inch		E F	7

Table 7.3: Stress range categories for various applications.

General Condition	Situation		Kind of Stress	Stress Range Category (See Table 12-3)	Illustrative Example (See Figure 12-1)
	S-No.	Description			
Complete Joint Penetration Grooves	S8*	Base metal and weld metal at complete penetration groove welded splices of rolled and welded sections having similar profiles when welds are ground flush and weld soundness is established by nondestructive examination.	Tension or Reversal	B	8,9
	S9*	Base metal and weld metal in or adjacent to complete penetration groove welded splices at transitions in width or thickness, with welds ground to provide slopes no steeper than 1 in 2 ½ with grinding in the direction of applied stress, and weld soundness established by nondestructive examination. A 24 inch curved radius transition shall be used for G40.21-100Q and 100QT steel.		B	10,11
	S10*	Base metal and weld metal in or adjacent to complete penetration groove welded splices, involving equal widths and/or thicknesses of material or involving transitions having slopes no greater than 1 in 2 ½ when in either case reinforcement is not removed and when weld soundness is established by non-destructive examination.		C	8,9,10,11
	S11	For base metal at details attached to flanges or webs by groove welds subjected to transverse or longitudinal loading – regardless of detail length except for condition as covered by Note (1) in tabulation for Example 12 – the stress range categories shall be as shown in Figure 12-1 in the tabulation for the same Example. Besides being dependent on transition radius the stress range categories, in the case of flange connections subject to transverse loading, are also a function of relative thickness of material and whether or not groove weld reinforcement is removed.		See Tabulation in Example 12, Figure 12-1	12

* Either RT or UT to meet the quality requirements of Clause 12.5.4.4 applicable to welds subject to tensile loads.

Table 7.3 Continued

General Condition	Situation		Kind of Stress	Stress Range Category (See Table 12-3)	Illustrative Example (See Figure 12-1)
	S-No.	Description			
Fillet Welded Connections	S12	Base metal at intermittent fillet welds	Tension or Reversal	E	
	S13	Base metal adjacent to fillet welded attachments where the length L of the attachment in the direction of stress is less than 2 inches and stud-type shear connectors.		C	6,13,14,15
	S14	Base metal at details attached by fillet welds subject to longitudinal loading only when the detail length, L, in direction of stress is between 2 inches and 12 times the plate thickness, but less than 4 inches, and the transition radius R is less than 2 inches.		D	14
	S15	For base metal at details attached to webs by fillet welds subjected to transverse and/or longitudinal loading – regardless of detail length – the stress range categories shall be as shown in Figure 12-1 in the tabulation for the same Example. Shear stress on the throat of fillet welds shall be governed by stress range category “W”.		See Tabulation in Example 12, Figure 12-1.	12
	S16	Except for cover plates (S6, S7) and details attached to webs (S15) base metal at end of details 4 inch or longer attached by fillet welds where the length of weld is in the direction of stress.		E	16
Fillet Welds	S17	Shear stress on throat of fillet welds.	Shear	W	16
Stud-Type Shear Connectors	S18	Shear stress on the nominal area of stud shear connectors.		W	13

Table 7.3 Concluded

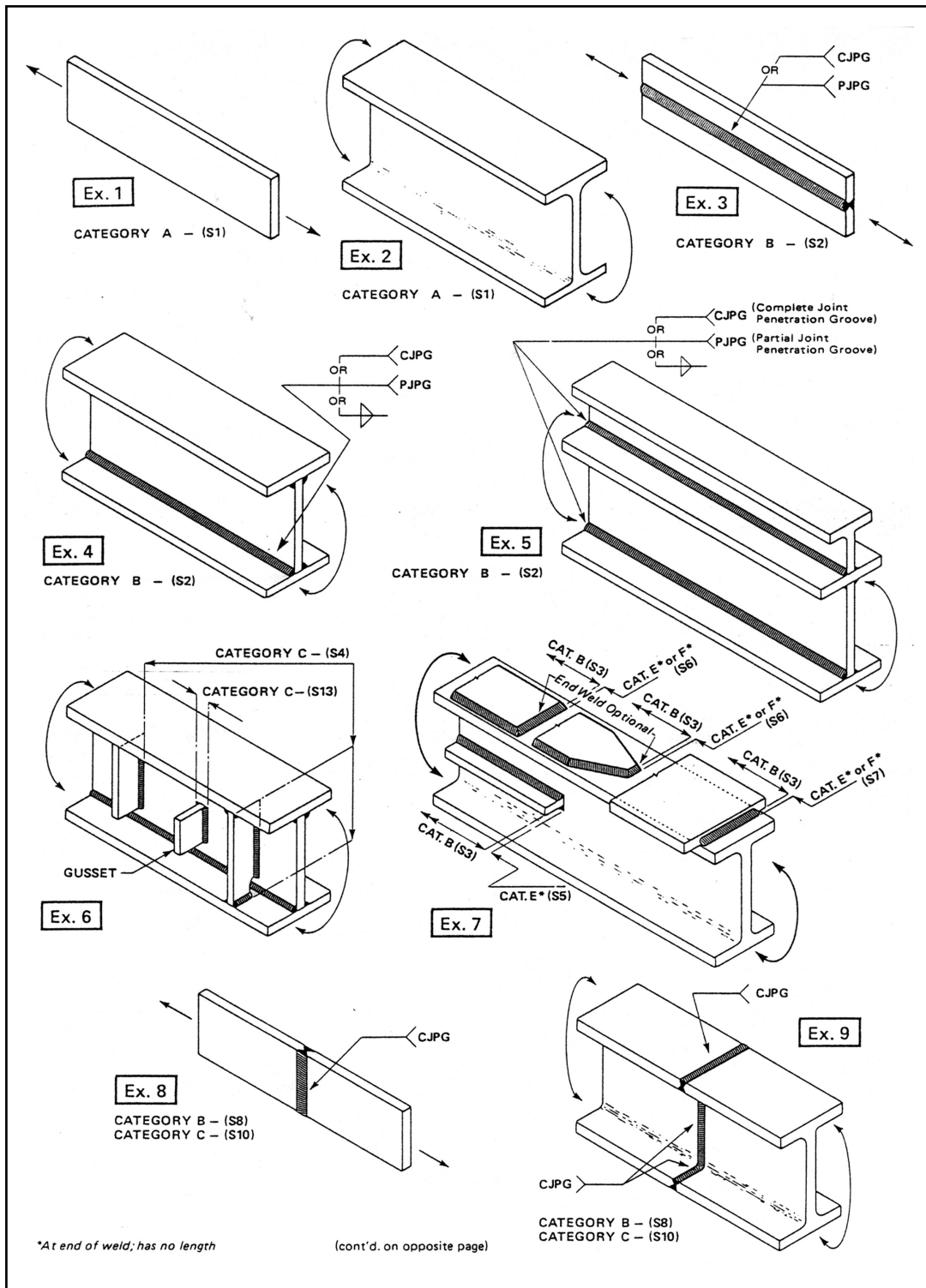


Figure 7.34: Illustrative examples of various details representing stress range categories. (CSA W59)

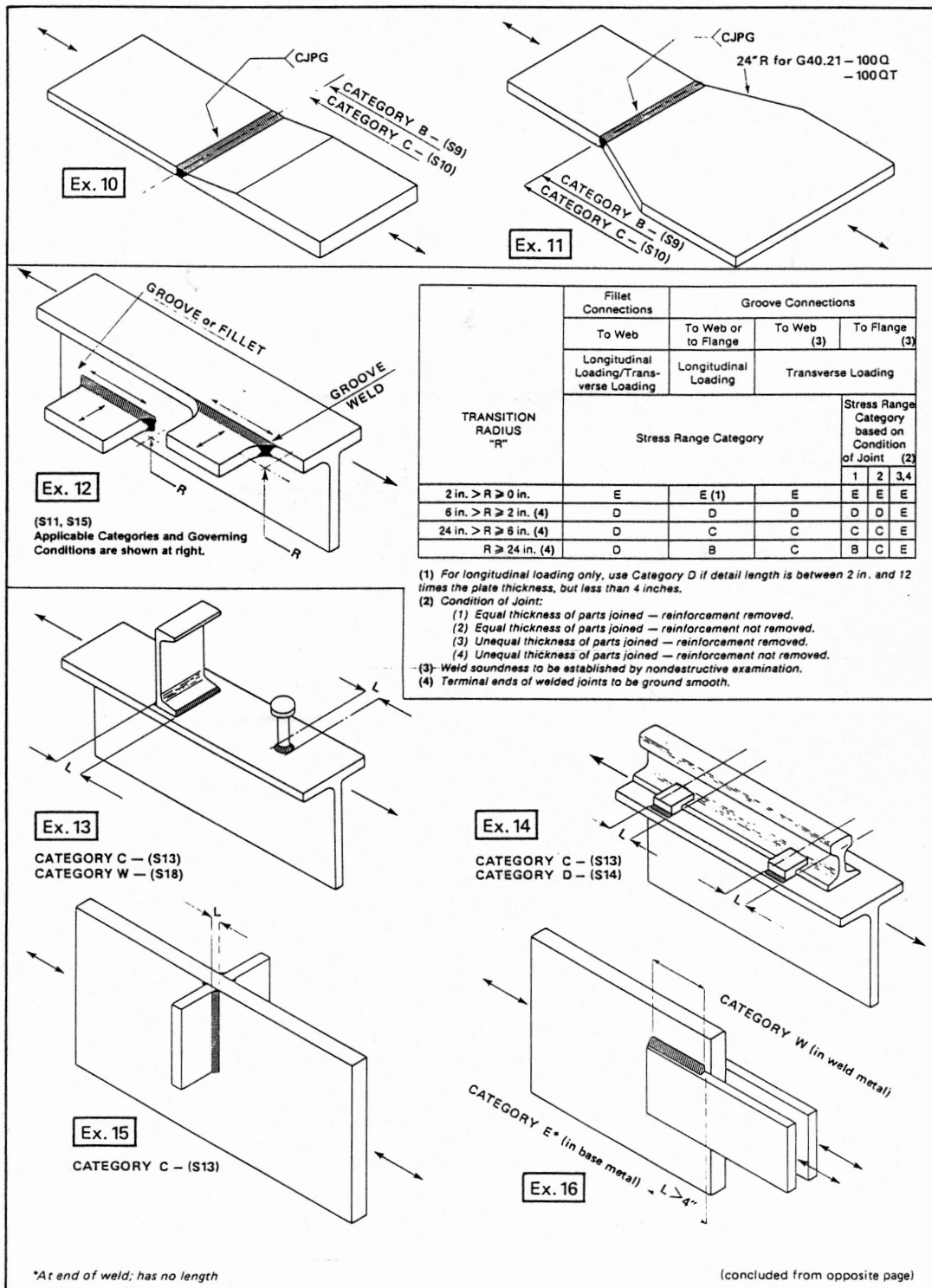


Figure 7.34: Continued
(CSA W59)

The log-log plot of the S/N data is a straight line, and can be represented by a simple formula. The general form is given by:

$$N = C/S^m$$

Where,

N = number of load cycles

S = stress range

C = constant (different for each stress range category)

m = slope of S/N line

Thus, accurate calculations are now possible; instead of trying to pick off values from a small log-log graph or using Table 12-3 of CSA W59 where values between 500,000 cycles and 2,000,000 cycles are not listed.

The constants for the basic equation are tabulated below; a sample calculation follows.

Table 7.4

Fatigue Category	Equation (10^8) Constant, C	Slope m
A	651	3.27
B	254	3.27
C	101	3.33
D	20.8	3.02
E	12.7	3.10

Thus, for Category C, at N = 2,000,000 cycles, one can find the permissible stress range.

$$N = C/S^m$$

$$2 \times 10^6 = 101 \times 10^8 / S^{3.33}$$

$$S^{3.33} = 50.5 \times 10^2$$

$$S = 12.95 \text{ ksi (compare with Table 12-3: } S = 13 \text{ ksi)}$$

The equation can be rearranged:

$$N_1/N_2 = (S_2/S_1)^m$$

where,

N_1 = Original number of cycles

N_2 = Revised number of cycles

S_1 = Original stress range

S_2 = Revised stress range

Now the effect of changes in “**stress range**” or “**number of cycles**” can be evaluated. For example, if the stress range for a CAT.C detail is **increased by 25%**, its fatigue life will be **reduced by 50%**. For example:

$$S_2 = 1.25 S_1$$

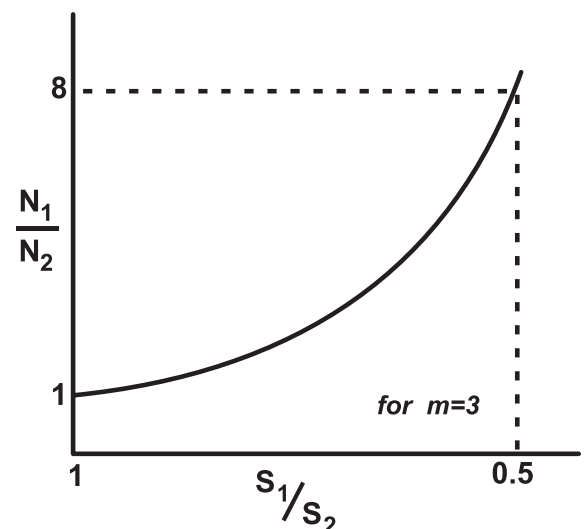
$$N_1/N_2 = 1.25^{3.27} = 2.0744155$$

$$N_2/N_1 = 1.0 / 2.0744155 = 0.48$$

The stress range in the fatigue equation is raised to the 3rd power ; thus, small changes in stress cause large changes in fatigue life (**Figure 7.35**). When investigating an existing structure subject to fatigue, it is imperative to use the actual state of stress, rather than the assumed (used for original design).

In conjunction with the values given in **Table 7.2** and the rearranged S/N formula, the constant “C” can be calculated for each stress range. See **Example 1** for the calculation of the equation constant for Category B.

Figure 7.35: Because the equation for the S/N curve is raised to the 3rd power, small increases in load result in rather large reductions in fatigue life.



S/N Curve Equation

Because tables of fatigue data have only selected values of S for widely spaced values of N, and since reading directly from curves may be imprecise, it is often more useful to work from the logarithmic equation. In this example the equation for the S/N curve representing a specific welded joint detail - designated category "B" - is determined from the values given in Table 12-3 from CSA W59.

Category	Allowable Range of Stress, MPa (ΔS)			
	For 100,000 Cycles	For 500,000 Cycles	For 2,000,000 Cycles	Over 2,000,000 Cycles
A	415	250	165	165
B	310	190	125	110
C	220	130	90	70*
D	185	110	70	48
E	145	85	55	32
F	110	65	40	18
W	115	85	65	48

* See notes in W59.

The equation is $N = C \Delta S^{-m}$ First determine m.

We have $N_2/N_1 = (\Delta S_1/\Delta S_2)^m$

From the table above take $N_1 = 100,000$ $\Delta S_1 = 310$
 $N_2 = 2,000,000$ $\Delta S_2 = 125$

Therefore $\frac{2,000,000}{100,000} = \left(\frac{310}{125} \right)^m$ $20 = (2.48)^m$
 i.e. $m = \log 20 / \log 2.48 = \boxed{3.3}$

Next determine the constant C

$$C = N \times \Delta S^m = 2 \times 10^6 \times 125^{3.3} = \boxed{1.663 \times 10^{13}}$$

The equation is therefore

$$\boxed{N = 1.663 \times 10^{13} (\Delta S)^{-3.3}}$$

ΔS in MPa

Example 1: Determination of the "constant" of an S/N curve equation.

7.12.2 Cumulative Damage Formula

The S/N graph is for a constant amplitude stress range, while many applications are subject to a variable stress range. In a practical application, if one analyses a crane runway girder for the maximum stress range only, a severe economic penalty is paid.

A crane runway sees a wide spectrum of loading:

- ◆ crane full
- ◆ crane empty
- ◆ crane with empty ladle
- ◆ the above loads, but with load located at different distances from the girder

By using the **Miner's Rule**, an equivalent stress can be calculated, with subsequent savings. For each stress range, S, the corresponding design life, N (number of cycles) is determined directly from a standard S/N diagram.

Miner's Rule:

Stress range	S	S ₁	S ₂	S ₃
Number of actual cycles	n	n ₁	n ₂	n ₃
Number of allowable cycles for stress range, S	N	N ₁	N ₂	N ₃
Fraction of endurance used	$\frac{n}{N}$	$\frac{n_1}{N_1}$	$\frac{n_2}{N_2}$	$\frac{n_3}{N_3}$

To avoid failure, the sum of the fractions must be less than 1.0.

That is to say: $\Sigma n/N \leq 1.0$

See **Example 2** for detailed calculation.

Miner's Rule

A member containing a category "B" detail is subject to three sources of repeated loads. These produce the following stress ranges and number of cycles during the life of the component.

$$1) \quad \Delta S_1 = 150 \quad n_1 = 250,000$$

$$2) \quad \Delta S_2 = 125 \quad n_2 = 500,000$$

$$3) \quad \Delta S_3 = 115 \quad n_3 = 800,000$$

Miner's Rule is applied to determine whether the component has adequate fatigue life under the combined stresses. The first step is to calculate N , the total fatigue life, for each of the stress range components from the equation for a category "B" detail found in the example on page 338.

$$N = 1.663 \times 10^{13} (\Delta S)^{-3.3}$$

The next step is to determine the fraction of life (n/N) used by each component. The total of these fractions is then found. If the total is less than one, the component is considered to have adequate fatigue life. The results of the calculations are given in the table below.

	1)	2)	3)
ΔS	150	125	115
n	250,000	500,000	800,000
N	1,096,000	2,000,000	2,634,000
n/N	0.228	0.250	0.304
$\Sigma n/N$	0.782 < 1 O.K.		

Example 2: Cumulative damage example using Miner's Rule.

7.12.3 Fatigue Life Enhancement

The British and Danish Codes have provisions for enhancing the fatigue life of new or existing structures by a factor of 2. The economic benefits are real and meaningful, especially on existing structures.

Research at The Welding Institute in Cambridge, England, identified an acute line of intrusions along the toes of all welds made by the arc process, with the exception of GTAW. All processes, however, produce some degree to undercut at the toe, notwithstanding good looking weld profiles. The practical implication is that all welds have a pre-existing defect, in the form of either *microscopic undercut* or *slag intrusions*, or both (**Figure 7.36**).

This is the basic reason that welded connections have a much lower fatigue life than equivalent plain materials. Weldment life is primarily one of *propagation*, while plain materials experience a crack *initiation* stage. See **Figure 7.37**.

7.12.4 Toe Grinding Method

A burr grinder is lightly run over the weld toes, always moving parallel to the weld, as shown in **Figure 7.38**. Grinding to a depth of $1/32$ " (0.8mm) below the point of undercut is the easiest, quickest and most effective enhancement. The small pre-existing defects are either removed or the sharp openings dulled. The resulting profile modification also complements the overall effectiveness.

In **Figure 7.39** the "toe dressing" on the left was ineffective because grinding was restricted to the weld face; on the opposite side, the "dressing" was effective because grinding was directed at the weld toe. A bit of base material must be removed.

On new designs, toe grinding at critical points can be specified right on the engineering drawing. When these pre-existing "toe" defects are perpendicular to the applied stress, fatigue crack propagation is accelerated.

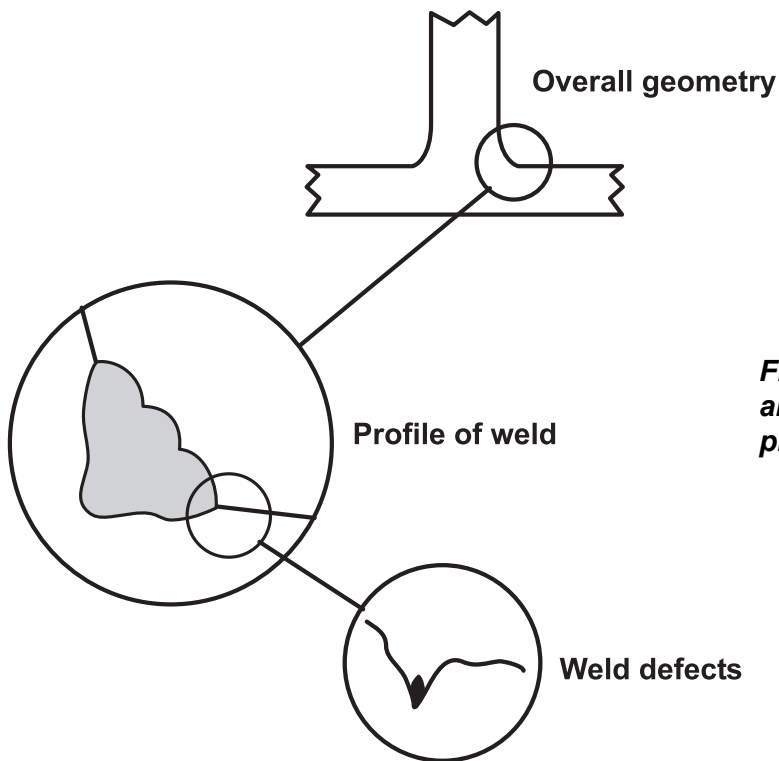


Figure 7.36(a): Stress concentrations arise from overall geometry, weld profile, and weld defects.

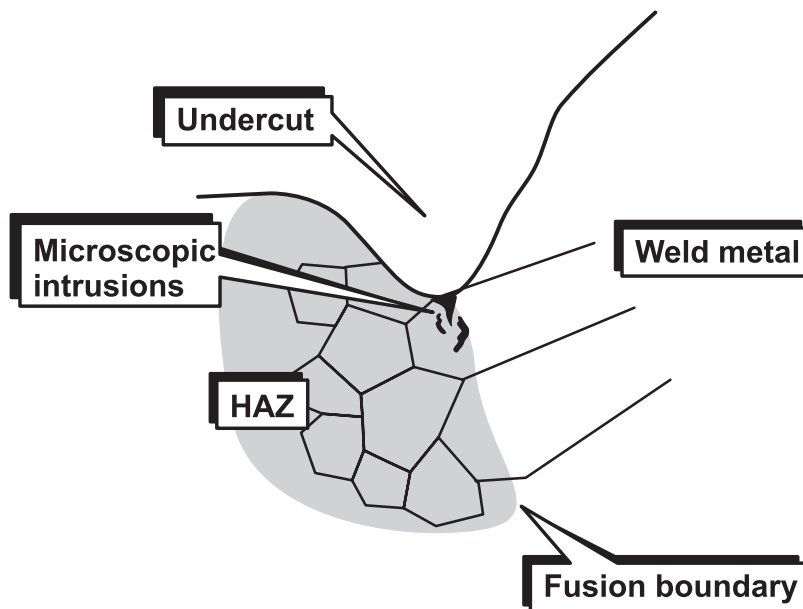


Figure 7.36(b): The arc welding process is prone to lines of intrusions and severe undercut along the “toe” of the weld. They are not detectable by normal NDE.

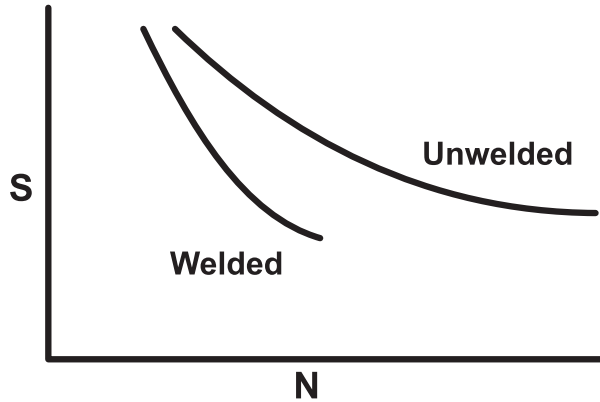


Figure 7.37(a): These “toe” defects greatly contribute to the reduced fatigue life of a welded specimen.

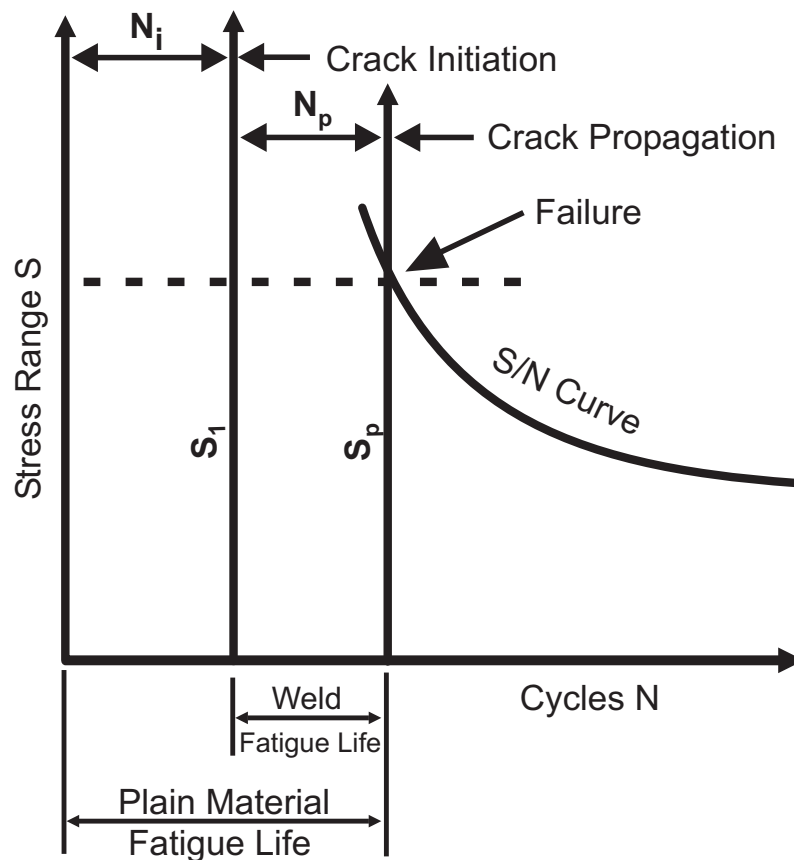


Figure 7.37(b): The fatigue life of a weldment is essentially one of crack propagation because of inherent defects, while plain material has a crack initiation phase.

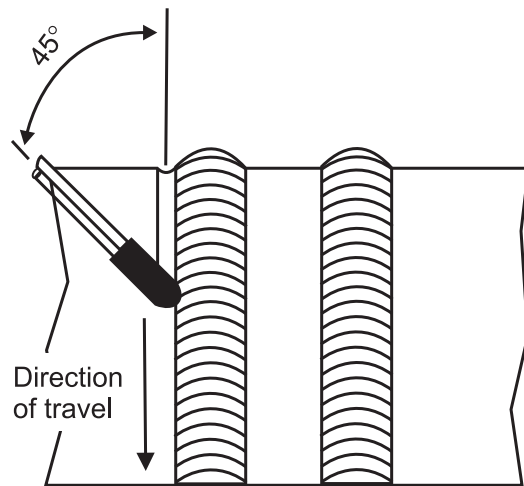
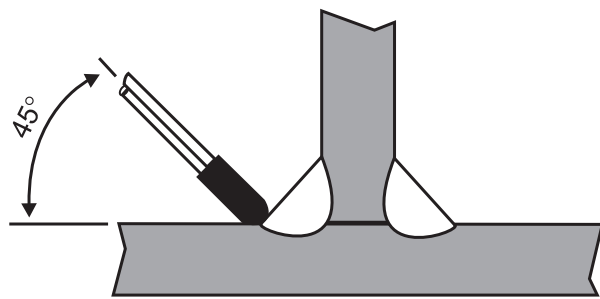


Figure 7.38: Light grinding along the weld toe with a burr grinder will enhance fatigue life of an existing weldment.

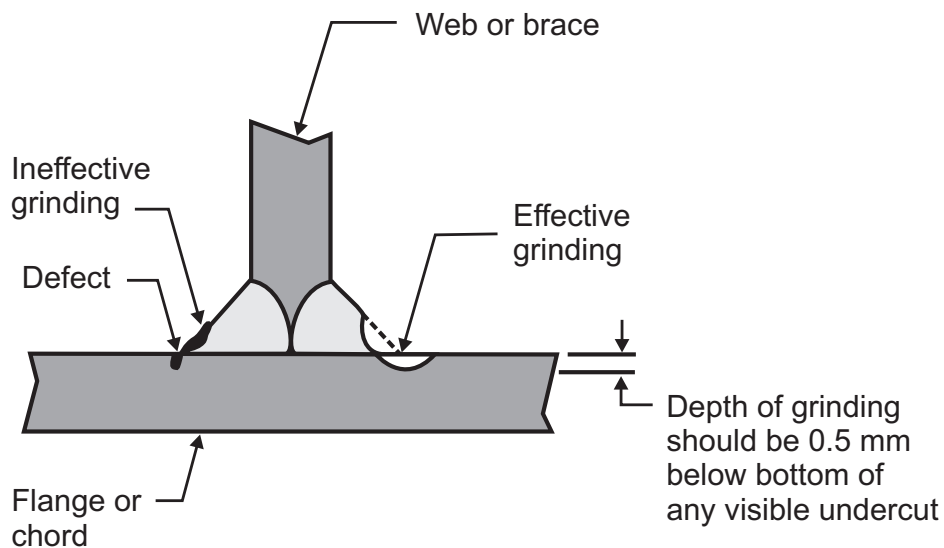


Figure 7.39: To be effective, the grinding must be along toe (not weld face), removing material 0.5mm below bottom of visible undercut.

There is little advantage to placing an attachment parallel to the stress (**Figure 7.40(b)**), because the end of the weld is category “E” in both cases. Much time and money have often been expended on such a task, even after the fact.

Another method of fatigue life enhancement is to use a bolted connection (ASTM A325, fully torqued, friction tight); the existing crane runway girder in **Figure 7.41** was modified, changing the controlling fatigue category from “E” to “B”.

Shot peening is also an effective fatigue enhancement method, especially for irregularly shaped components that don’t readily lend themselves to grinding (the benefits are about equal).

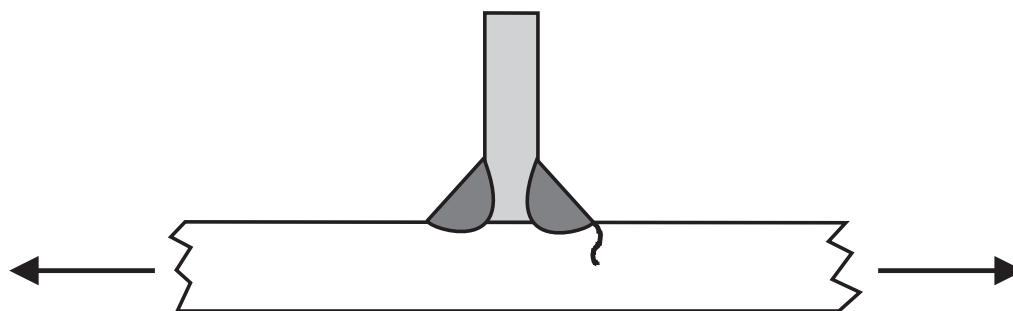
Good Details

In **Figure 7.42** a number of preferred details are shown. In addition, there are a number of prudent design steps that will tend to avoid fatigue problems.

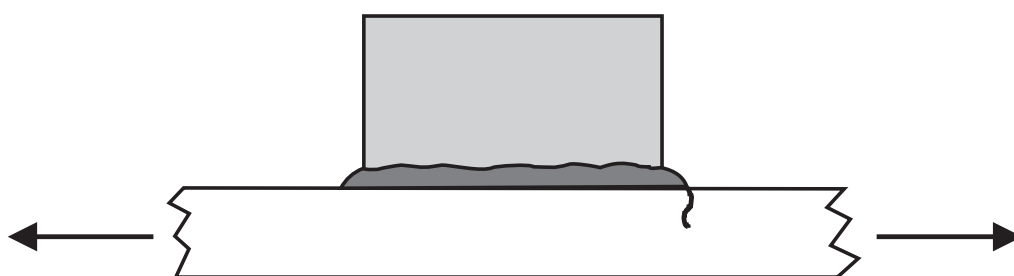
7.12.5 Prudent Design Measures

Certain prudent design measures can be taken routinely. They do not add cost and just may keep you out of trouble when the unexpected occurs. The following points are especially appropriate for miscellaneous attachments, doubly so if they must be field welded:

- a) Use smooth shapes and transitions. Avoid notches.
- b) Locate welds in areas of low stress, e.g., weld to the web rather than the flange.
- c) Locate member splices in areas of lower stress.
- d) Do not weld on the edge of flanges unnecessarily. Keep welds approximately 1/2 in from the edge of plates.
- e) Avoid intermittent welds. Consider smaller continuous welds.
- f) Avoid intersecting welds. Cope the ends of stiffeners.
- g) Interrupt fillet welds at corners.
- h) Show and locate welds clearly for drafting office to follow.
- i) Specify that all temporary welds, if removed, be done carefully and the area ground smooth. This includes such items as lifting lugs, scaffolding lugs, etc.
- j) Remove tack welds and grind properly.



(a) Attachment perpendicular to stress.



(b) Attachment parallel to stress.

Figure 7.40: Stress applied perpendicular to the toe defect tends to open the defect, while stress applied parallel to the toe has little benefit. The orientation of the two welded attachments are both Category “E”.

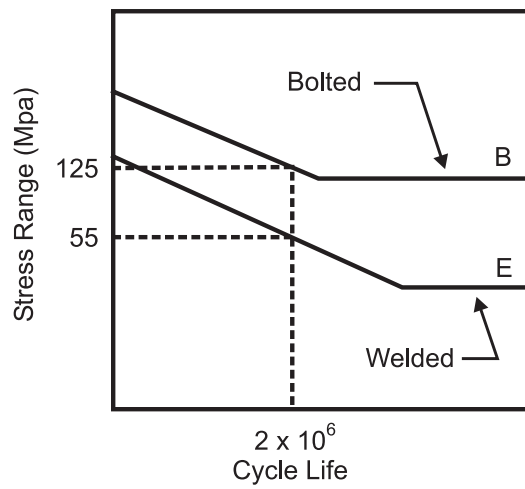
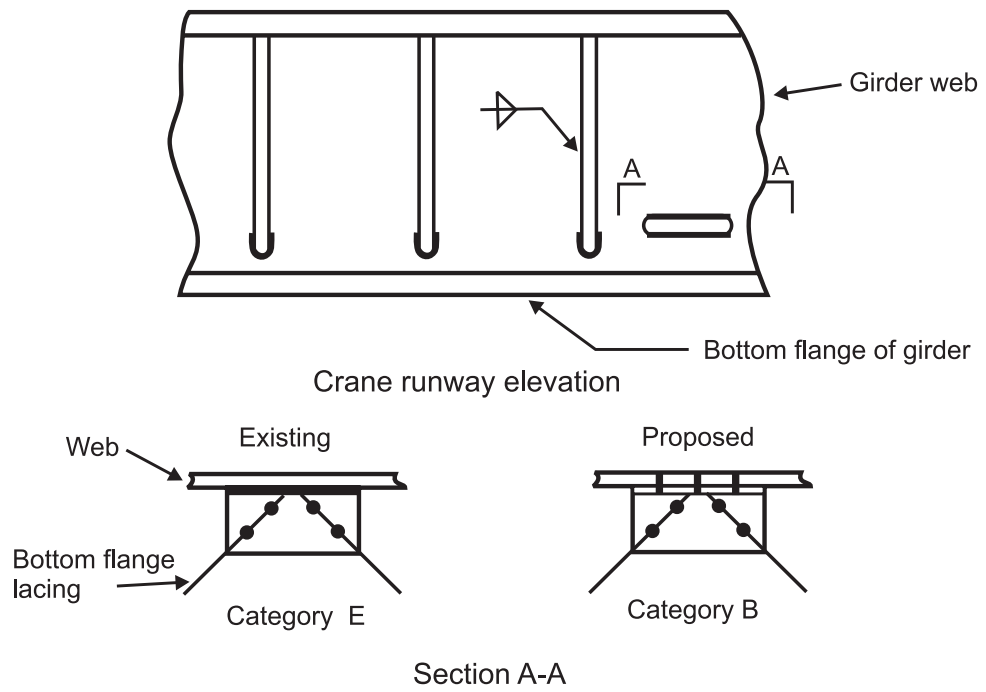


Figure 7.41: Friction tight ASTM A-325 H.T. bolts raised the fatigue category from “E” to “B”.

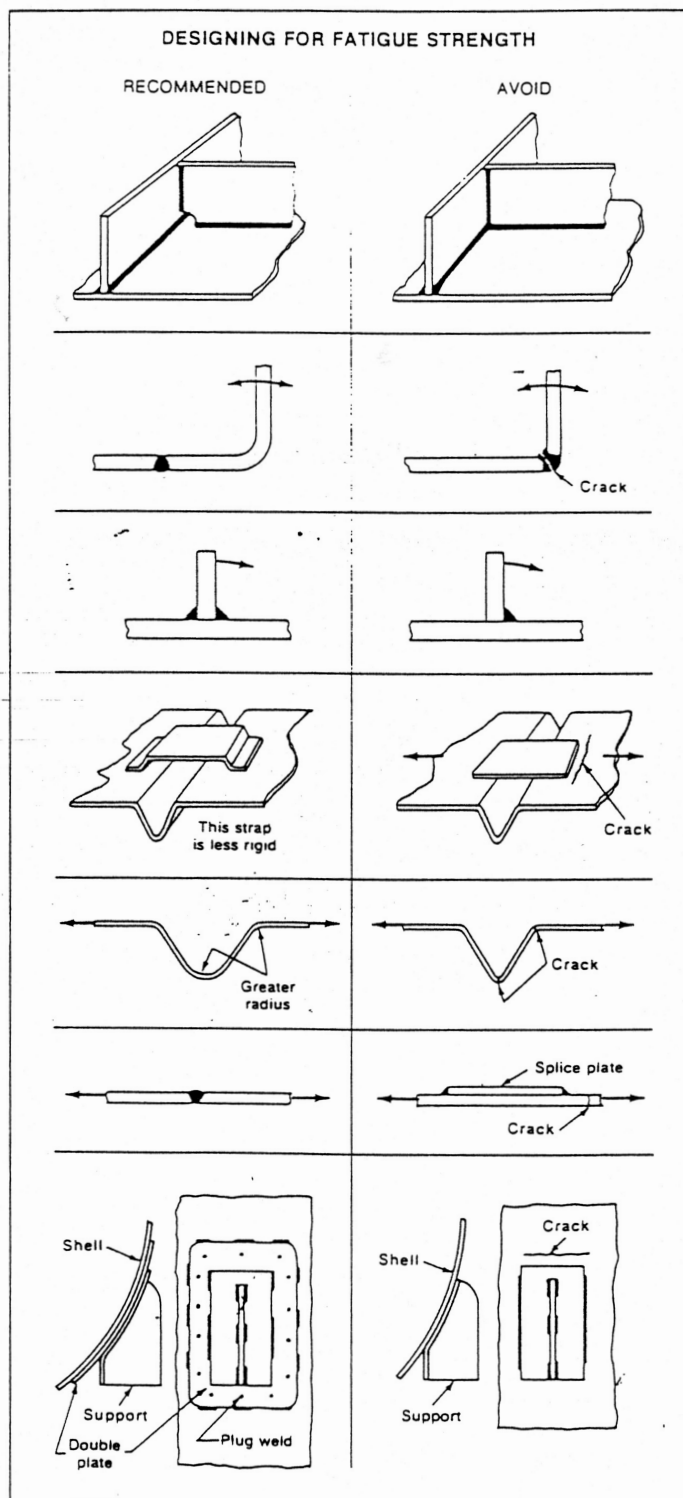


Figure 7.42: Fatigue design tips.

7.12.6 Prohibited Welds

There are a number of welds that are prohibited under fatigue loading by CSA W59 (Clause 12.4.14). Some of the more common ones are:

- 1) intermittent welds
- 2) partial joint penetration groove welds in tension
- 3) welds with backing bar
- 4) plug and slot welds

7.12.7 Alternate Codes

Another problem associated with fatigue calculations is that no single Code contains all the “categories”. Even the allowable stresses vary within some specifications. Thus, the designer should be aware of alternate codes. A list is given below for reference.

Standards Providing Fatigue Design Guidance

Standard	Comments
CSA W59-2003	Follows CAN/CSA S16-01
Ontario Highway Bridge Design Code	Includes aluminum
CAN/CSA S16-01	Includes mechanical fasteners
AISC Handbook of Steel Construction	Includes Tee joints
British Standard BS-5400	Excellent written descriptions accompany diagrams. Shows where cracking is likely to occur.
German Standard DIN 4132	Includes concentrated loads (e.g. wheel loads) on web to flange welds
AISE Std No 13	Covers industrial mill buildings, crane runway girders
AASHTO requirements for highway bridges	Excellent diagrams
AWS D1.1-2004 Structural Welding Code	Covers hollow structural sections

Note that each standard or code may give different designations to the same or similar details.

Chapter 8

Welding Design

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8.1 Introduction

The subject of welding design can cover a wide range of products. The design method of each application may be different, because of the configuration, type of base material and the nature of loading.

Welding design involves steels and ferrous alloys, all classes of stainless steels, aluminum, copper, cobalt, titanium and other metals and their alloys. Welding design also involves non-metallic materials such as plastics, ceramics and composite materials.

The following list gives some idea of the extent of the welding industry:

- ◆ medical and bioengineering equipment
- ◆ electronics
- ◆ household utensils
- ◆ automobiles and all transportation equipment
- ◆ pressure vessels and the energy industry
- ◆ power generation
- ◆ petroleum industry (including off-shore oil drilling platforms)
- ◆ underwater welding
- ◆ pulp and paper industries
- ◆ plastics
- ◆ machinery
- ◆ buildings
- ◆ crane girder and runways
- ◆ bridges
- ◆ ship building
- ◆ aerospace industry

It should be pointed out that in the above list, in addition to buildings and bridges, weldments in the aerospace industry, ship building, pressure vessels and other industries are designed and fabricated under the supervision of civil engineers who are predisposed to design disciplines. In other words, civil engineers are not limiting their playing field to buildings and bridges. Any engineered product or structure, excluding engines and mechanical components, can be analyzed and designed by civil engineers if they choose to do so.

8.2 Scope and Objectives

The objective of this chapter is to focus on all elements necessary for making a sound and economical welding design decision. Most of the factors that bear on an engineering judgment will be identified.

In addition, design guidance is provided by due consideration of established good welding practices, and specifically to the related welding design rules of the governing standards, such as CSA S16-01, CSA W59 and AWS D1.1.

There are two fundamental welding design-related considerations requiring individual and knowledgeable engineering attention:

First – for the welds to fulfill the exact design function assigned to them in the structure or the product and to reliably maintain their integrity under the anticipated handling, shipping and ultimately service loads.

Second – for the welded joints to fully satisfy the requirements of optimum economy in their execution and adequate access for inspection.

Since welding design involves all kinds of fabricated products, it is beyond the scope of this chapter to cover every aspect of welding application. The following discussion is closely related to building structures.

It is not intended to describe how the entire structure is analyzed. Instead, when all the external forces are given, the welds at the joint will be judged accordingly to the internal stresses.

The following CWB Modules are suggested for those who would like to pursue further studies:

Module 30	General Design Considerations for Welding
Module 31	Design of Flexible Connections
Module 32	Design of Moment Connections
Module 33	Welded Trusswork
Module 34	Miscellaneous Structural Welding Design

The following paragraphs are valuable guidelines when dealing with welding design and fabrication. A good welding design must be good for fabrication. Welding design is the starting point of the whole fabrication process.

Although the design effort makes only about 5% of a product's total cost, it usually determines more than 70% of a product's manufacturing cost.

Real economies will not necessarily be achieved on the shop floor, but in the design office and in the drawing office. The cost of a joint is largely determined *before* it reaches the shop floor. Quality and profit begin when the designer first puts pen to paper and all else follows. Those first decisions predetermine the rest of the job.

The designer or the draftsman must specify the most economical joint design and welding process. Should the designer use a full strength weld? a 100% butt weld? a partial butt weld? a pair of fillets? continuous or intermittent welding? Should the joint be gapped? Should the designer use a single V or a double V? a bevel or a V joint? backgouged or not?

Overwelding can be more detrimental than underwelding. Design values provide a safety factor that will cover a considerable degree of underwelding error, but do not provide for some of the distortions and stress raisers that could result from overwelding. Designers should recognize that overwelding can be as serious as underwelding.

What Does a Weld Do?

1. If it is to provide a path for the transfer of forces, a welded design is justified as are all the calculations made to determine stresses and weld sizes.
2. If it is simply to hold parts together, continuous welds are invariably wasteful, and a few intermittent welds will prove to be more efficient.

Excessive Welding Results When:

1. Designers call for 100% butt welds or continuous all-around fillets because:
 - a) It looks solid
 - b) Loads are not given, so make it 100%
 - c) Designing the welds is too much trouble
 - d) The design basis is not known or might change
 - e) The customer expects it and will not challenge the adequacy
 - f) Two pieces of steel are in contact
2. Designers increase fillet weld sizes because they suggest that:
 - a) The shop might underweld
 - b) The basic design assumptions are questionable
 - c) The calculations are approximate only
 - d) They are only asking for visual inspection so they have to be sure

A Responsible Designer Will:

1. Size the weld to suit the load not the member
2. Use stitch welds when minimum size fillets govern the weld size
3. Use stitch welds and give an alternate continuous size for automatic welding when not restricted by minimum fillet size
4. Remember that even at an allowable stress of 925 lbs per inch per 16th, a fillet weld still has a safety factor of 2.9 to 4.0.
5. Remember that welders invariably tend to overweld rather than underweld
6. Use partial penetration butt welds whenever conditions permit
7. Always use a balanced weld design (developing the connected part 100%) as an upper limit for the amount of weld specified

A Responsible Designer Will Not:

1. Cause welding to be done where it offers no benefit
2. Require a consistency in welder performance that is difficult to maintain
3. Forget the practicalities of production
4. Uncritically repeat the way it has been done in the past
5. Specify more welding than is necessary

It is important to set down hard and fast rules for joint design. However, in this chapter we shall review definite steps, on several topics, that should lower your costs through effective design.

8.2.1 Accessibility for Welding

Figure 8.1 shows the requirement of welding access. A practical design engineer will never design a weld which is hard to reach by the welder. If it cannot be reached or does not have minimum access, it cannot be welded. Or, the welder manages to get it welded, but the quality or soundness of the weld may be questionable. If it is difficult to weld because of access problems, it will be difficult to inspect it. Therefore, good access is essential for good quality welds.

8.2.2 Formula for Success

The formula for success is quite straight forward. Although the process starts with engineering, there must be open communications and genuine cooperation with all involved personnel, particularly those in the shop and field.

8.3 Design Principles

There are two major design principles, i.e., Allowable Stress Design Principle (ASD) and Limit States Design Principle (LSD). The former design principle has been in use over one hundred years. The latter design principle has emerged since the 1970s and it is replacing the former in Canada, Europe and other countries. In the United States at present, both design principles are acceptable. At present in Canada, the official design principle is Limit States Design. Therefore, in this chapter, both Limit States Design (in metric and imperial units) and Allowable Stress Design (in imperial units) are given for cross reference.

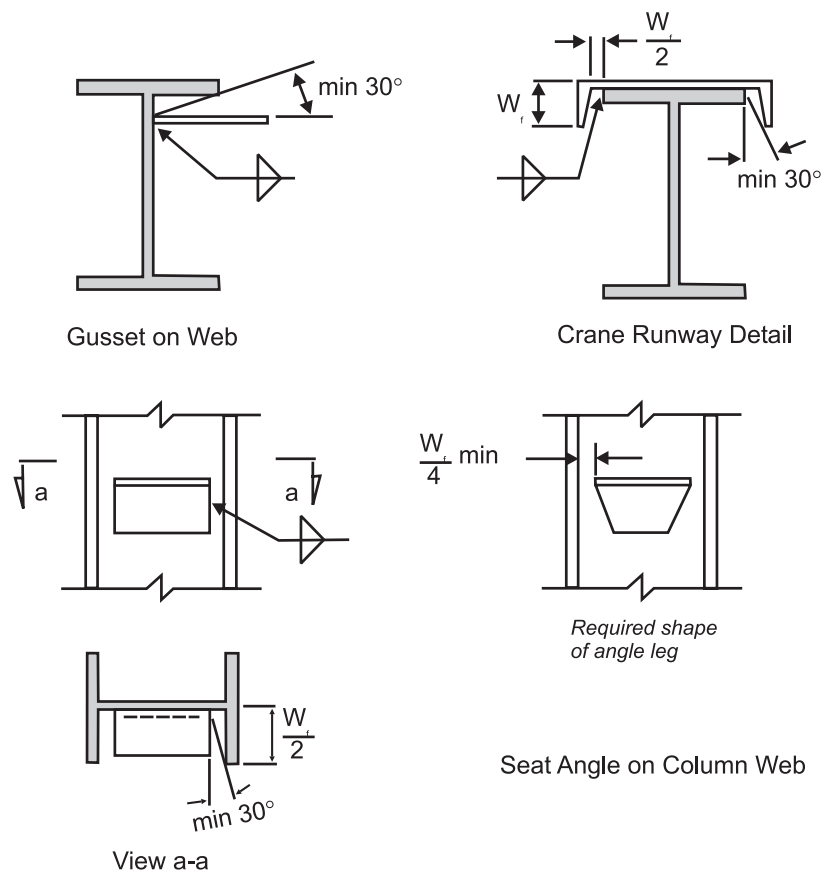


Figure 8.1: Minimum access requirement for welding.

8.3.1 Allowable Stress Design (ASD)

In allowable stress design the actual loads are used to calculate the stresses in a weld joint.

Table 11.2(a) of CSA W59, gives the allowable design stresses for various types of welds. This table is for statically loaded structures. For dynamically loaded structures, see **Table 12.2(a)** of CSA W59. Columns 4 and 5 in both tables give the allowable stress and joint capacity for matching conditions. Columns 7 and 8 give the non-matching conditions. Matching or non-matching means that the strengths of electrodes and base metals are equal or unequal respectively.

Table 11.2(a):
Allowable Stresses for Welds and Joint Capacities for Statically Loaded Structures
(extracted from CSA W59-03 - see Clause 11.3.4)

Type of Weld	Type of Load and Its Direction Respective to Line of Weld	Matching Conditions			Nonmatching Conditions		
		Requirements for Matching (1)	Allowable Stress on Throat of Weld	Resulting Capacity of Joint (7)	Extent of Nonmatching	Allowable Stress on Throat of Weld	Resulting Capacity of Joint
1	2	3	4	5	6	7	8
Complete Joint Penetration Groove Welds (2)	Tension or compression parallel to axis of weld (3)	Not mandatory, but if matching electrode classification used, see Col. 4 For nonmatching, see Cols. 6, 7 and 8	Same as for base metal	Same as calculated for base metal	Electrode classification lower or higher than matching	Same as for base metal (3)	Same as calculated for base metal (3)
	Compression normal to axis of weld	Mandatory					
	Tension normal to axis of weld						
	Shear	Mandatory (for exceptions see Note (2) and Cols. 6, 7 and 8)			Electrode classification lower than matching	0.3 X_u of electrode classification used	Lesser of: (a) base metal $V=0.4A_mF_y$ (b) weld metal $V=0.3A_wX_u$
Partial Joint Penetration Groove Welds (4)	Tension or compression parallel to axis of weld (3)	Not mandatory, but if matching electrode used, see Col. 4. For nonmatching, see Cols. 6, 7 and 8	Same as for base metal	Same as calculated for base metal	Electrode classification lower or higher than matching	Same as for base metal (3)	Same as calculated for base metal (3)
	Compression normal to axis of weld	Mandatory		See Note (5)			
	Tension normal to axis of weld	Not mandatory, but if matching electrode classification used, see Col. 4	0.3 X_u of matching electrode classification (Clause 11.3.4.2)	Lesser of: (a) base metal $T=0.6A_mF_y$ or, (b) weld metal $V=0.3A_wX_u$	Electrode classification lower than matching	0.3 X_u of electrode classification used	Lesser of: (a) base metal $T=0.6A_mF_y$ (b) weld metal $V=0.3A_wX_u$
	Shear	For permitted condition of nonmatching, see Cols. 6, 7 and 8		Lesser of: (a) base metal $V=0.4A_mF_y$ or, (b) weld metal $V=0.3A_wX_u$ (6)			Lesser of: (a) base metal $V=0.4A_mF_y$ (b) weld metal $V=0.3A_wX_u$ (6)

Table 11.2(a): Continued

Type of Weld	Type of Load and its Direction Respective to Line of Weld	Matching Conditions			Nonmatching Conditions		
		Requirements for Matching (1)	Allowable Stress on Throat of Weld	Resulting Capacity of Joint (7)	Extent of Nonmatching	Allowable Stress on Throat of Weld	Resulting Capacity of Joint
1	2	3	4	5	6	7	8
Fillet Welds	Tension or compression parallel to axis of weld (3)	Not mandatory, but if matching electrode used, see Col. 4. For nonmatching, see Cols. 6, 7, and 8	Same as for base metal	Same as calculated for base metal	Electrode classification lower or higher than matching	Same as for base metal (3)	Same as calculated for base metal (3)
	Tension or compression normal to axis of weld	Not mandatory, but if matching electrode classification used, see Col. 4. For permitted condition of nonmatching, see Cols. 6, 7 and 8	0.3X _e of matching electrode classification	Lesser of: a) base metal V=0.4A _m F _y b) weld metal V=0.3A _w X _e	a) Electrode classification lower than matching b) Electrode classification one designation higher than matching	a) 0.3X _e of electrode classification used b) 0.3X _e of matching electrode classification	Lesser of: a) base metal V=0.4A _m F _y or b) weld metal V=0.3A _w X _e
	Shear						
	Shear						
Plug and Slot Welds							

Notes:

- (1) For matching materials and electrode classification refer to Table 11.1.
- (2) Electrodes of strength lower than that shown for the corresponding base metal group of Table 11.1 may be used for complete joint penetration groove welds when approved by the Engineer.
- (3) If shear is transferred between components, the design value is the smaller of that for the base metal or the weld metal.
- (4) For hollow structural sections, the provisions of Appendix L may be used.
- (5) The resulting capacity of the joint = (A_m + area of base metal in contact bearing) x allowable compressive stress in base metal (see Clause 11.3.4.4)
- (6) See Appendix M, Figure M3.
- (7) The capacity of the member is to be determined independently.

Table 12.2(a):
Allowable Stresses for Welds and Joint Capacities for Cyclically Loaded Structures
 (extracted from CSA W59-03 - see Clause 12.3.4)

Type of Weld	Type of Load and its Direction Respective to Line of Weld	Matching Conditions			Nonmatching Conditions		
		Requirements for Matching (1)	Allowable Stress on Throat of Weld	Resulting Capacity of Joint (7)	Extent of Nonmatching	Allowable Stress on Throat of Weld	Resulting Capacity of Joint
1	2	3	4	5	6	7	8
Complete joint penetration groove welds (2)	Tension or compression parallel to axis of weld (3)	Not mandatory, but if matching electrode classification used, see Col. 4. For nonmatching, see Cols. 6, 7, and 8			Electrode classification lower or higher than matching	Same as for base metal (3)	Same as calculated for base metal (3)
	Compression normal to axis of weld	Mandatory	Same as for base metal	Same as calculated for base metal			
	Tension normal to axis of weld						
	Shear	Mandatory (for exceptions see Note (2) and Cols. 6, 7 and 8			Electrode classification lower than matching	0.3X _u of electrode classification used	Lesser of: base metal $V=0.4A_{mf}F_y$ or weld metal $V=0.3A_{mw}X_u$
Partial joint penetration groove welds (4)	Tension or compression parallel to axis of weld (3)	Not mandatory, but if matching electrode used, see Col. 4 For nonmatching, see Cols. 6, 7 and 8	Same as for base metal	Same as calculated for base metal	Electrode classification lower or higher than matching	Same as for base metal (3)	Same as calculated for base metal (3)
	Compression normal to axis of weld	Mandatory					
	Tension normal to axis of weld	For permitted condition of nonmatching, see Cols. 6, 7 and 8	0.3X _u of matching electrode classification (Clause 11.3.4.2)	Lesser of: base metal $T=0.6A_{mf}F_y$ or weld metal $V=0.3A_{mw}X_u$	Electrode classification lower than matching	0.3X _u of electrode classification used	Lesser of: base metal $T=0.6A_{mf}F_y$ or weld metal $V=0.3A_{mw}X_u$
	Shear			Lesser of: base metal $V=0.4A_{mf}F_y$ or weld metal $V=0.3A_{mw}X_u$ (6)			Lesser of: base metal $V=0.4A_{mf}F_y$ or weld metal $V=0.3A_{mw}X_u$ (6)

Table 12.2(a): Continued

Type of Weld	Type of Load and its Direction Respective to Line of Weld	Matching Conditions			Nonmatching Conditions		
		Requirements for Matching (1)	Allowable Stress on Throat of Weld	Resulting Capacity of Joint (7)	Extent of Nonmatching	Allowable Stress on Throat of Weld	Resulting Capacity of Joint
1	2	3	4	5	6	7	8
Fillet Welds (8)	Tension or compression parallel to axis of weld (3)	Not mandatory, but if matching electrode used, see Col. 4. For nonmatching, see Cols. 6, 7, and 8	Same as for base metal	Same as calculated for base metal	Electrode classification lower or higher than matching	Same as for base metal (3)	Same as calculated for base metal (3)
	Tension or compression normal to axis of weld	Not mandatory, but if matching electrode classification used, see Col. 4	0.3X _u , of matching electrode classification	Lesser of: a) base metal $V=0.4A_mF_y$ or b) weld metal $V=0.3A_wX_u$	a) Electrode classification lower than matching	a) 0.3X _u , of electrode classification used b) 0.3X _u , of matching electrode classification	Lesser of: a) base metal $V=0.4A_mF_y$ or b) weld metal $V=0.3A_wX_u$
	Shear	For permitted condition of nonmatching, see Cols. 6, 7 and 8			b) Electrode classification one designation higher than matching		
Plug and Slot Welds For restrictions, see Clause 12.4.14(g)	Shear						

Notes:

- (1) For matching materials and electrode classification refer to Table 12.1.
- (2) Electrodes of strength lower than that shown for the corresponding base metal group of Table 12.1 may be used for complete joint penetration groove welds when approved by the Engineer.
- (3) If shear is transferred between components, the design value is the smaller of that for the base metal or the weld metal.
- (4) For hollow structural sections, the provisions of Appendix L may be used.
- (5) The resulting capacity of the joint = (A_m + area of base metal in contact bearing) x allowable compressive stress in base metal (see Clause 11.3.4.4)
- (6) See Appendix M, Figure M3.
- (7) The capacity of the member is to be determined independently.
- (8) For fillet welds in railway bridges, use 0.9 of the allowable joint capacity calculated from this Table.

8.3.2 Limit States Design (LSD)

The basic concept of the Limit States Design method is briefly presented by means of a number of statements and definitions. It should be noted that the design method as such is outside the scope of this book. Only general information and specific reference pertaining to welding have been briefly provided. Of particular interest should be the calibration of the method to yield results comparable to those obtained with the ASD method. It should be further pointed out that the LSD method has been accepted by the International Standards Organizations (ISO). Canadian engineers continue to contribute significantly to the development of ISO standards backed by the expertise and experience gained with this method nationally.

Principle: All buildings must be designed to prevent – with sufficiently small probability – the occurrence of various types of collapse and unserviceability.

Limit States are those conditions that correspond to the onset of various types of collapse or unserviceability.

Ultimate Limit States are conditions associated with collapse.

Serviceability Limit States are conditions associated with unserviceability.

Ultimate Limit States are concerned with strength and stability. For these states the structure must retain its capacity up to the factored load levels.

Serviceability Limit States are concerned with satisfactory performance of the structure at specified loads and impose requirements on maximum deflections, permanent deformations, fatigue cracking and so forth.

Load Factor (α) is applied to specific loads to take account of loads higher than anticipated and of shortcomings of methods of analysis.

Resistance Factor (ϕ) is applied to resistances (R) or strength of members and takes account of variations in material properties, dimensions, workmanship and uncertainty in the prediction of the resistance.

Resistance Factor (ϕ) for the base metal is taken to be 0.9 to maintain uniformity and simplicity in design, with adjustments made to resistance formulae for other types of member failures than that by yielding (buckling).

The Resistance Factor (ϕ) for weld metal has been set at 0.67 in line with its value for other fasteners (bolts) to ensure that connector failure will not occur prior to general failure of the member as a whole.

Load Factor (α)

Consistent probabilities of failure have been determined for Dead-to-Live load ratios.

$$\frac{\alpha_{Dead}}{\alpha_{Live}} = \frac{1.25}{1.50}$$

In order to take full advantage of the proven, successful application of the ASD method, the LSD method has been *calibrated* to yield reasonably comparable results.

$$\frac{\alpha_{Live}}{\phi} = \frac{1.5}{0.9} = 1.67$$

This is equal to the factor of safety for conventional Allowable Stress Design.

8.3.2.1 Load Combinations

The load combinations (not including earthquake) is expressed as follows:

$$\alpha_D D + \gamma \psi (\alpha_L L + \alpha_W W + \alpha_T T) \quad (\text{CSA-S16-01})$$

Load factors, α , shall be taken as follows:

$\alpha_D = 1.25$ except that

$\alpha_D = 0.85$ when the dead load resists overturning, uplift, or load reversal effects

$\alpha_L = 1.50$

$\alpha_W = 1.50$ for wind

$\alpha_T = 1.25$

The load combination factor, Ψ , shall be taken as follows:

$\Psi = 1.00$ when only one of L, W, and T acts

$\Psi = 0.70$ when two of L, W, and T act

$\Psi = 0.60$ when all of L, W, and T act

The most unfavourable effect shall be determined by considering L, W, and T acting along with $\Psi = 1.00$, or in combination with $\Psi = 0.70$ or 0.60

The importance factor, γ , shall be not less than 1.00 except for those structures where it can be shown that collapse is not likely to cause injury or other serious consequences, it shall be not less than 0.80.

For load combinations including earthquake, the effect of factored loads (in force units), is the structural effect due to the factored load combinations taken as follows:

- (a) $1.0D + \gamma (1.0E)$; and either
- (b) $1.0D + \gamma (1.0L + 1.0E)$ for storage and assembly occupancies; or
- (c) $1.0D + \gamma (0.5L + 1.0E)$ for all other occupancies.

The AISC load factors and combinations are similar to CSA S16-01, but with minor differences, such as the factors for live load and dead load:

Loads, Load Factors, and Load Combinations
(excerpts from AISC Manual of Steel Construction)

The following nominal loads are to be considered:

- D*: dead load due to the weight of the structural elements and the permanent features on the structure
- L*: live load due to occupancy and moveable equipment
- L_r*: roof live load
- W*: wind load
- S*: snow load
- E*: earthquake load determined in accordance with Part I of the AISC *Seismic Provisions for Structural Steel Buildings*
- R*: load due to initial rainwater or ice exclusive of the ponding contribution

The required strength of the structure and its elements must be determined from the appropriate critical combination of factored loads. The most critical effect may occur when one or more loads are not acting. The following load combinations and the corresponding load factors shall be investigated:

$1.4D$	(A4-1)
$1.2D + 1.6L + 0.5 (L_r \text{ or } S \text{ or } R)$	(A4-2)
$1.2D + 1.6 (L_r \text{ or } S \text{ or } R) + (0.5L \text{ or } 0.8W)$	(A4-3)
$1.2D + 1.3W + 0.5L + 0.5 (L_r \text{ or } S \text{ or } R)$	(A4-4)
$1.2D \pm 1.0E + 0.5L = 0.2S$	(A4-5)
$0.9D \pm (1.3W \text{ or } 1.0E)$	(A4-6)

In this chapter, our concerns are mainly the factors applicable to weld strength and welding design. The following formulas for weld strength are based on the CSA W59 Standard, Limit States Design. **Table 11.2(b)** Factored Resistance of Welds for Statically Loaded Structures and **Table 12.2(b)** Factored Resistance of Welds for Dynamically Loaded Structures are attached for reference. The following highlights the factored resistances of limit states design.

8.4 Shear Resistance

(A) Complete and Partial Joint Penetration Groove Welds, Plug and Slot Welds:

The factored shear resistance shall be the lesser of:

$$(a) \text{ Base metal} \quad V_r = 0.67 \phi_w A_m F_u \quad \text{or}$$

$$(b) \text{ Weld metal} \quad V_r = 0.67 \phi_w A_w X_u$$

where $\phi_w = 0.67$

A_m – shear area of effective fusion face of base metal

A_w – area of effective weld throat, plug or slot weld

(B) Fillet Welds (static load):

The factored resistance for tension or compression-induced shear shall be taken as the lesser of:

$$(a) \text{ Base metal} \quad V_r = 0.67 \phi_w A_m F_u \quad \text{or}$$

$$(b) \text{ Weld metal} \quad V_r = 0.67 \phi_w A_w X_u (1.00 + 0.5 \sin^{1.5} \theta)$$

where $\phi_w = 0.67$

θ = angle of axis of weld with the line of action of force (0° in parallel, 90° in transverse)

It should be noted that when $\theta = 0^\circ$

$$V_r = 0.67 \times \phi_w X_u$$

$$\text{when } \theta = 90^\circ \quad V_r = 0.67 \times \phi_w X_u (1.5)$$

It indicates that a transverse weld line is 1.5 times stronger than a parallel one. This fact is verified by testing and also shows in the design tables in the Handbook of Steel Construction (CISC or AISC).

**Table 11.2(b):
Factored Resistances of Welds for Statically Loaded Structures
(extracted from CSA W59 - see Clause 11.3.5)**

Type of Weld	Type of Load and its Direction Respective to Line of Weld	Matching Conditions		Nonmatching Conditions	
		Requirements for Matching (1)	Factored Resistances	Extent of Nonmatching	Factored Resistances
1	2	3	4	5	6
Complete joint penetration groove welds (2)	Tension or compression parallel to axis of weld	Not mandatory, but if matching electrode classification used, see Col. 4. For nonmatching, see Cols. 5 and 6	Same as calculated for base metal	Electrode classification lower or higher than matching	Same as for base metal (3)
	Compression normal to axis of weld	Mandatory			
	Tension normal to axis of weld				
	Shear	Mandatory (for exceptions see Note (2) and Cols. 5 and 6)	Lesser of: base metal $V_r = 0.67 \phi_w A_m F_u$ or weld metal $V_r = 0.67 \phi_w A_w X_u$	Electrode classification lower than matching	Lesser of: (a) base metal $V_r = 0.67 \phi_w A_m F_u$ or (b) weld metal $V_r = 0.67 \phi_w A_w X_u$ X_u of electrode classification used
Partial joint penetration groove welds (4) (6)	Tension or compression parallel to axis of weld	Not mandatory, but if matching electrode classification used, see Col. 4 For nonmatching, see Cols. 5 and 6	Same as calculated for base metal	Electrode classification lower or higher than matching	Same as calculated for base metal (3)
	Compression normal to axis of weld	Mandatory	See Note (5)		
	Tension normal to axis of weld (7) (9) (10)	Not mandatory, but if matching electrode classification used, see Col. 4 For permitted condition of nonmatching, see Cols. 5 and 6	$T_r = \phi_w A_n F_u \leq \phi A_g F_y$ Partial joint penetration groove weld combined with a fillet weld: $T_r = \phi_w \sqrt{(A_n F_u)^2 + (A_w X_u)^2} \leq \phi A_g F_y$ where A_n refers to the partial joint penetration groove weld and A_w refers to the fillet weld	Electrode classification lower than matching	Lesser of: (a) $T_r = \phi_w A_n F_u \leq \phi A_g F_y$ or (b) $T_r = \phi_w A_n X_u \leq \phi A_g F_y$ Partial joint penetration groove weld combined with a fillet weld, lesser of: (a) $T_r = \phi_w \sqrt{(A_n F_u)^2 + (A_w X_u)^2} \leq \phi A_g F_y$ or (b) $T_r = \phi_w \sqrt{(A_n X_u)^2 + (A_w X_u)^2} \leq \phi A_g F_y$ X_u of electrode classification used
	Shear		Lesser of: (a) base metal $V_r = 0.67 \phi_w A_m F_u$ or (b) weld metal $V_r = 0.67 \phi_w A_w X_u$		Lesser of: (a) base metal $V_r = 0.67 \phi_w A_m F_u$ or (b) weld metal $V_r = 0.67 \phi_w A_w X_u$ X_u of electrode classification used

Table 11.2(b): Continued

Type of Weld	Type of Load and its Direction Respective to Line of Weld	Matching Conditions		Nonmatching Conditions	
		Requirements for Matching (1)	Factored Resistances	Extent of Nonmatching	Factored Resistances
1	2	3	4	5	6
Fillet Welds	Tension or compression parallel to axis of weld	Not mandatory, but if matching electrode classification used, see Col. 4. For nonmatching, see Cols. 5 and 6	Same as calculated for base metal	Electrode classification lower or higher than matching	Same as for base metal (3)
	Tension or compression normal to axis of weld	Not mandatory, but if matching electrode classification used, see Col. 4 For permitted conditions of nonmatching see Cols 5 and 6	Lesser of: (a) base metal $V_r = 0.67 \phi_w A_m F_u$ or (b) weld metal $V_r = 0.67 \phi_w A_w X_u (1.00 + 0.50 \sin^{1.5} \theta)$ (8)	Electrode classification lower than matching Electrode classification one designation higher than matching	Lesser of: (a) base metal $V_r = 0.67 \phi_w A_m F_u$ or (b) weld metal $V_r = 0.67 \phi_w A_w X_u (1.00 + 0.50 \sin^{1.5} \theta)$ (8)
	Shear		Lesser of: (a) base metal $V_r = 0.67 \phi_w A_m F_u$ or (b) weld metal $V_r = 0.67 \phi_w A_w X_u$ (8)	X_u of lower electrode classification when used; OR of matching electrode classification, when higher classification than matching is used	X_u of lower electrode classification when used; OR of matching electrode classification, when higher classification than matching is used
Plug and slot welds	Shear				

Notes:

- (1) For matching materials and electrode classification refer to Table 11.1.
- (2) Electrodes of strength lower than that shown for the corresponding base metal group of Table 11.1 may be used for complete joint penetration groove welds when approved by the Engineer.
- (3) If shear is transferred between components, the design value is the smaller of that for the base metal or the weld metal.
- (4) For hollow structural sections, the provisions of Appendix L may be used.
- (5) Factored resistances of the joints are calculated as for base metal, but on Area A = area of the effective fusion face projected normal to the compression + area of base metal in contact bearing.
- (6) See Appendix M, Figure M3.
- (7) When overall ductile behaviour is desired (i.e., member yielding before weld fracture), $A_n F_u$ must be greater than $A_g F_y$.
- (8) θ = angle of axis of weld with the line of action of force (0° for a longitudinal weld and 90° for a transverse weld). Conservatively, $(1.00 + 0.50 \sin^{1.5})$ can be taken as 1.0.
- (9) A_n = effective area of fusion face normal to the tensile force.
- (10) A_g = gross area of tension member.

**Table 12.2(b):
Factored Resistances of Welds for Cyclically Loaded Structures
(extracted from CSA W59 - see Clause 12.3.5)**

Type of Weld	Type of Load and its Direction Respective to Line of Weld	Matching Conditions		Nonmatching Conditions	
		Requirements for Matching (1)	Factored Resistances	Extent of Nonmatching	Factored Resistances
1	2	3	4	5	6
Complete joint penetration groove welds (2)	Tension or compression parallel to axis of weld	Not mandatory, but if matching electrode classification used, see Col. 4. For nonmatching, see Cols. 5 and 6	Same as calculated for base metal	Electrode classification lower or higher than matching	Same as calculated for base metal (3)
	Compression normal to axis of weld	Mandatory			
	Tension normal to axis of weld				
	Shear	Mandatory (for exceptions see Note (2) and Cols. 5 and 6)	Lesser of: (a) base metal $V_r = 0.67 \phi_w A_m F_u$ or (b) weld metal $V_r = 0.67 \phi_w A_w X_u$	Electrode classification lower than matching	Lesser of: (a) base metal $V_r = 0.67 \phi_w A_m F_u$ or (b) weld metal $V_r = 0.67 \phi_w A_w X_u$ X_u of electrode classification used
Partial joint penetration groove welds (4) (6)	Tension or compression parallel to axis of weld	Not mandatory, but if matching electrode classification used, see Col. 4 For nonmatching, see Cols. 5 and 6	Same as calculated for base metal	Electrode classification lower or higher than matching	Same as calculated for base metal (3)
	Compression normal to axis of weld	Mandatory	See Note (5)		
	Tension normal to axis of weld (7) (9) (10)	Not mandatory, but if matching electrode classification used, see Col. 4 For permitted condition of nonmatching, see Cols. 5 and 6	$T_r = \phi_w A_n F_u \leq \phi A_g F_y$ Partial joint penetration groove weld combined with a fillet weld: $T_r = \phi_w \sqrt{(A_n F_u)^2 + (A_w X_u)^2} \leq \phi A_g F_y$ where A_n refers to the partial joint penetration groove weld and A_w refers to the fillet weld	Electrode classification lower than matching	Lesser of: (a) $T_r = \phi_w A_n F_u \leq \phi A_g F_y$ or (b) $T_r = \phi_w A_n X_u \leq \phi A_g F_y$ Partial joint penetration groove weld combined with a fillet weld, lesser of: (a) $T_r = \phi_w \sqrt{(A_n F_u)^2 + (A_w X_u)^2} \leq \phi A_g F_y$ Or (b) $T_r = \phi_w \sqrt{(A_n X_u)^2 + (A_w X_u)^2} \leq \phi A_g F_y$ X_u of electrode classification used
	For restrictions see Clause 12.4.14(b)				

Table 12.2(b): Continued

Type of Weld	Type of Load and its Direction Respective to Line of Weld	Matching Conditions		Nonmatching Conditions	
		Requirements for Matching (1)	Factored Resistances	Extent of Nonmatching	Factored Resistances
1	2	3	4	5	6
	Shear		Lesser of: (a) base metal $V_t = 0.67 \phi_w A_m F_u$ or (b) weld metal $V_t = 0.67 \phi_w A_w X_u$ Same as calculated for base metal		Lesser of: (a) base metal $V_t = 0.67 \phi_w A_m F_u$ or (b) weld metal $V_t = 0.67 \phi_w A_w X_u$ Same as calculated for base metal
Fillet Welds (11)	Tension or compression parallel to axis of weld	Not mandatory, but if matching electrode classification used, see Col. 4.		Electrode classification lower or higher than matching	
	Shear induced by tension or compression normal to axis of weld	For nonmatching, see Cols. 5 and 6 Not mandatory, but if matching electrode classification used, see Col. 4 For permitted conditions of nonmatching see Cols 5 and 6	Lesser of: (a) base metal $V_t = 0.67 \phi_w A_m F_u$ or (b) weld metal $V_t = 0.67 \phi_w A_w X_u (1.00+0.50 \sin^{1.5} \theta)$ (8)	Electrode classification lower than matching or electrode classification one designation higher than matching	Lesser of: (a) base metal $V_t = 0.67 \phi_w A_m F_u$ or (b) weld metal $V_t = 0.67 \phi_w A_w X_u (1.00+0.50 \sin^{1.5} \theta)$ (8) X_u of lower electrode classification when used; OR of matching electrode classification, when higher classification than matching is used
Plug and slot welds For restrictions see Clause 12.4.14 9(g)	Shear		Lesser of: (a) base metal $V_t = 0.67 \phi_w A_m F_u$ or (b) weld metal $V_t = 0.67 \phi_w A_w X_u$ (8)		Lesser of: (a) base metal $V_t = 0.67 \phi_w A_m F_u$ or (b) weld metal $V_t = 0.67 \phi_w A_w X_u$ (11) X_u of lower electrode classification when used; OR of matching electrode classification, when higher classification than matching is used

Notes:

- (1) For matching materials and electrode classification refer to Table 12.1.
- (2) Electrodes of strength lower than that shown for the corresponding base metal group of Table 12.1 may be used for complete joint penetration groove welds when approved by the Engineer.
- (3) If shear is transferred between components, the design value is the smaller of that for the base metal or the weld metal.
- (4) For hollow structural sections, the provisions of Appendix L may be used.
- (5) Factored resistances of the joints are calculated as for base metal, but on Area A = area of the effective fusion face projected normal to the compression + area of base metal in contact bearing.
- (6) See Appendix M, Figure M3.
- (7) When overall ductile behaviour is desired (i.e., member yielding before weld fracture), $A_w F_u$ must be greater than $A_g F_y$.
- (8) θ = angle of axis of weld with the line of action of force (0° for a longitudinal weld and 90° for a transverse weld). Conservatively, $(1.00+0.50 \sin^{1.5})$ can be taken as 1.0.
- (9) A_w = effective area of fusion face normal to the tensile force.
- (10) A_g = gross area of tension member.
- (11) For fillet welds in railway bridges use 0.9 of the factored resistances calculated from this Table.

8.5 Fillet Weld Strength

Before we get into the actual design, we should be familiar with the weld strengths and how they are derived. Fillet welds are the most commonly used type of weld. The following explanation shows the geometry and the derivation of its shear strength in both LSD and ASD methods. **Figure 8.2** illustrates the shear condition in which the applied load is parallel to the weld A ($\theta = 0^\circ$)

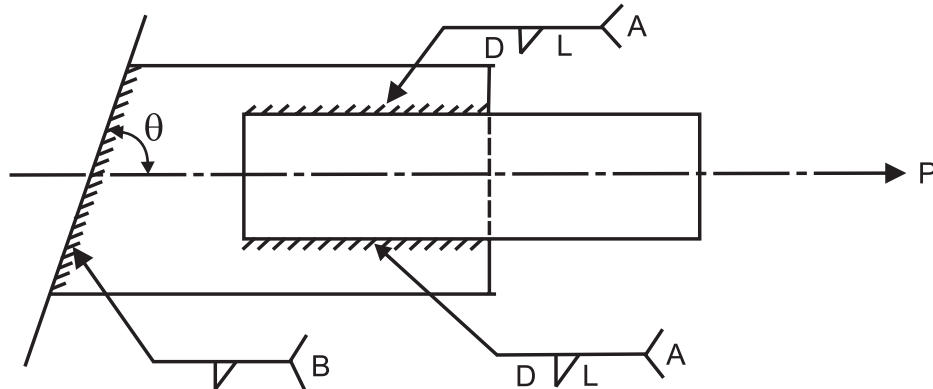


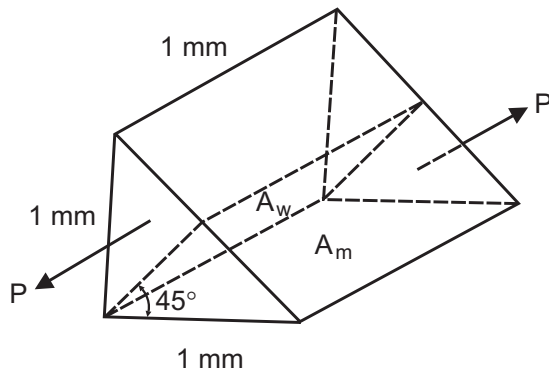
Figure 8.2: Shear condition in which applied load is parallel to the weld.

For weld B, under static loading in limit states design:

$$\text{weld metal} \quad V_r = 0.67 \times \phi_w A_w X_u (1.00 + 0.5 \sin^{1.5} \theta)$$

Fillet Weld Strength

Limit States Design (LSD) – metric units



Electrodes: E4918, $X_u = 490$ MPa
 Steels: G40.21-350W, $F_u = 450$ MPa
 (see strengths given in CAN/CSA S16-01)

See CSA W59, Table 11.2(b) Fillet Welds

Weld shear strength at throat, $\theta = 0^\circ$:

$$\begin{aligned} V_{rw} &= 0.67 \phi_w A_w X_u \\ &= 0.67 \times 0.67 \times 490 \times A_w = 220 A_w \text{ (N)} \end{aligned}$$

Shear on the faying surface: $A_m = 1.414 A_w$

$$\begin{aligned} V_{rm} &= 0.67 \phi_w A_m F_u \\ &= 0.67 \times 0.67 \times 450 \times A_m = 286 A_w > V_{rw} \end{aligned}$$

therefore, weld strength governs.

The weld shear strength on the faying surface to balance strength at throat will be:

$$V_{rw} = \frac{220 A_w}{1.414 A_w} = 156 \text{ MPa}$$

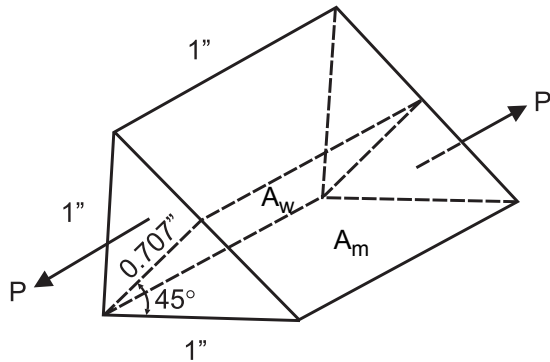
A fillet weld is usually designed according to the leg size. The factored shear resistance of various fillet sizes is shown in Table 3-24 and Table 3-25 of CISC Handbook of Steel Construction.

Example:

Calculate the strength of 8 mm fillet weld:

$$V_r = 8 \times 156/1000 = 1.24 \text{ kN/mm}$$

Fillet Weld Strength
Limit States Design (LSD) - Imperial Units



Electrodes: E70XX, $X_u = 71.0$ ksi
 Steels: G40.21-350W, $F_u = 65.0$ ksi
 (see strengths given in CAN/CSA S16-01)

See CSA W59, Table 11.2(b) Fillet Welds

Weld shear strength at throat:

$$V_{rw} = 0.67 \phi_w A_w X_u$$

$$= 0.67 \times 0.67 \times 71 \times A_w = 31.9 A_w \text{ (kips)}$$

Shear on faying surface: $A_m = 1.414 A_w$

$$V_{rw} = 0.67 \phi_w A_m F_u$$

$$= 0.67 \times 0.67 \times 65 \times A_m = 41.3 A_w > V_{rw}$$

therefore, weld strength governs.

The weld shear strength on faying surface to balance strength at throat will be:

$$V_{rw} = \frac{31.9 A_w}{1.414 A_w} = 22.6 \text{ ksi}$$

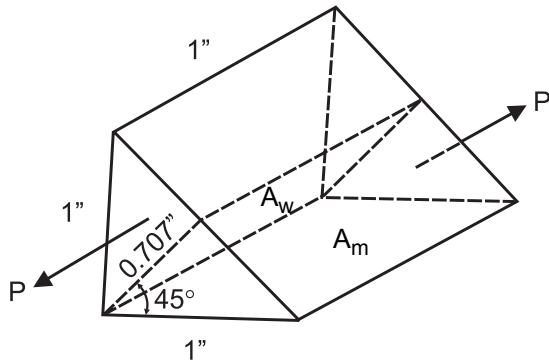
Fillet weld is usually designed according to the leg size. The factored shear resistance of various fillet sizes is shown in Table 3-24 and Table 3-25 of the CISC Handbook of Steel Construction (in KN/mm).

In imperial units, the fillet weld strength of 1/16 per inch is: $\frac{22.6}{16} = 1.41 \text{ K} / \frac{1}{16} \text{ in}$

Example: Calculate the strength of 1/4 in fillet welds:

$$V_r = 4 \times 1.41 = 5.64 \text{ kips/in}$$

Fillet Weld Strength
Allowable Stress Design (ASD) - Imperial Units



Electrodes: E70XX, $X_u = 71.0$ ksi
 Steels: CSA G40.21 350W or
 ASTM A572 Grade 50
 $F_y = 50$ ksi

See CSA W59, Table 11-2(a) Fillet Welds

Weld shear strength at throat:

$$\begin{aligned} V_{rw} &= 0.3 A_w X_u \\ &= 0.3 \times 71.0 \times A_w = 21.3 A_w \text{ (kips)} \end{aligned}$$

Shear on faying surface: $A_m = 1.414 A_w$

$$\begin{aligned} V_{rw} &= 0.4 A_m F_u \\ &= 0.4 \times 50 \times 1.414 A_w = 28.28 A_w > V_{rw} \end{aligned}$$

Therefore, weld strength governs.

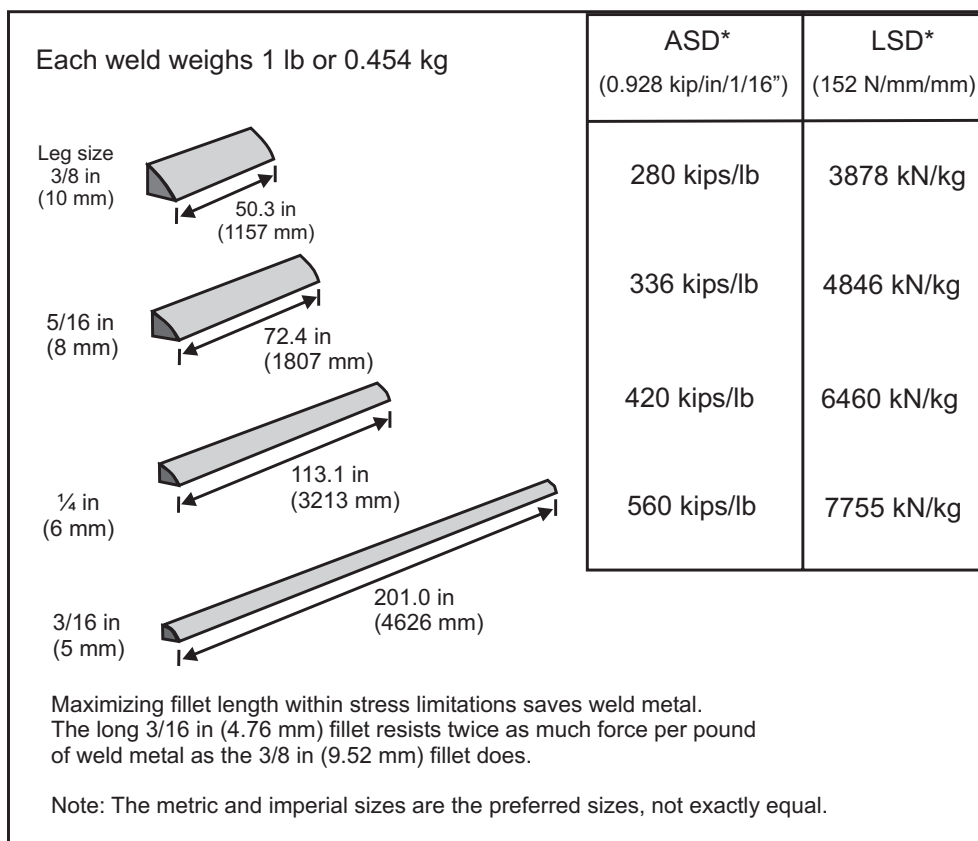
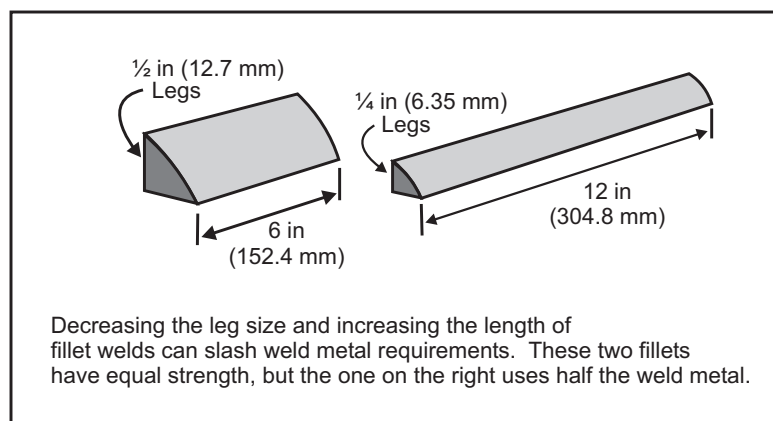
The shear stress on faying surface in the weld to balance that in the throat will be:

$$\frac{21.3}{1.414} = 15.06 \text{ ksi, and } \frac{15.06}{16} = 0.941 \text{ K} / \frac{1}{16} \text{ in.}$$

Example: Calculate the strength of 1/4 in fillet by ASD method.

$$V_r = 4 \times 0.941 = 3.76 \text{ kips/in}$$

It should be noted that in sizing the fillet weld, the designer should be aware that the smaller size and longer fillet is more economical than the larger size and shorter fillet. **Figure 8.3** illustrates this fact by comparing different fillet sizes and lengths of the same weight of weld metal.



* Based on $X_u = 70$ ksi or 480 MPa

Figure 8.3: Smaller, longer welds can reduce weld deposit by 50%.

8.6 Fillet Weld Groups

Design tables of fillet weld groups are given in both the CISC Handbook of Steel Construction and AISC Manual of Steel Construction. It should be noted that these coefficients in the tables were derived by testing under ultimate loading. Therefore, they should only be used in similar weld configurations and loading directions. The loadings in the CISC Tables are given in parallel to one weld line of each weld group. The loadings in the AISC Tables are given at 15° angle intervals to one weld line of each weld group. If the actual loading is in between the angles (for example 23° is between 15° and 30°), the coefficients in the lower angle (15°) should be used. Otherwise, direct analysis should be carried out. Straight line interpolation may give unsafe results. **Figure 8.4** shows the weld group configurations.

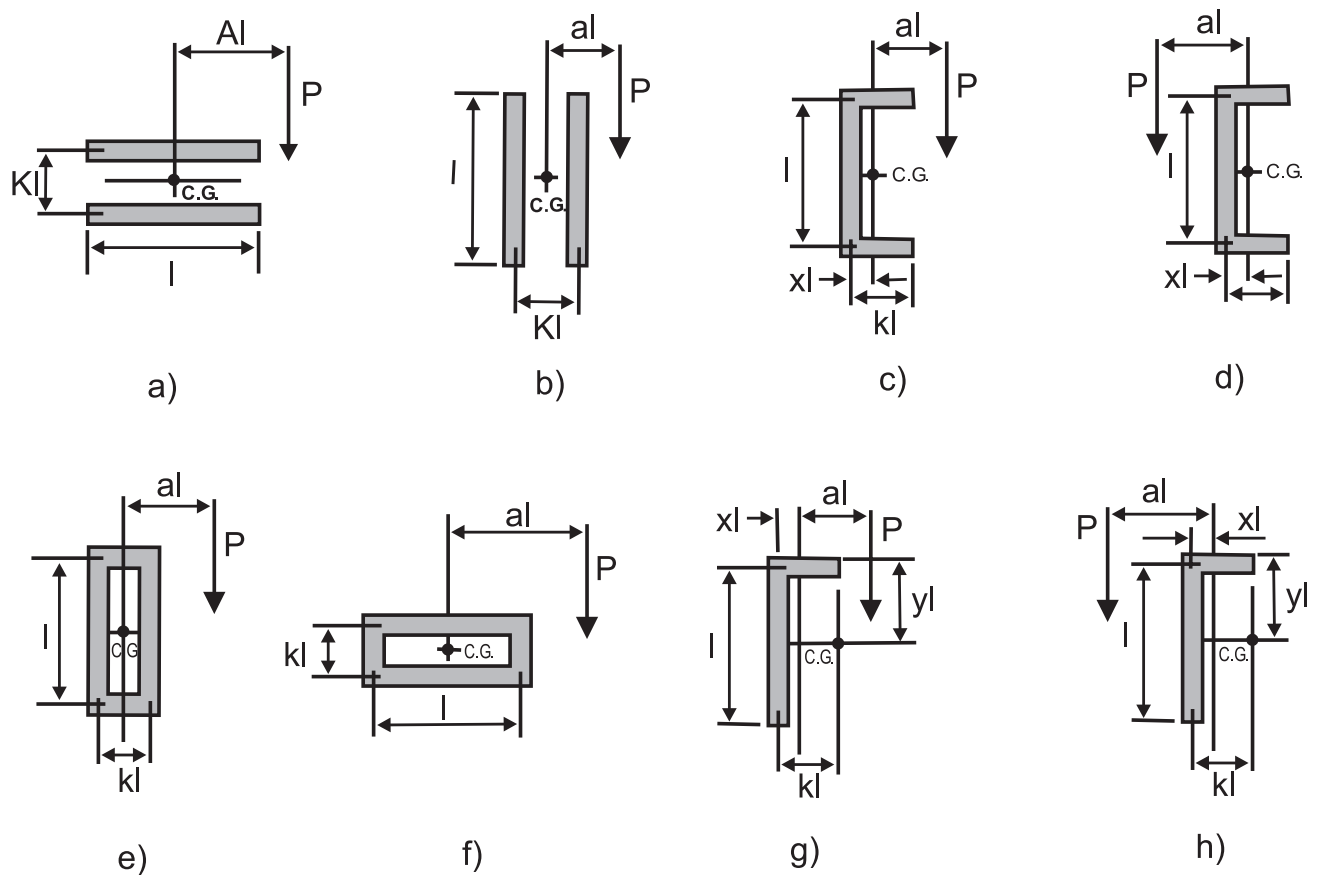


Figure 8.4: Weld group configurations.

In designing weld joints with fillet welds, the designer should first inspect the member thickness. There is a minimum required fillet size for the thickest member connected which is given by **Table 4-4** in CSA W59. The reason for this requirement is to prevent weld cracking due to fast cooling and restraint.

Table 4-4: Minimum Fillet Size

Material Thickness, t of Thicker Part Joined (mm)	Minimum Size of Fillet Weld (mm)	
$T \leq 12$	5	Single pass welds must be used.
$12 < t \leq 20$	6	
$20 < t$	8	

Note: The minimum fillet sizes in Table 4-4 need not apply if welding procedures have been established to prevent cracking as provided in Clause 5.7.

The following example illustrates the use of the fillet weld group tables in the *CISC Handbook*, 7th Edition. The weld strengths are also based on *CISC Handbook*, 7th Edition.

Example 1

Given: A column bracket as shown in the figure. The fillet weld group is rectangular shaped. E4918 electrodes and CSA G40.21, 350W steels. Find the fillet weld size required.

Solution: Use fillet weld group Table 3-30:

$$l = 400 \text{ mm}$$

$$a\ell = 420 - \frac{120}{2} = 360 \text{ mm}$$

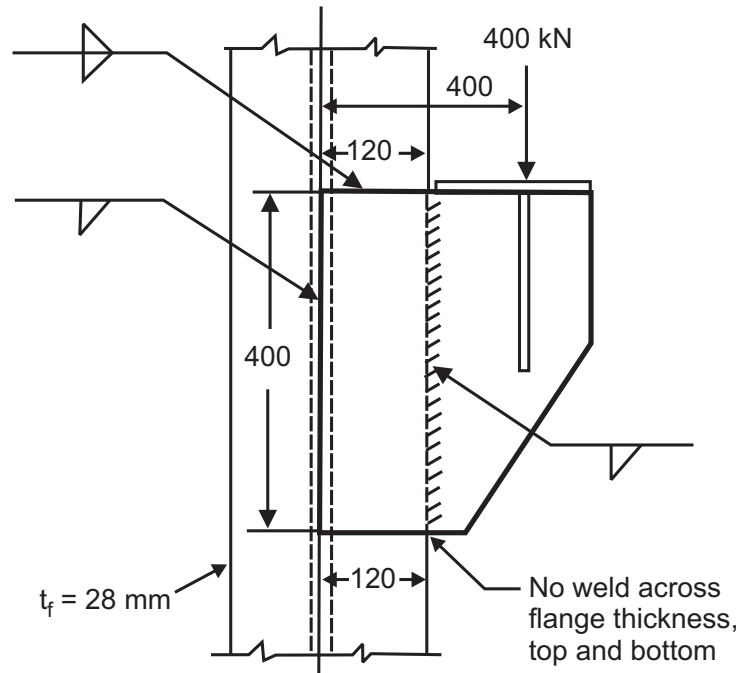
$$\alpha = 0.9$$

$$kl = 120 \text{ mm}$$

$$K = \frac{120}{400} = 0.3$$

From Table $C = 0.187$

Weld Size $D = \frac{400}{0.187 \times 400} = 5.35 \text{ mm}$



Use 8 mm fillet to satisfy $t_f = 28 \text{ mm}$. This is the minimum size required to meet Table 4.4, CSA W59.

Example 2: Truss Gusset Plate Connection

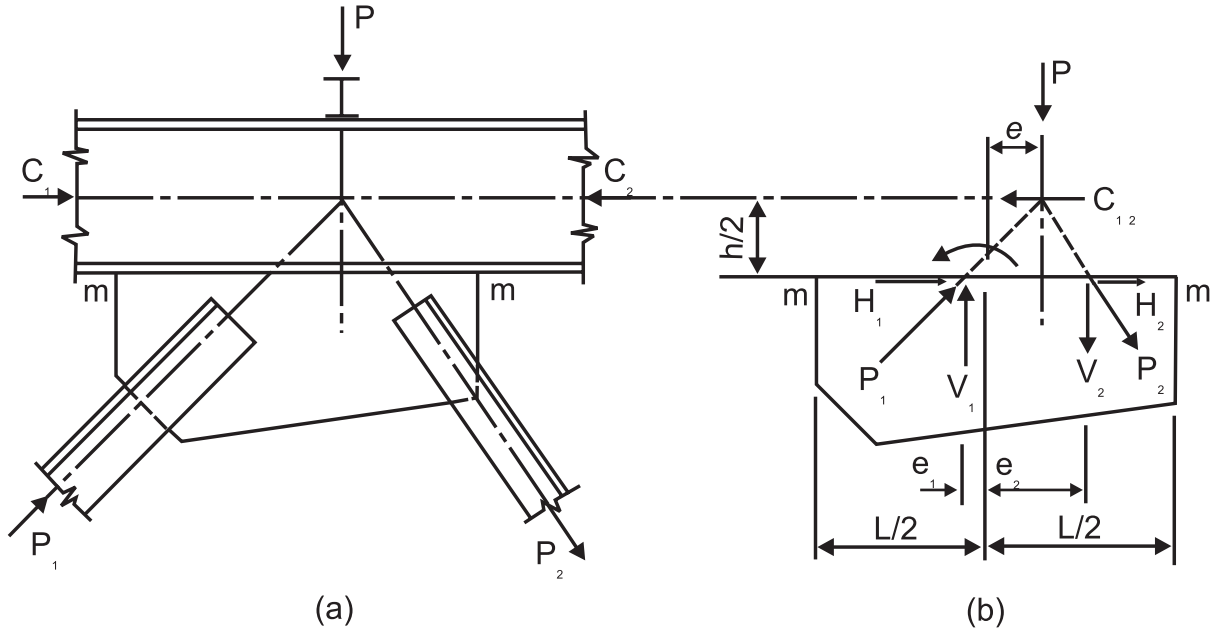


Figure 8.5: Truss joint with gusset plate.

A typical to chord joint with gusset plate is shown in **Figure 8.5(a)**. **Figure 8.5(b)** shows all the forces acting on the gusset plate. The gusset plate to chord may be welded by either CJPJ or double fillets.

Moment on section m-m:

$$M_m = C_{12} \times \frac{h}{2} - Pxe, \quad \text{where } C_{12} = C_2 - C_1, \quad \text{Assume } C_2 > C_1 \quad (1)$$

$$\text{or } M_m = V_1 \times e_1 + V_2 \times e_2 \quad (2)$$

Use of equation (1) is rather straightforward, no need to resolve P_1 and P_2 into H and V components.

$$\text{Direct forces, } \quad \Sigma V = 0 \quad P = V_1 - V_2 \quad (3)$$

$$\text{Shear forces, } \quad \Sigma H = 0 \quad C_{12} = H_1 + H_2 \quad (4)$$

Calculate the maximum stress in gusset plate along m-m:

$$\text{bending} \quad f_b = \frac{M_m}{\frac{1}{6}L^2t} \quad \text{MPa}$$

$$\text{direct} \quad f_c = \frac{P}{Lt} \quad \text{MPa}$$

$$\text{shear} \quad f_v = \frac{C_{12}}{Lt} \quad \text{MPa}$$

$$\text{resultant stress} \quad f_r = \sqrt{(f_b + f_c)^2 + (f_v)^2} \quad \text{MPa}$$

The above formulae are applicable when the gusset plate is welded by CJPG. When double fillet welds are used:

$$\text{bending} \quad f_b = \frac{M_m}{\frac{1}{3}L^2} \quad \text{kN/mm/weld}$$

$$\text{direct} \quad f_c = \frac{P}{2L} \quad \text{kN/mm/weld}$$

$$\text{shear} \quad f_v = \frac{C_{12}}{2L} \quad \text{kN/mm/weld}$$

$$\text{select fillet size for} \quad f_r \geq \sqrt{(f_b + f_c)^2 + (f_v)^2} \quad \text{kN/mm/weld}$$

Example 3:

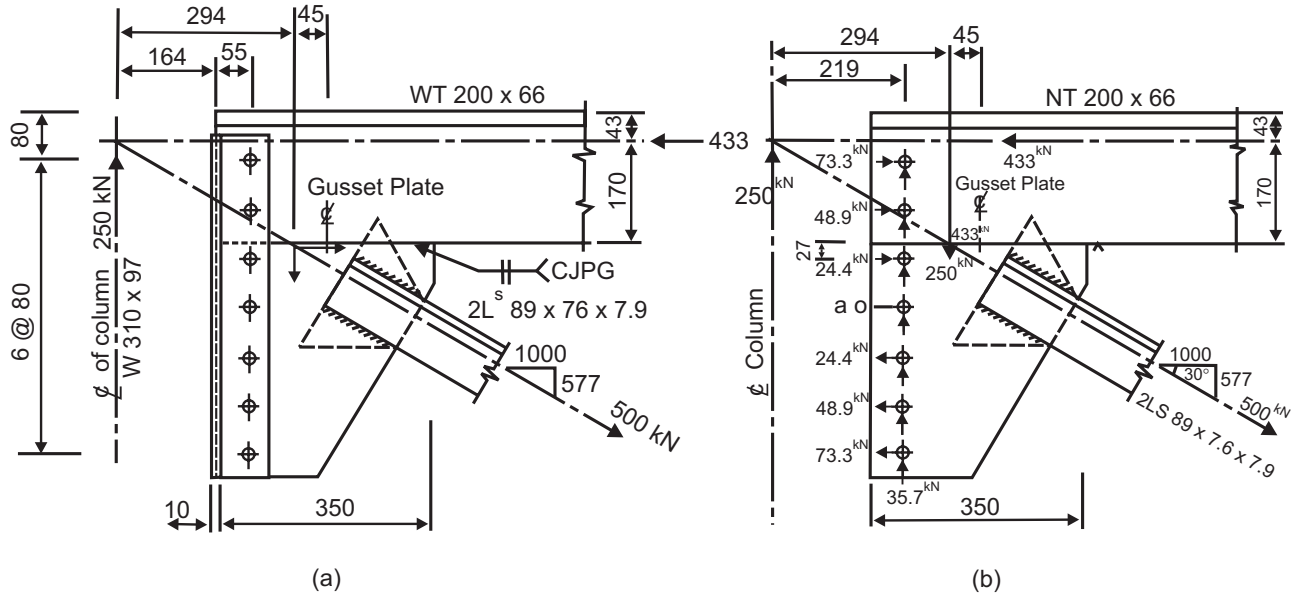


Figure 8.6: Typical truss end to column connection.

The detail of truss end connection is shown in **Figure 8.6(a)**. The header angles are bolted to the truss end. This type of connection is normally used because it provides more room for erection adjustment and reaming or short slotted holes can be used.

Find the forces applied at each bolt:

$$\text{Vertical force} \quad R_v = \frac{250}{7} = 35.7^{\text{kN}} \quad \text{on each bolt}$$

$$\text{Horizontal force} \quad M = 250 \times 219 = 54750 \text{ kN/mm} \quad (\text{a})$$

Let the force in the first bolt above and below the centroid of the bolt group (the fourth bolt) be P_H , then, the second and third bolts above and below the centroid will be $2P_H$ and $3P_H$ respectively.

Find P_H by taking moment about the centroid of the bolt group:

$$M = P_H (1 \times 160 + 2 \times 320 + 3 \times 480) = 2240 P_H \quad (\text{b})$$

Since (a) = (b)

$$P_H = \frac{54750}{2240} = 24.4^{\text{kN}}$$

$$2P_H = 48.9^{\text{kN}}$$

$$3P_H = 73.3^{\text{kN}}$$

The bolt loads are shown in **Figure 8.6(b)**.

Check gusset plate along line A-A, use CJPG weld:

Shear: $V = 433 + 24.4 - 24.4 - 48.9 - 73.5 = 310.8^{\text{kN}}$

$$f_v = \frac{310.8 \times 10^3}{350 \times 13} = 68.3 \text{ MPa}$$

Direct tension: $f_t = \frac{250 \times 10^3}{350 \times 13} = 55.0 \text{ MPa}$

Bending: take moment about the centre of the gusset plate

$$M = 250 \times 45 + 24.4 \times 27 - 24.4 \times 187 - 48.9 \times 267 - 73.3 \times 347 = 41270^{\text{kN/mm}}$$

$$f_b = \frac{41270 \times 10^3}{\frac{1}{6} \times 13 \times 350^2} = 155.5 \text{ MPa}$$

Resultant stress: $f_r = \sqrt{(68.3)^2 + (55.0 + 155.5)^2} = 221.3 \text{ MPa} < 0.9F_y$

Other design check: Shear yielding and rupture, and tension yielding and rupture, should all be checked.

8.7 Restrained Members and Moment Connections

When beams, girders or trusses are subject to both reaction shear and end moment due to full or partial end restraint or to continuous or cantilever construction, their connections shall be designed for the combined effect of shear, bending and axial load.

When beams are rigidly framed to the flange of an I-shaped column, stiffeners shall be provided on the column web if the following bearing and tensile resistances of the column flange are exceeded:

(a) opposite the compression flange of the beam when:

$$B_r = \phi w_c (t_b + 10t_c) F_{yc} < \frac{M_f}{d_b}$$

except that for members with Class 3 or 4 webs,

$$B_r = \phi \frac{640000}{(h_c/w_c)^2} w_c (t_b + 10t_c)$$

(b) opposite the tension flange of the beam when:

$$T_r = \phi 7t_c^2 F_{yc} < \frac{M_f}{d_b}$$

where

w_c = thickness of column web

t_b = thickness of beam flange

k = distance from outer face of column flange to web-toe of fillet, or to web-toe of flange-to-web weld in a welded column

F_{yc} = specified yield point of column

d_b = depth of beam

h_c = clear depth of column web

t_c = thickness of column flange

The stiffener or pair of stiffeners opposite either beam flange must develop a force equal to:

$$F_{st} = \frac{M_f}{d_b} - B_r$$

Stiffener shall also be provided on the web of columns, beams or girders if V_r calculated from Clause 13 is exceeded, in which case the stiffener or stiffeners must transfer a shear force equal to:

$$V_{st} = V_f - 0.55 \phi w d F_y$$

In all cases, the stiffeners shall be connected so that the force in the stiffener is transferred through the stiffener connection. When beams frame to one side of the column only, the stiffeners need not be longer than one-half of the depth of the column.

Note: The factored shear resistance of column web: $V_r = 0.55 \phi w d F_y$.

In the case of direct beam-to-column moment connections, the full moment capacity can be developed with flanges fully welded and the beam web is either bolted or welded to a single shear plate connection. The column stiffeners, when required, are usually of same size and thickness for both tension and compression beam flanges.

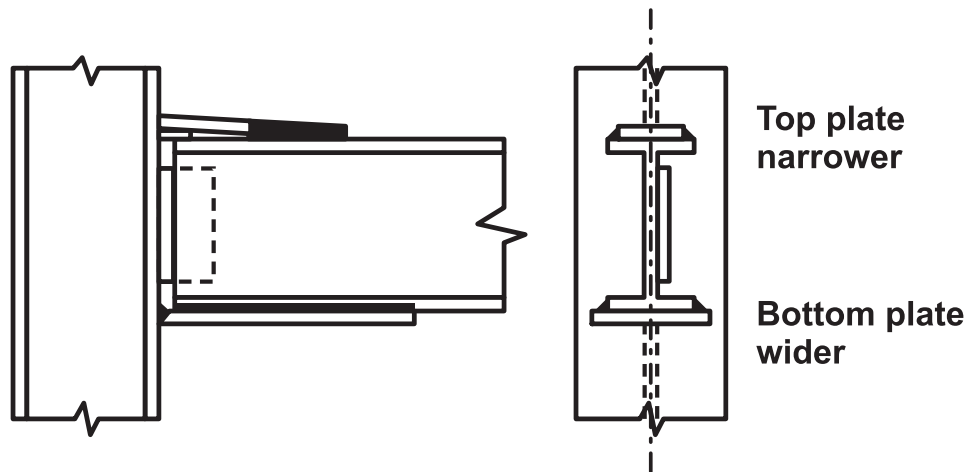


Figure 8.7: Plated moment connection.

However, in the case of plated rigid moment connections, the top and bottom plates are usually of different thicknesses since downhand welding considerations will dictate a narrower, thicker top plate and wider, thinner bottom plate (**Figure 8.7**).

When beams are framed to both column flanges, their flanges are not always on the same elevation. If the difference in elevation is not more than 50 mm (2 in) Graham, Sherbourne and Khabbaz suggest that one horizontal stiffener may be used provided that its thickness is increased by a factor of 1.7.

In the case that the beam is framed only to one flange of the column, the stiffeners, if required, need only be extended to within half of the column depth. However, the welds connecting the stiffener to the column web must be sufficient to develop the force P :

$$P = \phi A_{st} F_y$$

In the case of built-up column sections the web-to-flange welds may require strengthening before these provisions are applied.

8.7.1 Panel Zone

In addition to the stiffeners opposite the tension and compression flanges for transferring the flange forces, the column web between the horizontal flange stiffeners, the “panel zone” (**Figure 8.8**), may also require stiffening if the plastic shear capacity of the web, $0.55w_dF_y$, is exceeded. This is based on the Huber-Henckey-von Mises criterion in consideration of the coexistence of axial load in the column web.

In the case of built-up columns where there is a large differential in beam moments causing high longitudinal shear stresses between the column web and flange, larger weld capacity (hence larger weld size) may be required in the connection region. Increased fillet size or partial grooves with superimposed fillets may be appropriately used here. **Figure 8.8** illustrates the basic requirements for the welds holding the component plates in a built-up column section together. Further explanation can be itemized as follows:

1. The entire length of the column must have sufficient welds to withstand any longitudinal shear between floors resulting from the floor load or other external loads – with or without earthquake loads.
2. Within the region of beam connection to the column, the longitudinal shear is much higher because of the abrupt change in flexural stresses within the depth of the beam.
3. The regions of column flange in contact with beam flanges also transfer the direct forces (tension or compression), through a portion of the web-to-flange welds.

Summing up these conditions, heavier weld is usually required in the connection region. There are several ways in which different types of welds can be combined when fabricating built-up columns to satisfy the above requirements, which are shown in **Figure 8.9**.

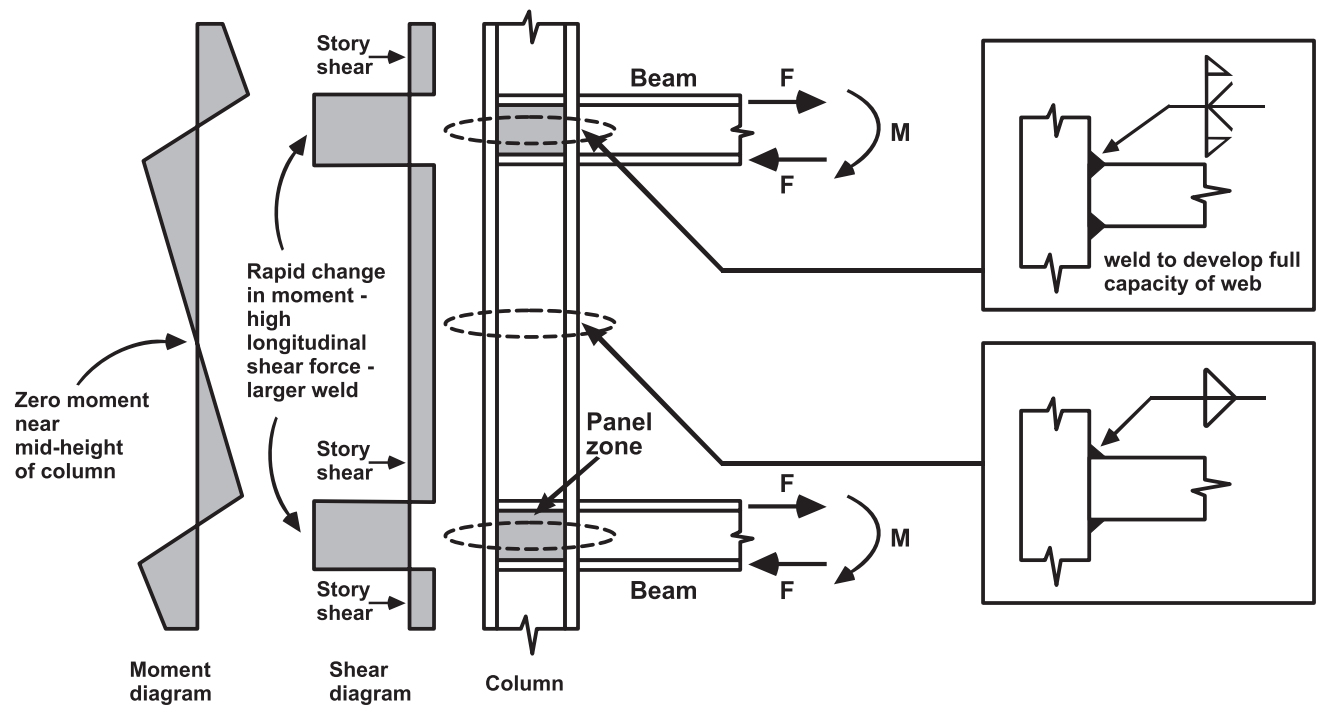
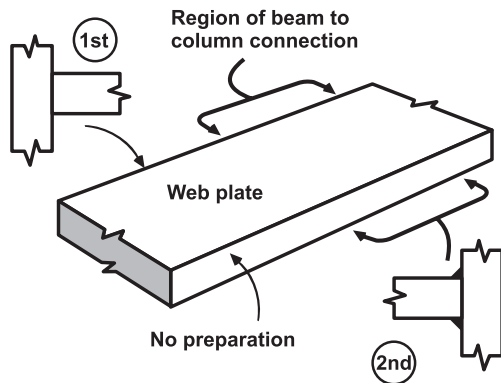


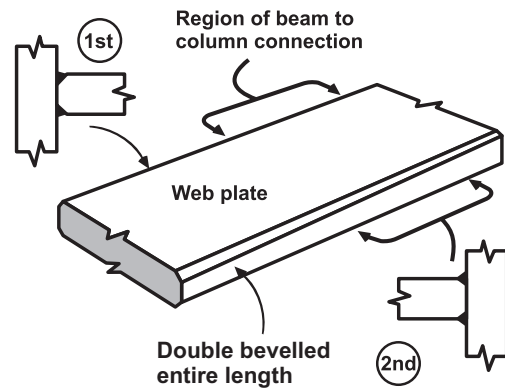
Figure 8.8: Welding requirements for built-up columns.

Typical analysis and design procedures as they apply to the basic types of two-way, one-way and square-knee rigid connections follow next. Some degree of repetition will be encountered in these general solutions. However, the intent is to present a complete design procedure in each individual case. Numerical examples illustrating these procedures are included at the end of this book.



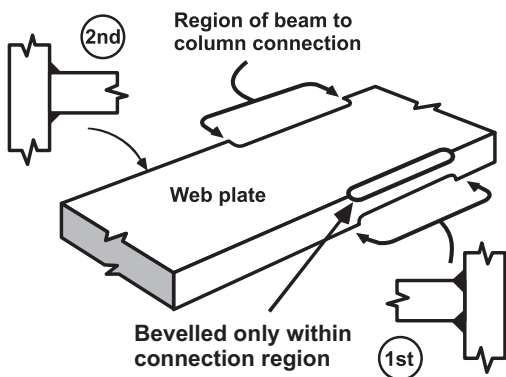
Case 1

If the weld sizes are not too large, the column may first be fillet welded along its entire length. Second, additional passes are made in the connection region to bring the fillet weld up to the proper size.



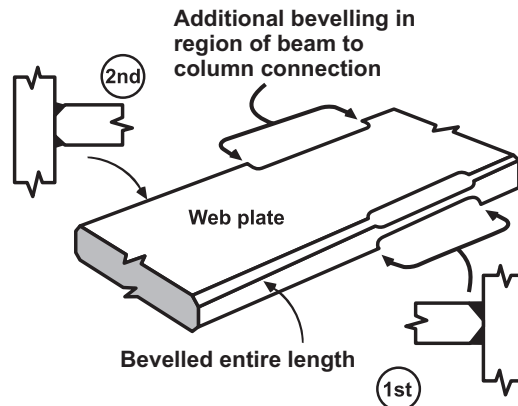
Case 2

The web plate is bevelled to the proper depth on all four edges along the entire length. The groove weld is first made along the entire length. Second, a fillet weld is made over the groove weld within the connection region to bring it up to the proper size.



Case 3

The web plate is bevelled to the proper depth along short lengths within the connection region. First, a groove weld is made flush with the surface within the connection region. Second, a fillet weld is made along the entire length of the column.

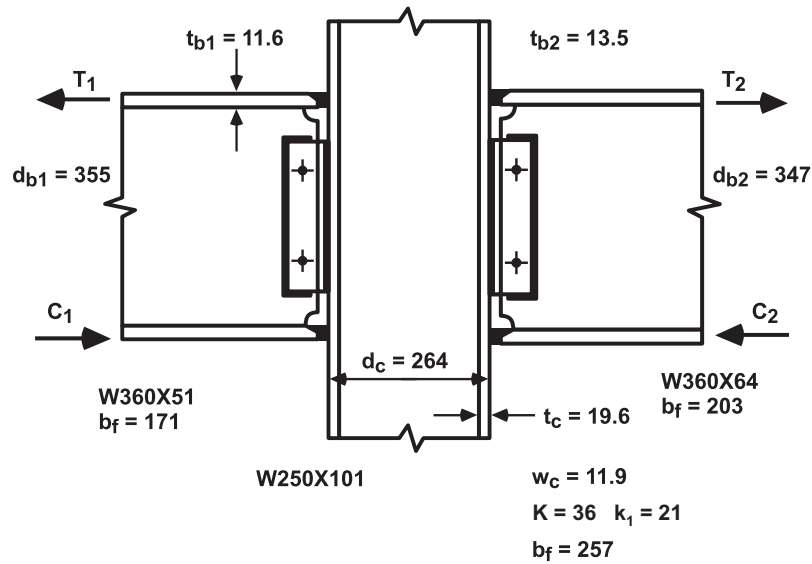


Case 4

The web plate is bevelled to the proper depth on all four edges along the entire length. Within the connection region the web is further bevelled to a deeper depth. First, a groove weld is made within the connection region until the plate edge is built up to the height of the first bevel. Second, a groove weld is made along the entire length.

Figure 8.9: Alternate methods for making welds in a built-up column at the point of beam framing.

Example 1 Two-Way Rigid Beam-Column Connection



Given:

Sections as shown in **Figure 8.10**
Steel designation: CSA G40.21 - 350W, $F_y = 350$ MPa.

Problem:

Investigate column stiffening requirements for the tension and compression flanges of beams.
Investigate column web for shear.

Figure 8.10: Data for Example 1.

Compression Flanges:

Since no moment values are given, the maximum moment capacities will be connected. From Beam Selection Table of CISC's *Handbook of Steel Construction* both beams are Class 1 sections (Table 5-1), and maximum moment is $M_r = M_p$.

From Beam Selection Tables of the Handbook M_p can be found under the Heading " M_r ".

for W360 x 51, $M_r = 281$ kN•m

W360 x 64, $M_r = 359$ kN•m

or M_p may be calculated as $\phi Z F_y$

for W360 x 51, $M_p = 0.9 \times 894 \times 10^3 \text{ mm}^3 \times 350 \text{ MPa} / 10^6$
 $= 281$ kN•m

W360 x 64, $M_p = 0.9 \times 1140 \times 10^3 \text{ mm}^3 \times 350 \text{ MPa} / 10^6$
 $= 359$ kN•m

(Divided by 10^6 converts newton-millimetres to kilonewton-metres)

Computing flange forces as M/d

for W360 x 51,

$$C_1 = \frac{281 \text{ kN} \cdot \text{m} \times 10^3 \text{ mm/m}}{355 \text{ mm}} = 792 \text{ kN}$$

for W360 x 64,

$$C_2 = \frac{359 \text{ kN} \cdot \text{m} \times 10^3 \text{ mm/m}}{347 \text{ mm}} = 1035 \text{ kN}$$

(a) Considering W360 x 64,

Minimum Column web thickness not requiring horizontal stiffening opposite compression flange:

$$w_c = \frac{C_2}{\phi(t_2 + 10t_c)F_{yc}} = \frac{1035 \text{ kN} \times 10^3 \text{ N/kN}}{0.9(13.5 + 10 \times 19.6) \times 350 \text{ MPa}} = 16.6 \text{ mm}$$

Since $16.6 \text{ mm} > 11.9 \text{ mm}$ stiffeners are required.

Column web capacity:

$$\begin{aligned} B_r &= \phi W_c (t_{b2} + 10 \times t_c) F_y \\ &= 0.9 \times 11.9 \times (13.5 + 10 \times 19.6) \times 350 \times 10^{-3} \\ &= 785 \text{ kN} < 1035 \text{ kN} \end{aligned}$$

Force to be carried by stiffeners, $C_s = C_2 - C_w$

$$\begin{aligned} &= 1035 - 785 \text{ kN} \\ &= 250 \text{ kN} \end{aligned}$$

(b) Considering W360 x 51

Minimum column web thickness not requiring horizontal stiffening opposite compression flange:

$$\begin{aligned} w_c &= \frac{C_1}{\phi(t_{b1} + 10t_c)F_{yc}} \\ &= \frac{792 \text{ kN} \times 10^3 \frac{\text{N}}{\text{kN}}}{0.9(11.6 + 10 \times 19.6) \times 350 \text{ MPa}} \\ &= 12.1 \text{ mm} > 11.9 \text{ mm, therefore stiffeners are required.} \end{aligned}$$

Force to be carried by stiffener,

$$\begin{aligned}
 C_s &= C_1 - B_r = C_1 - \phi w_c (t_{bl} + 10t_c) F_{yc} \\
 &= 792 \text{ kN} - 0.9 \times 11.9 \text{ mm} (11.6 \text{ mm} + 10 \times 19.6 \text{ mm}) \times \frac{350 \text{ MPa}}{10^3 \frac{\text{N}}{\text{kN}}} \\
 &= 14 \text{ kN}
 \end{aligned}$$

The stiffener must be designed for the larger of the two forces, 291 kN.

Area of stiffeners required.

$$A_s = \frac{C_s}{\phi F_y} = \frac{250 \text{ kN} \times 10^3 \frac{\text{N}}{\text{kN}}}{0.9 \times 350 \text{ MPa}} = 921 \text{ mm}^2$$

Width of stiffeners

- a) W360 x 64 – beam flange width = 203 mm
- b) W250 x 101 – column flange width = 257 mm

Maximum width = (257 mm - 11.9 mm)/2 = 122 mm

Minimum effective width = 203/2 – 22 = 79 mm

Area of one stiffener = 921/2 = 460 mm²

$$\text{Maximum } b/t = \frac{145}{\sqrt{F_y}} = 7.8$$

Try two plates 12 x 85: 85/12 = 7.1 < 7.8, OK

effective width $b_{\text{net}} = 85 - 21 + 11.9/2 = 70 \text{ mm}$

net area $A_{\text{net}} = 70 \times 12 = 840 \text{ mm}^2 > 460 \text{ mm}^2$, OK.

Note: Usually the total width of stiffeners needs not be wider than beam flange, but narrow stiffeners result in larger fillet size at the stiffener end. This will be seen later in the design of stiffener welds. The AISC Specification states that the minimum one stiffener width shall not be less than one-third of beam flange, and the minimum thickness shall not be less than one-half of beam flange thickness.

Tension Flange:

Capacity of column flange opposite tension flange

$$\begin{aligned} T_r &= \phi 7t_c^2 F_y \\ &= 0.9 \times 7 \times 19.6^2 \text{ mm} \times 350 \text{ MPa}/10^3 \text{ N/kN} \\ &= 847 \text{ kN} \end{aligned}$$

Force to be carried by stiffener $T_s = T_2 - T_r$

therefore, $T_s = 1035 - 847$
 $= 188 \text{ kN} < 250 \text{ kN}$ used to design stiffener opposite compression flanges.
 Therefore, use same stiffeners as for compression flange.

Shear in Column Web:

Minimum web thickness not requiring reinforcement (equation 24) is

$$w_c = \frac{C_2 - C_1}{\phi 0.55 d_c F_y} = \frac{(1035 \text{ kN} - 792 \text{ kN}) \times 10^3 \frac{\text{N}}{\text{kN}}}{0.9 \times 0.55 \times 264 \text{ mm} \times 350 \text{ MPa}} = 5.3 \text{ mm} < 11.9 \text{ mm}$$

Web does not need reinforcement.

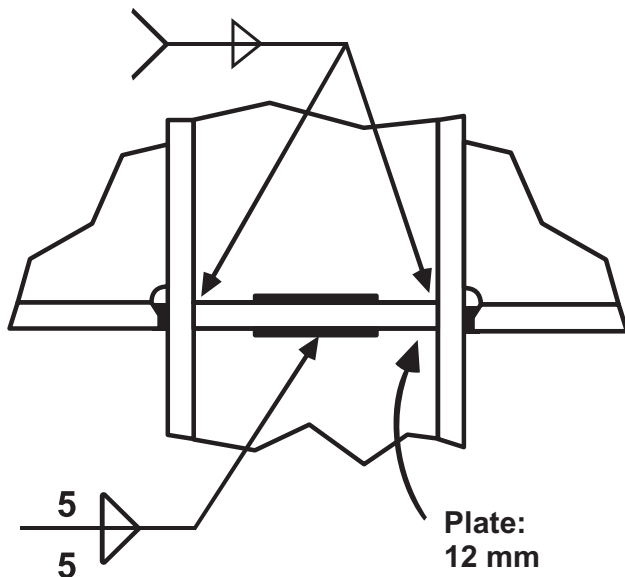


Figure 8.11: Detail of compression stiffener.

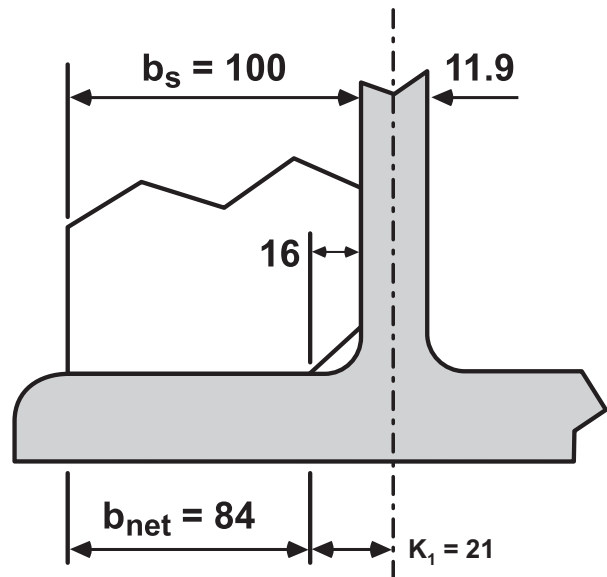


Figure 8.12: Detail of stiffener ends.

Welding of Stiffeners:

The shear force in the pair of stiffeners to be transferred into the column web is taken as

$$\begin{aligned}\text{compression flange} &= 1035 - 785 = 250 \text{ kN} \\ \text{tension flange} &= 1035 - 847 = 188 \text{ kN} < 250 \text{ kN}\end{aligned}$$

Although the tensile force to be resisted by the stiffeners is less than the compression force, the same size stiffener is usually used for both tension and compression stiffeners.

Design fillet welds for 250 kN, stiffeners to column web.

Try four 5 mm fillet welds, E49XX electrode
(0.778 kN/mm from Table 3-25, CISC Handbook, $\theta = 0^\circ$)

$$\text{length of each weld} = \frac{250}{4 \times 0.778} = 80 \text{ mm}$$

$$\text{web length} = 264 - 2 \times 37 = 190 > 80 \quad \text{OK}$$

The general shop practice is to weld the full length, otherwise, excessive unweld length should be checked for compression from beam flange.

Design welds for end of stiffener to column flange:

previously calculated the effective width = 70 mm

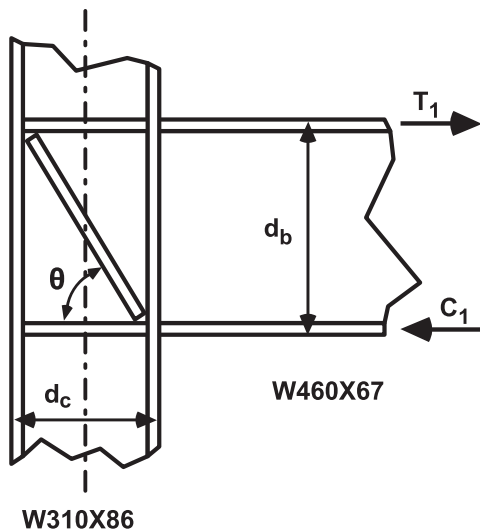
$$\text{fillet size} = \frac{250}{4 \times 70} = 0.893 \text{ kN/mm}$$

use four 6 mm fillet welds (1.21 kN/mm, $\theta = 90^\circ$, see Table 3-25, CISC Handbook)

According to Table 4-4, CSA W59, minimum fillet size required for $t_c = 19.6 \text{ mm}$ is 6 mm.

If the force is too large, complete penetration welds are usually used to connect the stiffener ends to column flanges.

Example 2 One-Way Rigid Beam-Column Connection



Given		
Steel: G40.21 – 350w	Electrode: E49XX	
Sections	Beam W460 x 67	Column W310 x 86
Depth	454 mm	310 mm
Flange thickness	12.7 mm	16.3 mm
Flange width	190 mm	254 mm
Web thickness	8.5 mm	9.1 mm
K		36 mm
K ₁		23 mm
Moment resistance	456 kN·m	
Class	1	1

Figure 8.13: Connection for Example 2.

Problem:

Investigate the requirements for column stiffeners and column web reinforcement for the moment connection and sizes given in **Figure 8.13**.

(a) Opposite compression flange (Clause 21.3(a) of CSA S16-01):

$$\begin{aligned}
 B_r &= \phi w_c (t_b + 10t_c) F_{yc} \\
 &= 0.9 \times 9.1 (12.7 + 10 \times 16.3) \times 350/10^3 \\
 &= 504 \text{ kN}
 \end{aligned}$$

$$\frac{M_r}{d_b} = \frac{456 \times 10^3}{454} = 1004 \text{ kN} > 504 \text{ kN}$$

Stiffener required for the force of $1004 - 504 = 500 \text{ kN}$

stiffener width according to beam flange $= (190 - 9.1)/2 = 90 \text{ mm}$

stiffener width according to column flange $= (254 - 9.1)/2 = 122 \text{ mm}$

Note that AISC Specification allows minimum stiffener width to equal one-third of beam flange.

Net area of one stiffener $A_s(\text{net}) = \frac{500 \times 10^3}{2 \times 0.9 \times 350} = 794 \text{ mm}^2$

Gross area of one stiffener $A_s(\text{gross}) = 794 + (K_1 - w_c/2) \times t_s$
 $= 794 + (23 - 9.1/2) \times t_s = 794 + 18.5 t_s$

Try 12 mm thick plate $A_s(\text{gross}) = 794 + 18.5 \times 12 = 1016 \text{ mm}^2 > 794 \text{ mm}^2$

width required $b_s = 1016/12 = 85 \text{ mm}$, use $b_s = 90 \text{ mm}$

$$\frac{b_s}{t_s} = \frac{90}{12} = 7.5 < \frac{145}{\sqrt{F_y}} \quad \text{OK}$$

(b) Opposite tension flange (Clause 21.3(b) - CSA S16-01):

$$T_r = 7 \phi (t_c)^2 F_{yc}$$

$$= 7 \times 0.9 \times 16.3^2 \times 350 \times 10^{-3}$$

$$= 586 \text{ kN} < 1004 \text{ kN} \quad \text{stiffener required}$$

Design stiffener: force = $(1004 - 586)/2 = 209 \text{ kN}$

Net area required: $A_s(\text{net}) = \frac{209 \times 10^3}{0.9 \times 350} = 663 \text{ mm}^2 < 794 \text{ mm}^2$ compression stiffener

Use same size as compression stiffeners, 2 plates 20 x 90.

Check shear in column web:

$$\text{Total shear force} = 1004 \text{ kN}$$

(Neglect the storey shear, i.e., the shear forces in column above and below the connection)

(c) Shear capacity of column web: $V_r = 0.55 \times 0.9 \times 9.1 \times 310 \times 350 \times 10^{-3}$

$$= 489 \text{ kN} < 1004 \text{ kN}$$

Therefore, stiffeners are required. Use diagonal or web doubler plate.

(d) Diagonal Stiffeners:

The force is carried by stiffeners $C_s = 1004 - 489 = 515 \text{ kN}$

This is the horizontal component of the shear force which will be carried by a pair of diagonal stiffeners. The resultant compressive force in the diagonal stiffeners will be:

$$\frac{C_s}{\cos \theta} = \frac{515}{0.564} = 913 \text{ kN}$$

$$\text{where } \cos \theta = \frac{d_c}{\sqrt{d_c^2 + d_b^2}} = \frac{310}{\sqrt{(310)^2 + (454)^2}} = 0.564$$

$$\text{Net area of stiffeners} = \frac{913 \times 10^2}{0.9 \times 350} = 2898 \text{ mm}^2$$

$$\text{Net area of one stiffener:} = 2898/2 = 1449 \text{ mm}^2$$

$$\text{Gross area of one stiffener: } A_s (\text{gross}) = 1449 + 18.5 t_s$$

$$\text{Try 18 mm thick plate: } A_s (\text{gross}) = 1449 + 18.5 \times 18 = 1782 \text{ mm}^2$$

$$\text{width of stiffener: } b_s = \frac{1782}{18} = 99 \text{ mm}, \text{ use } 18 \times 100 \text{ plate}$$

$$\text{Check: } \frac{b_s}{t_s} = \frac{100}{18} = 5.6 < \frac{145}{\sqrt{F_y}} = 7.8$$

As the tension and compression stiffeners selected were only 90mm wide and the diagonal is 100mm wide, all the stiffeners should be made 100mm wide.

(e) Welding of stiffeners:

Welding the ends of stiffeners

Tension stiffener load = 209 kN

$$\text{End weld length } L = 100 - 18.5 = 82 \text{ mm}$$

$$\text{fillet size required } S_1 = \frac{209}{2 \times 82} = 1.274 \text{ kN/mm}$$

use double fillet 8 mm size 1.62 kN/mm, see Table 3-25, $\theta = 90^\circ$, CISC Handbook

$$\begin{aligned}\text{Stiffeners to column web weld size } S_2 &= \frac{209}{2 \times (dc - 2k)} \\ &= \frac{209}{2 \times (310 - 2 \times 36)} = 0.439 \text{ kN/mm}\end{aligned}$$

Try 5 mm double fillets, 0.778 kN/mm, from Table 3-25, $\theta = 90^\circ$, CISC Handbook

$$\text{Length required } \frac{209}{2 \times 0.778} = 134 \text{ mm}$$

Use 5 mm x 150 mm for S_2 .

Compression stiffener load = $500/2 = 250 \text{ kN}$

End weld length $L = 82 \text{ mm}$

$$\text{Double fillet size } S_3 = \frac{250}{2 \times 82} = 1.524 \text{ kN/mm}$$

Use double fillet 8 mm size 1.62 kN/mm, $\theta = 90^\circ$. In this instance, double fillet is preferable.

$$\text{Stiffener to column web weld } S_4 = \frac{250}{2 \times (310 - 2 \times 36)} = 0.525 \text{ kN/mm}$$

Use double fillet size 5 mm, 0.778 kN/mm, $\theta = 0^\circ$. Since this size has higher strength than calculated, it is advantageous to check the weld length required:

$$L = \frac{250}{2 \times 0.778} = 160 \text{ mm} > \frac{dc}{2} = \frac{310}{2} = 155 \text{ mm}$$

Diagonal stiffener load = $913/2 = 457 \text{ kN}$

$$\text{End weld load: } \frac{457}{2 \times 82} = 2.786 \text{ kN/mm}$$

Use CJP at both ends. It is too big for fillet weld.

The diagonal stiffeners are under compressive load at both ends as compression struts. The weld required to column web is nominal to preclude buckling only. Use minimum size fillet, 6 mm (S_5) for $t_s = 18 \text{ mm}$.

Note: Web doubler plate can also be used instead of diagonal stiffeners. The AISC Manual of Steel Construction, LRFD Volume II - Connections, should be consulted. See **Figures 8.14 and 8.15** for final details.

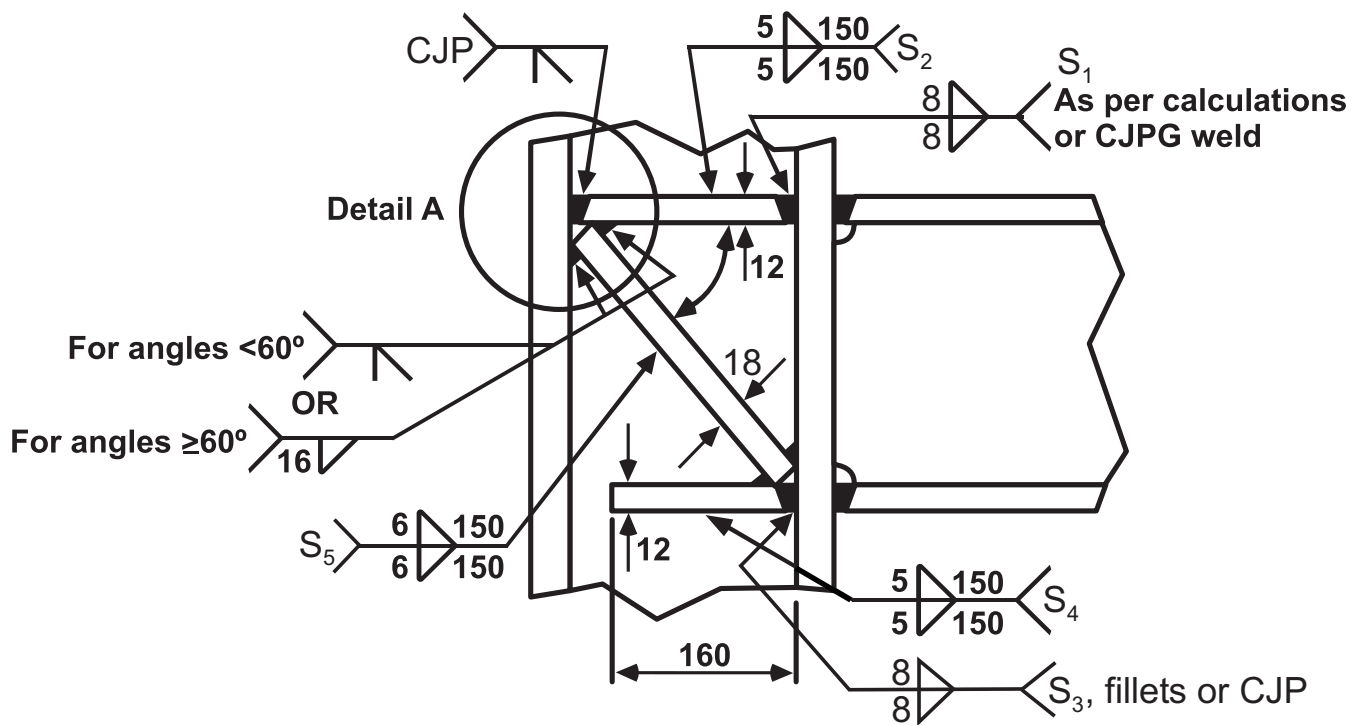
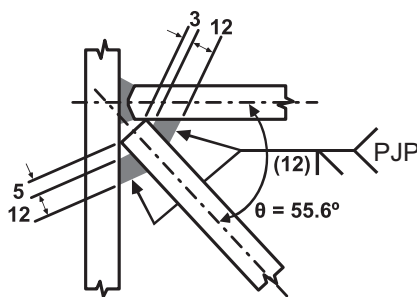
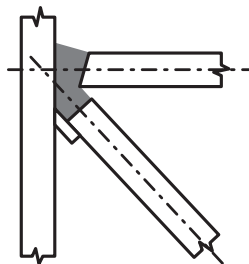


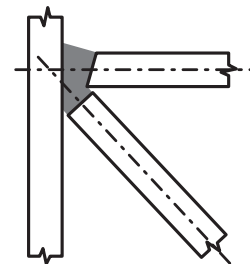
Figure 8.14: Details of welds for Example 3.



(a) Complete penetration groove on the horizontal stiffener, welded first. Fillets on diagonal welded second. Most economical. Used in example.



(b) Diagonal with a backing bar (single bevel groove) welded first with the top of the weld ground smooth horizontally to serve as backing for the complete penetration groove on the horizontal stiffener. Costly, but a likely choice where stiffener at smaller angle than 45° with the vertical



(c) Horizontal stiffener kept back for both the diagonal and the stiffener to be welded at the same time in one common groove. Results in excessive amount of weld metal. Costly.

Figure 8.15: Alternative for welding diagonals and top stiffeners (detail "A" of Figure 8.14).

8.8 Welding of Hollow Structural Section (HSS)

8.8.1 CIDECT

The hollow tube is the most efficient compression element. Because of the difficulty in connecting tubular members, however, their popularity as structural elements has only been fully realized as a direct result of the development of welding. Hollow structural sections have recently established a significant hold in the construction marketplace because of their efficiency and aesthetics. Their connections however, have offered a particular challenge to engineers: a challenge which has been met in particular by the international research organization CIDECT (Comité International pour le Developpement et l'Etude de la Construction Tubulaire). The CIDECT work has been performed on statically loaded joints.

Historically, the circular tube or pipe found favour in Europe in relatively light structures, often involving space frames. Joining the circular shapes however, required complex contour cutting at the ends, which was eventually simplified by the introduction of automatic cutting machines.

Square and rectangular sections then began to appear on the market which offered a new scope because the end connections were greatly simplified as they only involved flat cuts. In fact, HSS trusses can be successfully fabricated with different combinations of hollow sections and open sections. **Figure 8.16** identifies several of these combinations. It is the square and rectangular sections, member types RR, which have become very popular in Canada.

Although massive tubular sections are often seen in large offshore structures, the Hollow Structural Section found in more conventional structures is defined by CIDECT as being up to 508 mm in diameter maximum if round, 400 x 400 mm maximum if square and 500 x 300 mm maximum if rectangular. It is this range in size of sections which we will consider in this book.

WEB	CHORD	DESIGNATION OF MEMBER TYPES
		RR
		CR
		CC
		CI
		RI
		CU
		RU

Figure 8.16: Combinations of sections in tubular trusswork.

8.8.2 Typical Joint Configurations

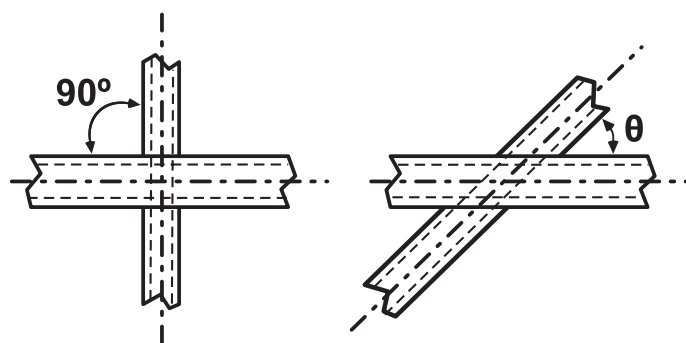
All typical joint configurations are possible with HSS (**Figure 8.17**). The N joint, a Pratt configuration, the K joint, a Warren configuration and the KT joint are the most relevant in truss design.

In an ideal truss, the centroids of the members at a joint intersect (**Figure 8.18**). However, in HSS trusses it may not be practical or desirable to create a zero eccentricity joint. Instead, it may be essential to build in a certain amount of positive or negative eccentricity through the use of gapped or overlapped joints (**Figure 8.19 (b), (c) & (d)**).

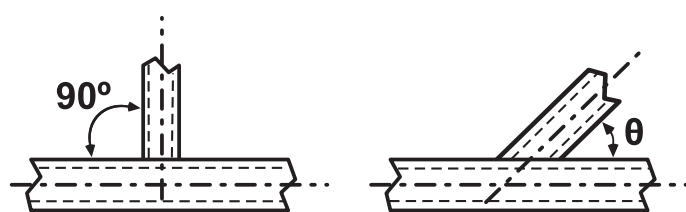
8.8.3 Possible Failure Modes

Traditionally, truss joints have been designed on elastic principles such as plane sections remaining plane to ensure adequate strength through the application of an allowable stress concept. The HSS joint, however, differs from the traditional concepts because of the flexibility of the tube walls within the joint. Several different failure modes of the joints in a truss with rectangular hollow sections are depicted in **Figure 8.19**. Combinations of these modes are also possible. The HSS joint differs conceptually from the joints in other trusses because of this flexibility. The manner in which the joint is welded may not therefore be the critical factor in its performance.

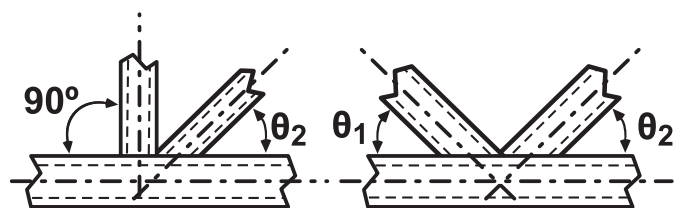
Because of the flexibility of the plate elements in the joint and the resulting redistribution of stresses, the strength of joints in structural hollow section trusses can best be assessed using “Limit States” concepts. Considerable experimental and theoretical work has been undertaken over the years, by CIDECT in particular, to establish the fitness of a particular combination of joint parameters and loads for their intended use.



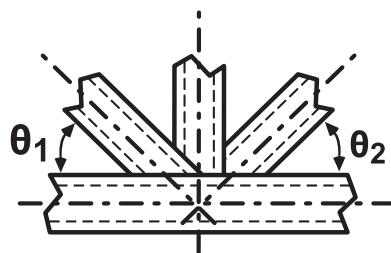
X - JOINT



T - and Y - JOINT

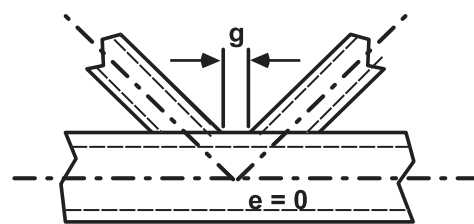


N - and K - JOINT

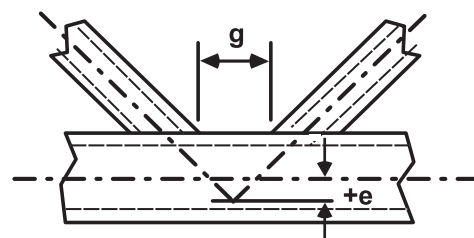


KT - JOINT

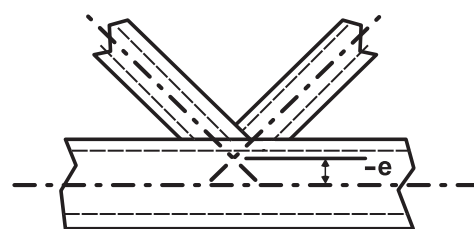
Figure 8.17: Typical joint configurations in HSS trusswork.



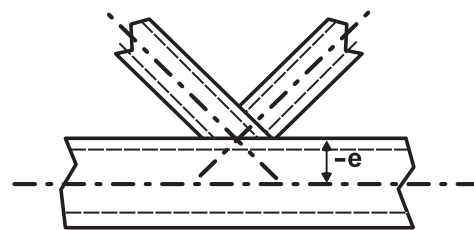
a) Gap joint - zero eccentricity



a) Gap joint - positive eccentricity

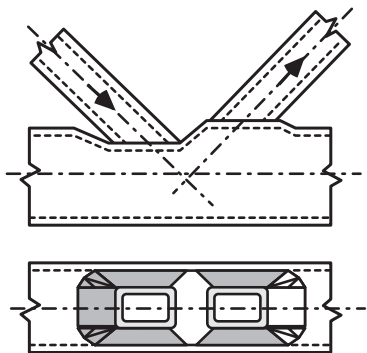


a) Partial overlap joint - negative eccentricity

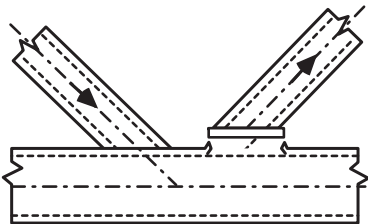


a) Full overlap joint - negative eccentricity

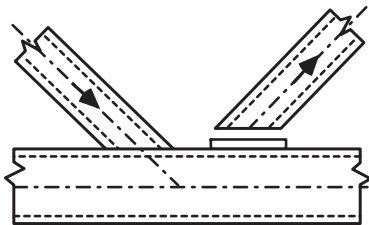
Figure 8.18: Eccentricities in HSS truss joints.



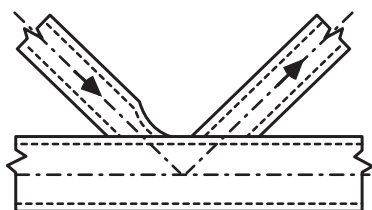
Mode A: Plastic failure of the chord face



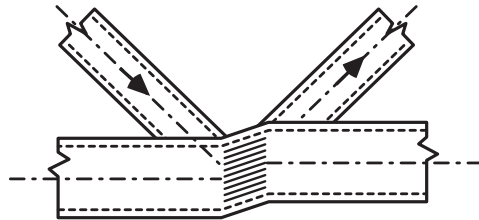
Mode B: Local shear failure of the chord face



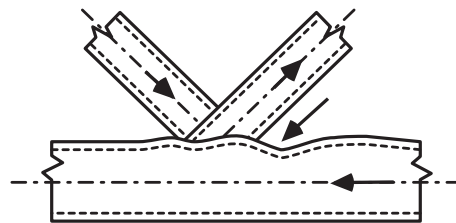
Mode C: Tension failure of the web or web welds



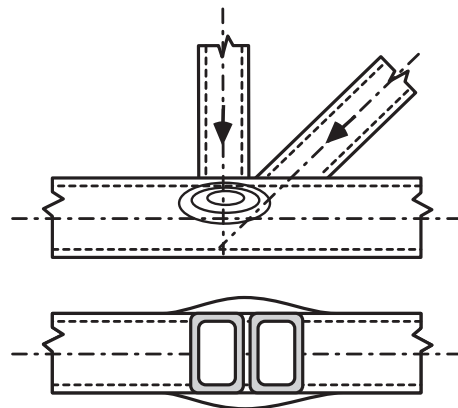
Mode D: Local buckling of the compression webs



Mode E: Overall shear failure of the chord



Mode F: Local buckling of the chord face



Mode G: Local buckling of the chord walls

Figure 8.19: Possible failure modes for HSS truss joints.

8.8.4 Joint Capacity

Essentially, the effort has been aimed at establishing the Ultimate Limit State, or maximum load capacity of a joint. This maximum load capacity may have been reached as a result of instability within the joint, rupture of a member, transformation of the joint into a mechanism, excessive deformation, excessive creep or cracking.

Additionally, Serviceability Limit States must be established relating to satisfactory performance under normal use. Serviceability criteria are associated with excessive deformation, premature cracking, excessive vibrations or excessive displacements without loss of equilibrium.

The performance of the HSS joint is thus directly dependent upon the geometry, size, wall thickness and configuration of the various members framing into the joint. The selection of the members in the truss by a designer to carry the principal axial forces, and the performance of the resulting joint, are thus closely linked. The truss design engineer must also assume the responsibility for ensuring the adequate performance of the resulting joint configuration. Unlike many other structures, the fabricator may have no opportunity for substitution when dealing with an HSS truss.

In 1986, CIDECT produced Monograph 6 “The Strength and Behaviour of Statically Loaded Welded Connections in Structural Hollow Sections”. The Monograph summarizes the work of CIDECT since its inception in 1963. Recommendations, strength equations, and supporting commentary are provided in the Monograph for the multitude of configurations possible with HSS. The rather voluminous work is recognized as being incomplete, however, and research continues.

It is not practical to attempt to duplicate the work of CIDECT in this book. For Canadian engineers familiar with the K and N joints on rectangular and square chord members, design aids based on the requirements of S16-01 have been presented by Dr. J.A. Packer.

8.8.5 CIDECT Recommendations

Section 3 of Monograph No. 6 has also listed a series of considerations which lead to the development of efficient hollow section trusses:

- 1) Chords should be the most compact section commensurate with requirements for stability and economy (i.e., keep d_o/t_o or h_o/t_o and b_o/t_o as small as possible where d_o = diameter of chord, h_o = depth of chord, t_o = thickness of chord, and b_o = width of chord).
- 2) For gap joints, web to chord wall thickness ratio (t_l/t_o) should be as small as possible (i.e., keep d_l/d_o as large as possible), where t_l and d_l are the thickness and width of the web members respectively. In general, the minimum gap for welding at toes, if fillet welding is used, should be four times the average thickness of the web members.
- 3) For overlap joints, smaller, thicker wall sections are often more suitable.

- 4) When selecting chord and web members always keep in mind the geometry of the connection.
- 5) Fillet welds should be used to connect web members to chords whenever possible, as they are more economical than full penetration groove welds.
- 6) With thin wall webs and square or rectangular chords with large corner radii, full width webs should be avoided because difficulties could arise in forming the weld between the web and the corner radius (**Figure 8.20(a)**). In some circumstances however, the corner geometry of the chord can be used with advantage to enable a groove weld to be made with the minimum of preparation.

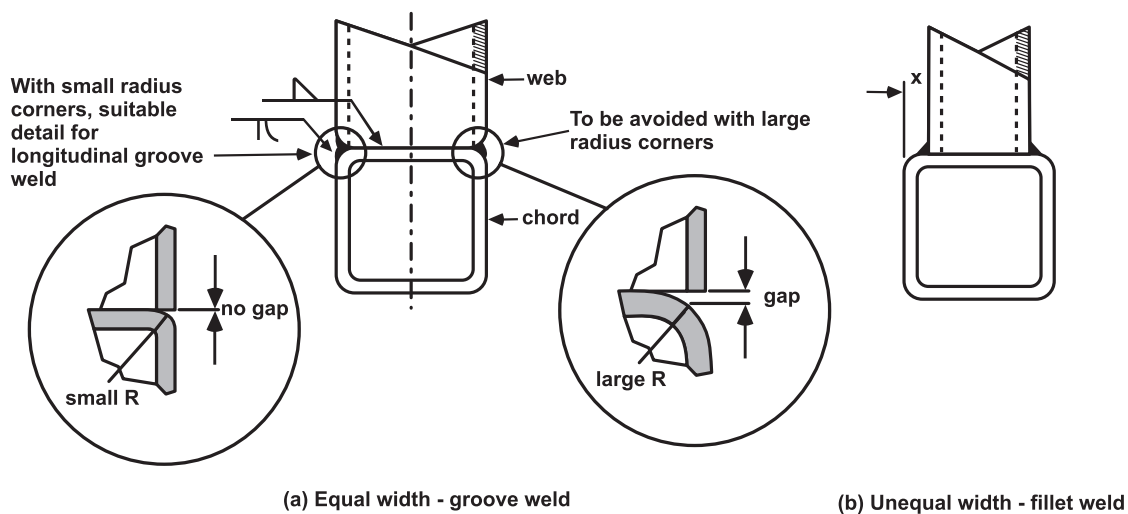


Figure 8.20: Side welds in web/chord joints.

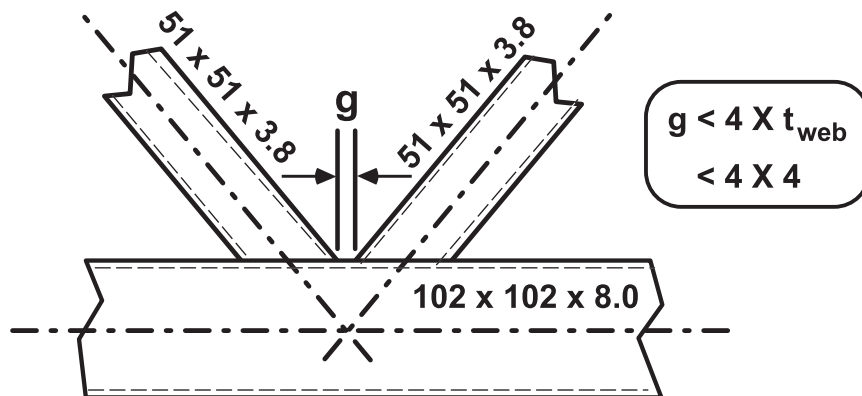


Figure 8.21: Insufficient gap between webs.

- 7) When webs of less than full width of the chord are used, sufficient “land” should be allowed to ensure that an adequate size of fillet weld can be obtained (**Figure 8.20(b)**). As a rule of thumb, for HSS having a width of 101.6 mm or less, the web should be 20-30 mm narrower than the chord ($x = 10$ to 15). For widths greater than 101.6 mm, x should be approximately 25 mm.
- 8) The intersection of web member centre lines should be kept as near as possible to the chord centre line. However, the gap or overlap of the web members must meet the joint strength requirements. Where centre line noding gives unacceptable gap (**Figure 8.21**) or slight overlap conditions, the webs should be moved apart to give sufficient gap (**Figure 8.22**) or moved together to give a reasonable overlap (**Figure 8.23**). If this results in an eccentricity of noding outside the range

$$-0.55 < \frac{e}{h_o} < 0.25$$

then the moments generated by this eccentricity must be taken into account in the design of the connections. Any moments should always be taken into account in the design of the members.

- 9) In lap joints, the tension web members can often be smaller than the compression web members and this will facilitate fillet welding. Item 7 above also applies.

Figure 8.22: Satisfactory gap joint detail
(not used where fatigue governs the design).

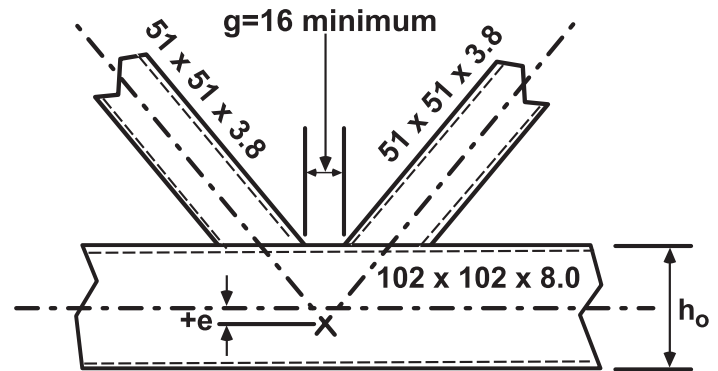
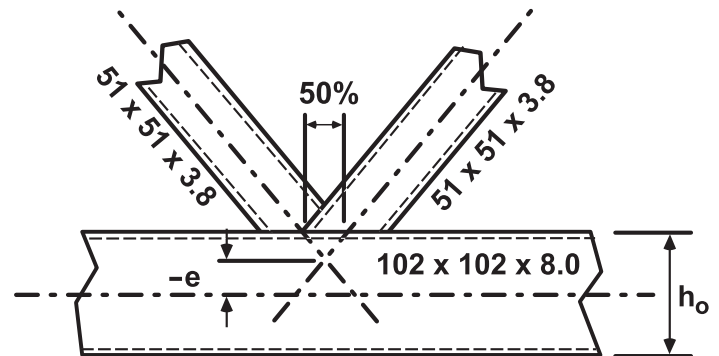


Figure 8.23: 50% overlap joint detail.



- 10) In lap joints, overlaps from 30% to 100% can be used. **Figure 8.23** shows a joint with 50% overlap.

When using circular webs, or when tension and compression bracings are of significantly different size, consideration should be given to providing a cross plate as shown in **Figure 8.24** to facilitate fit-up and welding.

- 11) Negative eccentricities are preferred to positive eccentricities since negative joint eccentricities tend to cancel secondary moments.
- 12) When overlapping is neither sufficient nor possible, a chord local stiffening plate may be used as shown in **Figure 8.25**. Welding, all around, must be used to attach the plate to the chord.

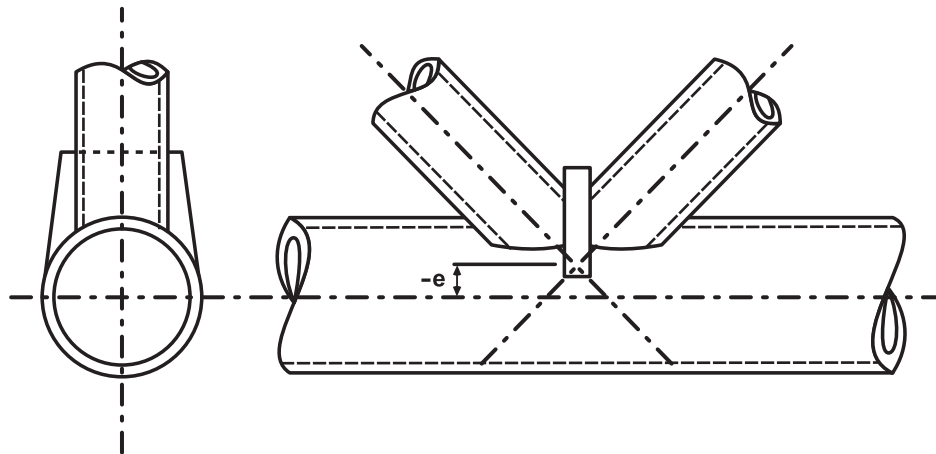


Figure 8.24: Cross plate to facilitate fit-up of overlapping webs.

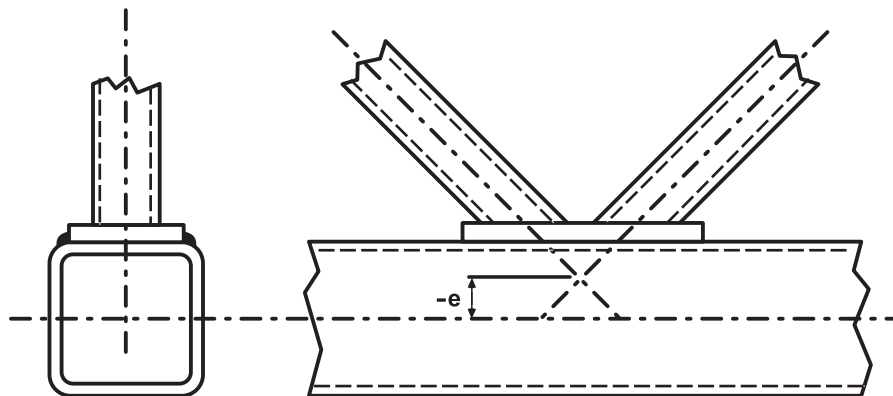


Figure 8.25: Gap joint with stiffener plate.

8.9 Design Procedures

The challenge of hollow section joint design is to satisfy all the above rules simultaneously. The procedure is not as difficult as it may at first seem and, with a little practice, the process becomes automatic. A flow chart for the suggested design procedure is outlined in **Figure 8.26**. The CISC has in fact developed a computer program for use in personal computers to assist the design process.

Consideration (5) of CIDECT Recommendations advises that fillet welds should be used to connect web members whenever possible because they are more economical than full penetration groove welds. In fact, the limited amount of testing performed by CIDECT to investigate the actual influence of welding on the joints has suggested that groove welds generally give a slightly lower ultimate strength than comparable fillet welds. In general, the joint strength criteria developed by CIDECT, which reflects the failure modes depicted in **Figure 8.19** have, except for perhaps Mode C, assumed that the welds would not be the failure mode.

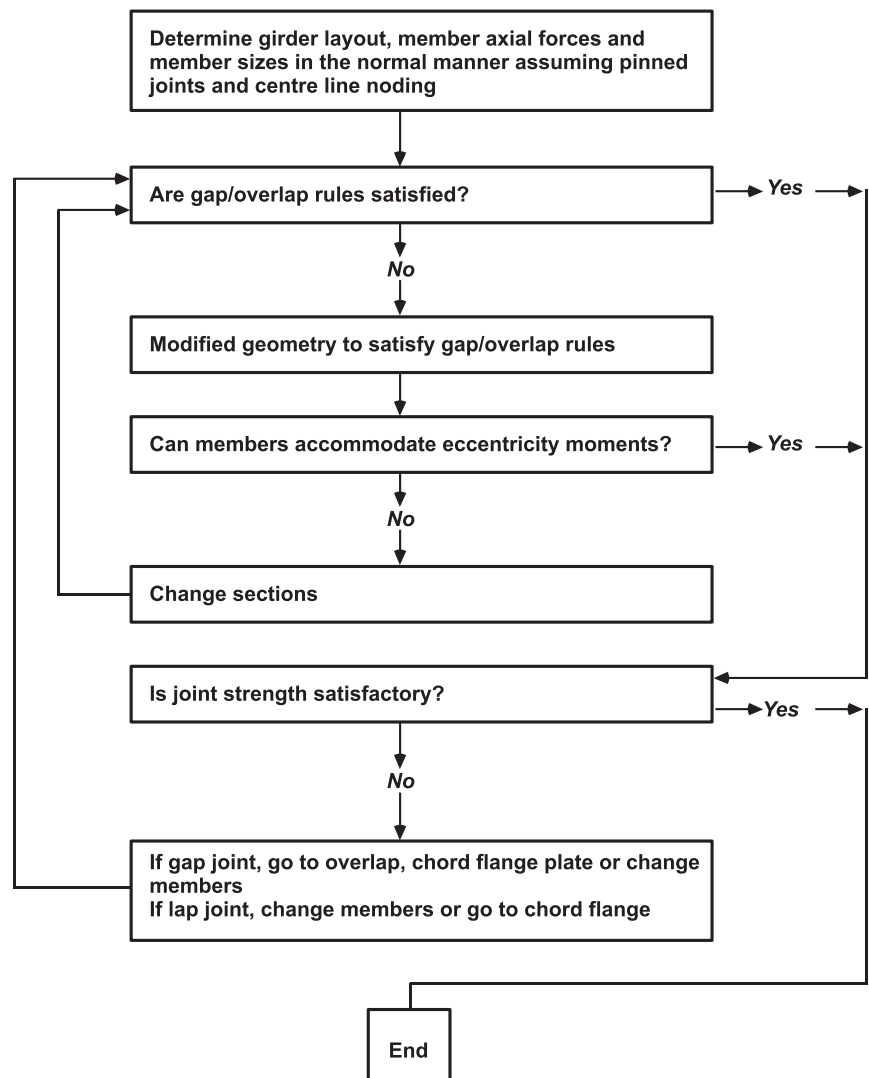


Figure 8.26: Flow chart for HSS truss design procedure.

8.10 Sizing Welds

When sizing the fillet welds it must be remembered that non-uniform stress distributions develop in the joints as shown in **Figure 8.27**. High stress concentrations develop in the corners of the tubes. When fitting members together, tack welds should never be placed at the corners. Finish welds should be established around the entire perimeter of the joint and never start or finish in the region of the corners. A suggested welding sequence is shown in **Figure 8.28**.

Figure 8.29 illustrates several fillet weld configurations and the minimum recommended leg size for truss joints to ensure adequate deformation and rotation capacity in the joint. In many cases these weld sizes in shear will develop the full member capacity in tension or compression. These sizes should be adhered to when the maximum joint strength is required. The weld sizes could, however, be reduced accordingly as the joint strength requirements are reduced. However, the structural code requires a minimum weld size to give a strength not less than 50% of the maximum capacity of the member connected.

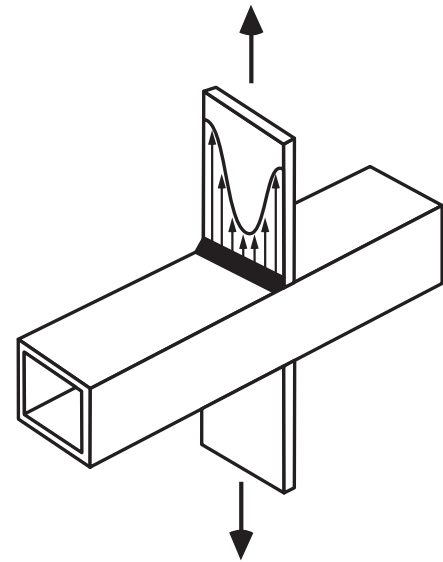
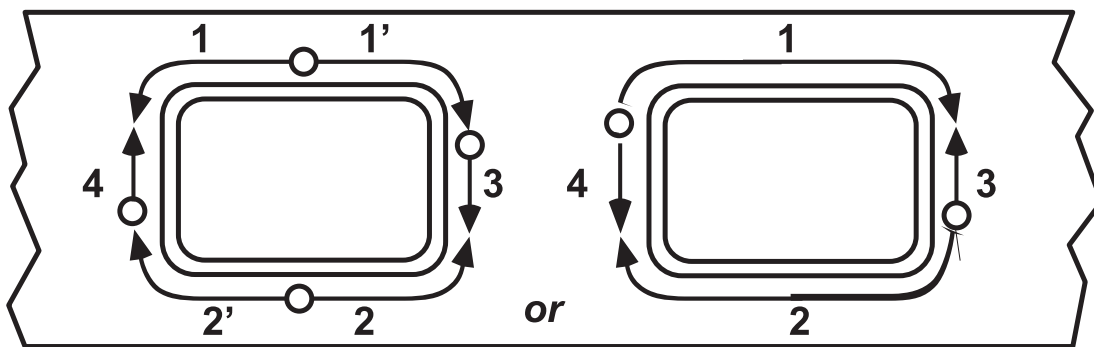
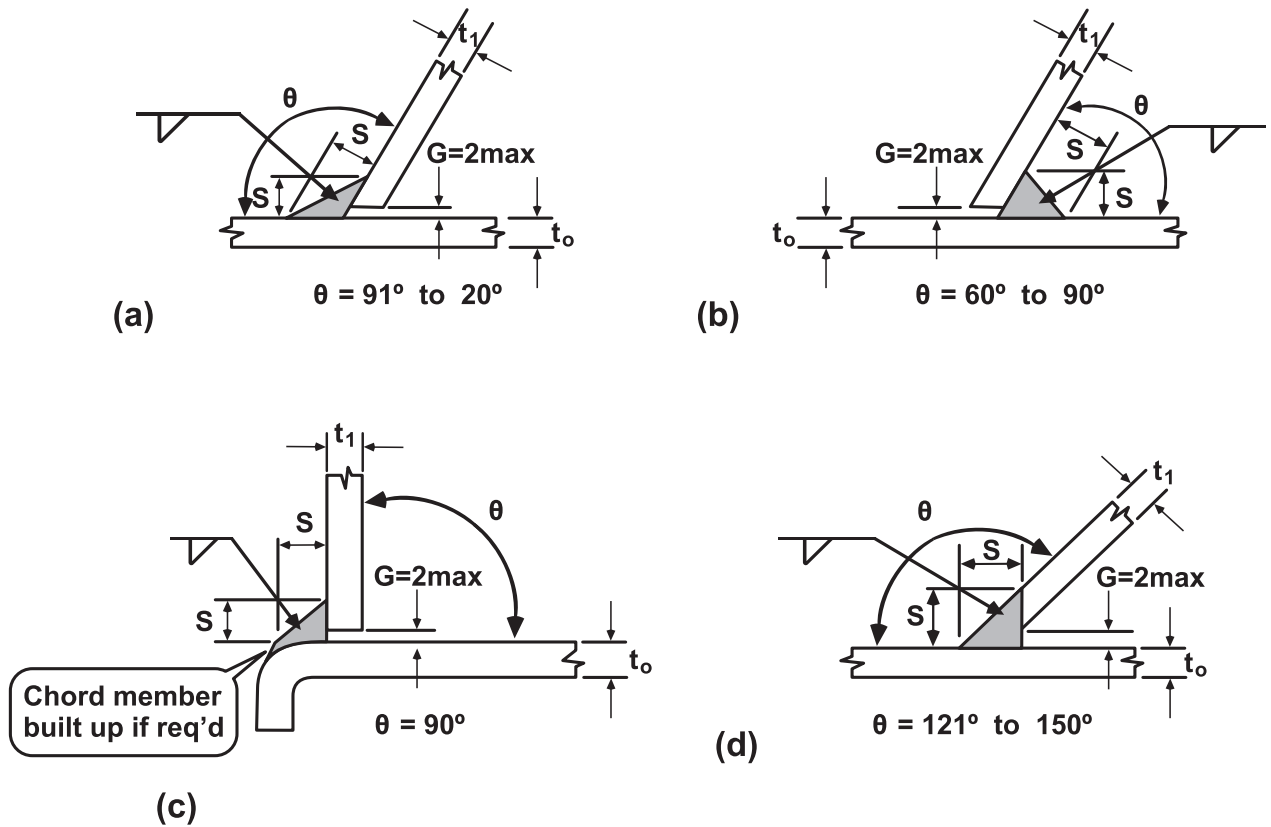


Figure 8.27: Stress distribution in transverse weld under applied tensile load.



O = start

Figure 8.28: Welding sequence for rectangular web-to-chord face.



Minimum fillet leg size (S) suggested for HSS truss joints													
$F_y = 350 \text{ MPa}$ and matching E480 electrodes													
Web member wall thickness (t_1) mm	Minimum fillet leg size for truss joints, (mm)												
	$\theta = 60^\circ$	$\theta = 65^\circ$	$\theta = 70^\circ$	$\theta = 75^\circ$	$\theta = 80^\circ$	$\theta = 85^\circ$	$\theta = 90^\circ$	$\theta = 95^\circ$	$\theta = 100^\circ$	$\theta = 105^\circ$	$\theta = 110^\circ$	$\theta = 115^\circ$	$\theta = 120^\circ$
3.18	4	5	5	5	5	6	6	6	6	8	8	8	8
3.81	5	5	6	6	6	8	8	8	8	8	8	8	8
4.78	6	8	8	8	8	8	10	10	10	10	10	10	10
6.35	8	10	10	10	10	12	12	12	12	14	14	14	14
7.95	10	12	12	12	14	14	14	16	16	16	16	18	18
9.53	12	14	14	14	16	16	18	18	18	20	20	20	20
11.13	14	16	16	18	18	20	20	20	22	22	22	24	24
12.7	16	18	18	20	20	22	22	24	24	27	27	27	27

Figure 8.29: Fillet weld configurations and minimum recommended leg sizes for HSS truss joints.

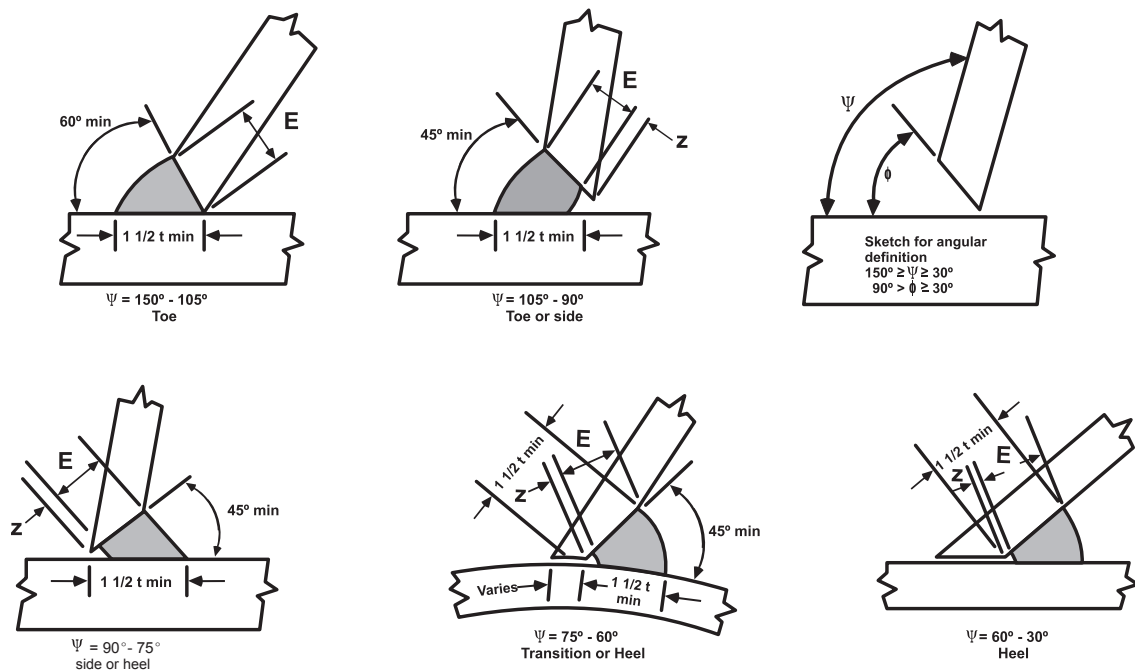
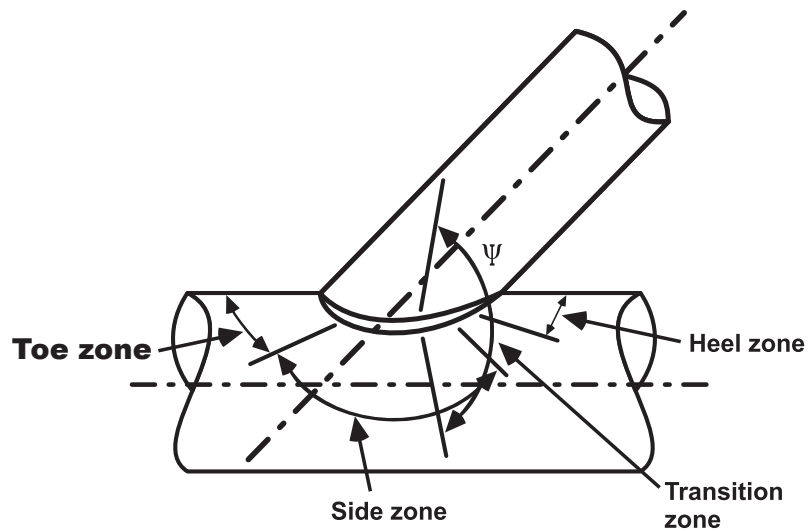
8.10.1 PJPG Welds

In tubular joints, because the welding is done from one side (outside), partial penetration groove welds (PJPG) are normally achieved if special conditions are imposed. These special conditions are required for complete joint penetration groove welds (CJPG). **Figure 8.30(a)** shows the common PJPG welds in tubular connections. To meet the prequalified joint details for PJPG, the joint preparations, fit-up and groove angles must be within the ranges of one of the details shown.

8.10.2 CJPG Welds

Figure 8.30(b) shows the prequalified joint details for CJPG welds. CSA Standard W59 and AWS D1.1 should be consulted to verify all of the relevant requirements. It should be noted that certain welding processes are excluded from use on these prequalified joint connections. Also, the welders making the CJPG welds must be qualified to the T classification requirement in accordance with CSA Standard W47.1.

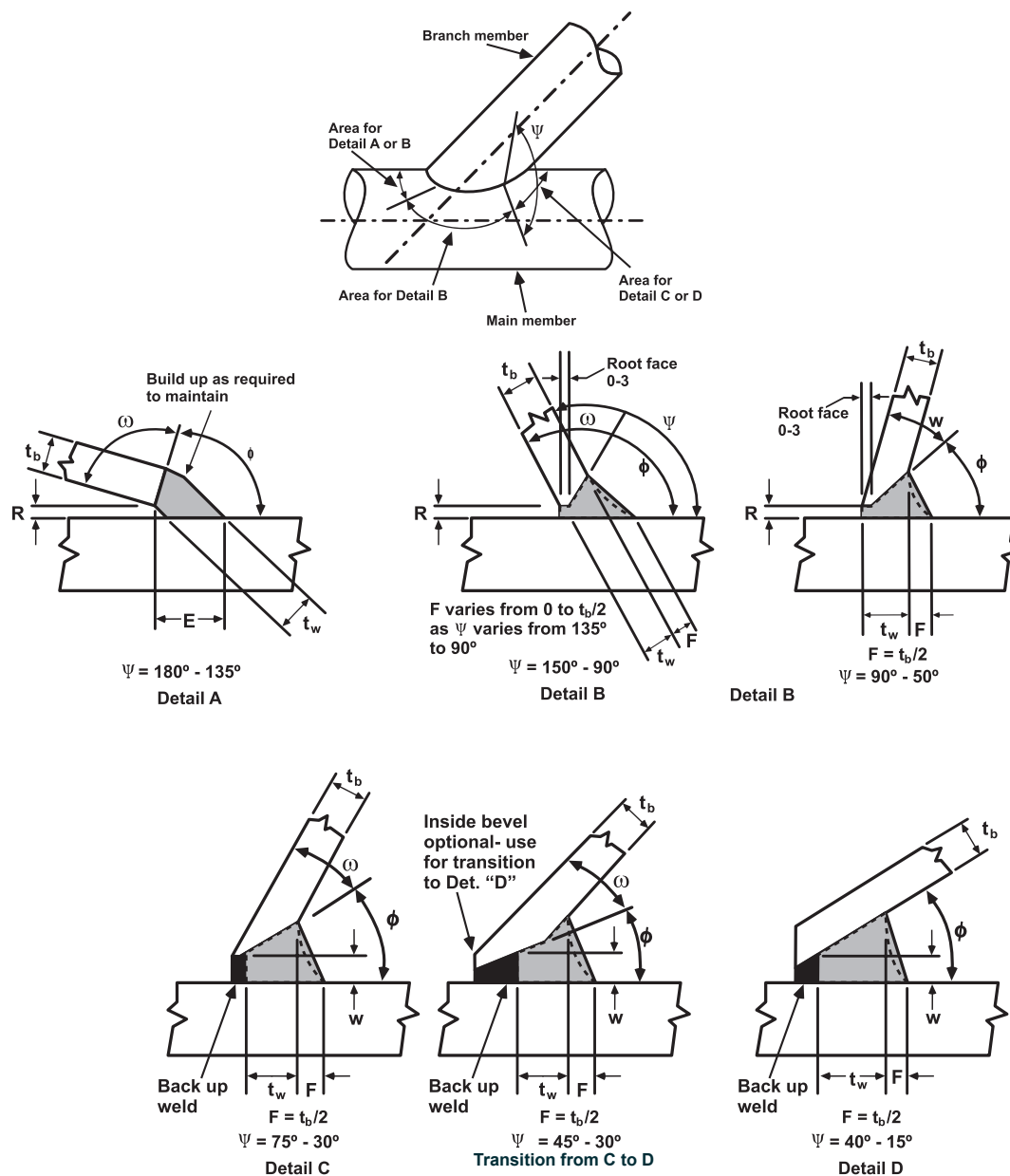
When overlapping web members, it is good engineering practice to position the weaker member on top of the stronger member. In partially overlapped joints, the toe of the overlapped member is not usually welded (**Figure 8.31**). In fully overlapped members the preparation and welding detail at the toe of the overlapped member is particularly important. The toe must be welded to the chord (**Figure 8.32**).



Notes:

- (1) t = thickness of thinner section
- (2) Bevel to feather edge except in transition and heel zones.
- (3) Root opening: 0 to 5 mm
- (4) Not prequalified for under 30°
- (5) Effective throat = E , where $E \geq t$; where z = loss factor shown in Table S2
- (6) Calculations must be done for leg length less than $1.5 t$, as shown.
- (7) See Table S3 for definition of local dihedral angle.

Figure 8.30(a): Prequalified joint details for partial joint penetration groove welds in circular tubular joints.



Notes:

- (1) Minimum standard flat weld profiles are shown by solid lines.
- (2) See Table S1 for dimensions t_w , L , R , W , ω , and ϕ .
- (3) Concave profiles, as shown by dashed lines are also acceptable.
- (4) Convexity, overlap, etc. are subject to the limitations of Figure 5-2 (W59).
- (5) Branch member thickness. t_b , is subject to limitations of Clause S4.4.1 and other pertinent design guidelines.

Figure 8.30(b): Prequalified joint details for complete joint penetration groove welds in T, Y or K connections (Standard flat profile for limited thickness). (From Supplement N:1-M1989 to W59-M1989).

Figure 8.31: Partially overlapped joint.

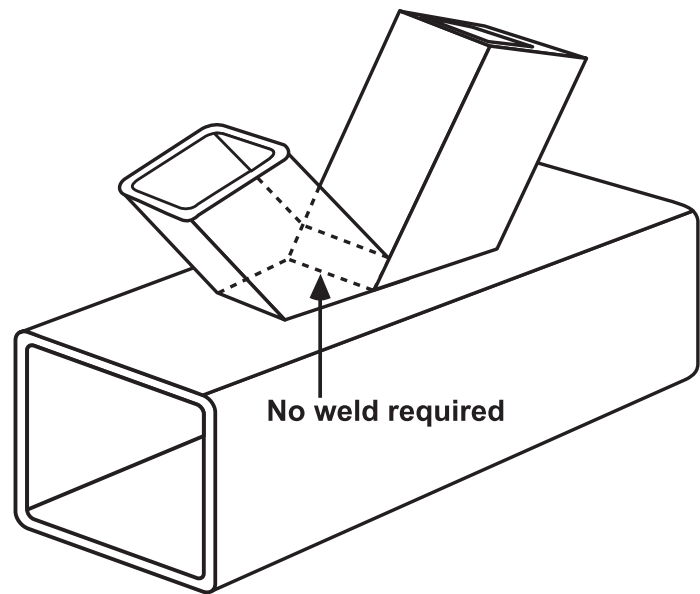
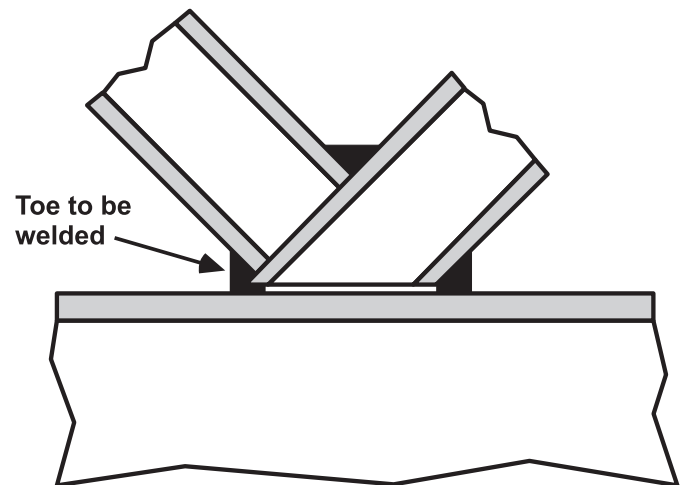


Figure 8.32: Welds in a fully overlapped joint.



While HSS trusses are light, strong and graceful, bad fit-up of the structural members can significantly increase welding and rectification costs. While it is not necessary to have machine fits, time spent to ensure proper preparation and assembly of the trusses is extremely important.

Table S1: Prequalified Joint Dimensions and Groove Angles for Complete Joint Penetration. Groove Welds for Tubular T, Y, or K Connections Made by Shielded Metal Arc, Flux-Cored Arc, and Gas Metal Arc (Short-Circuiting Transfer) Welding (1)

		Detail A $\psi = 180^\circ$ to 135°	Detail B $\psi = 150^\circ$ to 50°	Detail C $\psi = 75^\circ$ to 30° **	Detail D $\psi = 40^\circ$ to 15°
End preparation (ω)	Max		90°	†	
	Min		10° or 45° for $\psi > 105^\circ$	10°	
Fitup or root opening (R)	Max	FCAW GMAW SMAW‡ 5 mm FCAW-S 5 mm	FCAW GMAW SMAW‡ 6 mm FCAW-S** 6 mm for $\phi > 45^\circ$ 8 mm for $\phi < 45^\circ$	W‡max FCAW-S 3 mm SMAW‡ 5 mm	ϕ 25° to 40° 15° to 25°
	Min	2 mm No min for $\phi > 90^\circ$ 2mm No min for $\phi > 120^\circ$	2 mm 2 mm	GMAW 3 mm FCAW** 6 mm 9 mm 12 mm	30° to 40° 25° to 30° 20° to 25° 15° to 20°
Joint included angle (ϕ)	Max	90°	60° for $\psi < 105^\circ$	40° , if more use "B"	
	Min	45°	40° if less use "C"	$\frac{1}{2} \psi$	
Completed Weld	t_w	$> t_b$	$> t_b$ for $\psi > 90^\circ$ $> t_b/\sin \psi$ for $\psi < 90^\circ$	$> t_b/\sin \psi$ but need not exceed 1.75 t_b Weld may be built up to meet this	$> 2t_b$
	L	$> t_b/\sin \psi$ but need not exceed 1.75 t_b			

*Not prequalified for groove angles (ϕ) under 30° .

†Otherwise as needed to obtain required (ϕ).

‡Initial passes of back-up weld discounted until width of groove (W) is sufficient to ensure sound welding; the necessary width of weld groove (W) provided by back-up weld.

‡These root details apply to SMAW and FCAW (self-shielded), qualified in accordance with Table S1 in W47.1-S.

**These root details apply to GMAW (short circuiting transfer) and to FCAW (gas shielded), qualified in accordance with Table S1 in W47.1-S.

Note: (1) For GMAW see Clause S4.3.3. These details are not intended for GMAW (spray transfer).

Table S3: Joint Detail Application

Detail*	Applicable range of local dihedral angle
A	180° to 135°
B	150° to 50°
C	75° to 30° Not prequalified for groove
D	40° to 15° angles under 30°

* The angle and dimensional ranges given in Details A, B, C or D include maximum allowable tolerances.

Notes: (1) The applicable joint detail (A, B, C or D) for a particular part of the connection is determined by the local dihedral angle, γ , which changes continuously in progressing around the branch member.

(2) Local dihedral angle is the angle measured in a plane perpendicular to the line of the weld between tangents to the outside surfaces of the tubes being joined at the weld.

Chapter 9

Weld Faults and Inspection

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9.1 Introduction

Before we know what weld faults are, we should know what a good weld is. A good weld has complete fusion to base metal, good profile, no porosity or inclusions, no cracks, with adequate mechanical and metallurgical properties. If you know how a weld is made, you will realize that it takes a concerted effort of all parties of the welding operation to meet all these conditions and achieve a good weld.

Welding involves base metal, filler metal, machinery, electricity and human dexterity. When all the other factors are at an optimum, the human skill plays a decisive role. Welding is a relatively refined manufacturing process, not the same as concrete construction, which can tolerate more in dimension and handling. Remember that weld metal solidifies almost instantaneously. Concrete takes a few hours to set.

Therefore, when you read the words “weld faults”, do not be deterred. After all, a weld dimension may be only from a few millimetres (fillet weld, for instance) to a few centimetres (butt joint of thick plate), and the load it carries can be from a few kilonewtons (a few 100 lbs), to thousands of tonnes. The load path is much more critical than concrete structures and so is the design analysis, but a properly trained and certified welding fabrication shop can always produce sound weldments. Weld fault means repair. Codes or standards stipulate the tolerance and seriousness of different types of weld faults.

This chapter outlines the types of faults, causes and methods of detection (inspection). Inspection is another branch of technology. It requires special training, both in theory and practice, to be a qualified inspector. The following pages will provide the reader with an introduction to this subject. Further reading can be obtained in the following Modules:

Module 10	Weld Faults and Causes
Module 11	Basic Inspection Technology
Module 12	Mechanical Testing of Welds
Module 16	Techniques of Visual Inspection
Module 17	Surface Inspection
Module 18	Radiographic Inspection
Module 19	Ultrasonic Inspection

9.2 Weld Faults Classifications

Faults in welding may range from inadequate metallurgical properties to such physical imperfections as cracks, porosity, slag inclusions, incomplete fusion, undercut, incomplete penetration, dimensional defects, etc. The importance of weld defects, however, both as to type and quantity, is relative to the type of weldment and the service required; an imperfection harmful in one case need not be so where other types of welded work are concerned. It is, therefore, a difficult task to assess their relative importance, since the extent and type of a weld fault needs to be analyzed in relation to the function of a given weldment. Where existing experience is inadequate, this should be done by experimental research including necessary tests to establish standards of acceptability.

There are certain types of defects that may occur in arc welding and they are of three general classes:

1. Dimensional defects
2. Structural discontinuities in the weld
3. Defective properties (weld metal and joint)

These classes of defects can be subdivided under many headings, but since it is impossible to state rules where by an inspector can identify all the factors likely to cause defects in the welds, this chapter will describe only some of them briefly. An inspector will be better fitted to judge the chances of obtaining welds which are satisfactory for a particular service if he has a thorough knowledge of the limitations of a given welding process and an understanding of those conditions that are likely to cause the formation of defects.

9.2.1 Dimensional Faults

The production of satisfactory weldments depends upon, among other things, the maintenance of specified dimensions, whether it be size and shape of welds or the finished dimensions of an assembly. Requirements of this nature will be found in the drawings and specifications. Departure from the requirements in any respect should be regarded as a dimensional defect that must be corrected before final acceptance of the weldment. The more common types of these defects are discussed as follows.

9.2.2 Dimensional Faults Prior to Welding

- a) Incorrect bevel angles
- b) Incorrect J-groove radii
- c) Incorrect root face
- d) Incorrect fit up (mismatch)
- e) Incorrect root openings
- f) Irregularities in the surface of the joint preparation

9.2.3 Causes

Faults described previously (and illustrated in **Figure 9.1**) are the direct result of poor workmanship in operations leading up to the point at which the assembly is to be welded.

Faults of this nature indicate a lack of quality control and should be reported by the welding inspector so that corrective action may be initiated. **Figure 9.1** illustrates some dimensional faults.

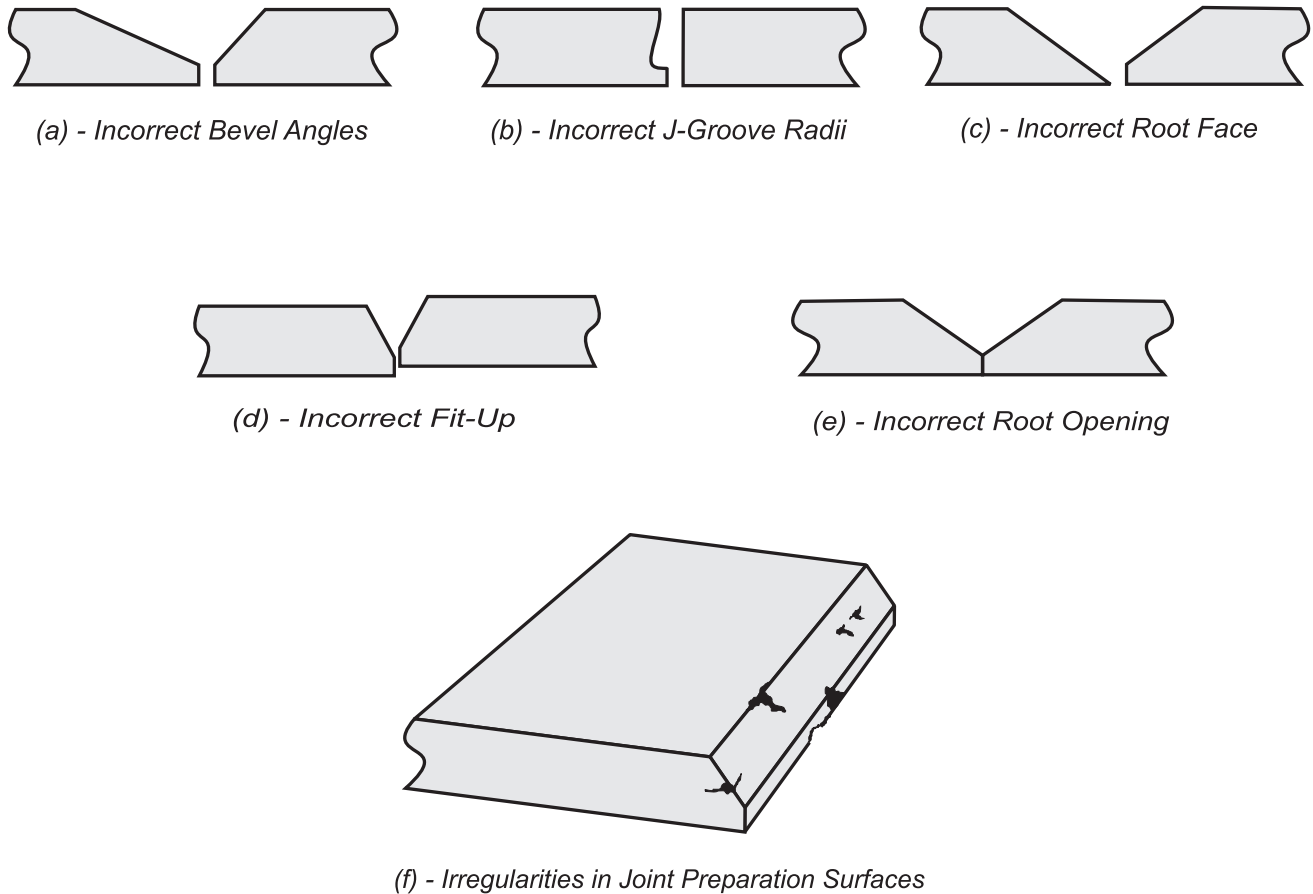


Figure 9.1

As illustrated in **Table 9.1**, codes and specifications provide for tolerances on bevel angle, root face thickness and root openings, and should be followed accordingly, e.g., a groove angle specified on the drawing as 60° should be between 55° and 70°.

Table 9.1: CSA Standard W59 and AWS D1.1
(not applicable to electroslag or electrogas welding).

	Root Not Gouged	Root Gouged
1. Root Face of Joint	1.6 mm (1/16")	Not limited
2. Root Opening of Joints:		
- Without Steel Backing	1.6 mm (1/16")	1.6 mm (1/16") 3 mm (1/8")
- With Steel Backing	6 mm (1/4") 1.6 mm (1/16")	Not applicable
3. Groove Angle of Joint	+ 10 degrees - 5 degrees	+ 10 degrees - 5 degrees

Incorrect joint fit up also represents difficulties in producing sound weld deposits. Care should be taken to meet the fit-up tolerances to avoid the following weld faults:

Insufficient Root Openings

- ◆ lack of penetration
- ◆ lack of fusion
- ◆ slag entrapment

Excessive Root Openings

- ◆ porosity
- ◆ slag entrapment
- ◆ excessive weld reinforcement
- ◆ additional distortion

9.2.4 Incorrect Joint Preparation and Fit Up

Good welding practice requires proper joint dimensions and preparation. Improper joint preparation makes it exceedingly difficult for the operator to make a sound weld and greatly increases the tendency to produce structural discontinuities in the weld. Therefore, it is important that the joint preparation meet the applicable welding standards within specified limits.

Incorrect joint preparation could be caused by one, or a combination of the following:

- ◆ improper bevel angles or J-groove radius
- ◆ improper root face
- ◆ irregularities in the finished surface

Irregularities in the finished surface to be welded may also lead to various weld faults and defects. The method or preparation usually determines the type of weld fault that may be experienced as illustrated below.

Sheared Surfaces

Depending on the condition of the shear blades and lubricants used, various undesirable foreign materials may be entrapped, leading to porosity, slag entrapment and lack of fusion.

Flame Cut Surfaces

When oxygen is used in flame cutting, notches and irregularities may occur. Quite often, slag may adhere to these notches and surfaces, and if it is not removed prior to welding, such faults as porosity, lack of fusion, slag entrapment and chemistry composition defects may occur.

Codes, standards and specifications often limit surface irregularities and should be followed accordingly. For example, when welding in accordance to CSA Standard W59 specifications (as in **Figure 9.2**), the following conditions and limitations are to be applied.

Preparation of Material

Surfaces and edges to be welded shall be smooth, uniform, and free from fins, tears, cracks and other defects which would adversely affect the quality of strength of the weld. Surfaces to be welded shall also be free, within 50 mm (2 in) of any weld location, from loose or thick scale (except for tightly adhering small islands of scale), slag, rust, paint, grease, moisture and other foreign material that will prevent proper welding or produce objectionable fumes.

Occasional notches, not more than 5 mm (3/16 in) deep, on otherwise satisfactory surfaces shall be removed by machining or grinding. Occasional notches, exceeding 5 mm (3/16 in) and less than 10 mm (7/16 in) deep, in oxygen cut edges of plate up to 100 mm (4 in) thick, not to be welded, may, with the Engineer's approval be repaired by welding. For material 4 in thick or over, the depth of the notch shall not exceed 15 mm (5/8 in).

Such repairs shall be made by suitably preparing the defective area, welding with basic electrodes to an approved procedure and grinding the completed weld smooth and flush with the adjacent surface to produce a workmanlike finish.

Figure 9.2: Excerpt from CSA Standard W59.

Dimensional Faults After Welding

- a) Distortion
- b) Incorrect weld profile such as:
 - i) Convexity
 - ii) Concavity
 - iii) Insufficient throat
 - iv) Insufficient leg
 - v) Excessive reinforcement
 - vi) Undercutting (internal & external)
 - vii) Overlap
 - viii) Out-of-line weld beads

9.3 Distortion or Warpage

9.3.1 Causes

The welding operation involves the application of heat and the fusion of metal in localized sections in the weldment. Stresses of sufficient magnitude may be induced (due to thermal expansions and contractions), which will cause distortion of the structure.

Distortion may have a number of contributing causes such as:

- ◆ lack of control of heat input
- ◆ inadequate control of weld pass sequencing
- ◆ inaccurate preparation of the joint
- ◆ inadequate control of the fit up
- ◆ incorrect joint design
- ◆ over-welding

Various codes and specifications provide dimensional tolerances as illustrated in **Figure 9.3**. It should be noted that other codes, such as AWS D1.1, for example, have similar specifications.

CSA W59

Dimensional Tolerances

Unless otherwise specified in the applicable design Code or Standard, the dimensions of welded structural members shall be within the following special tolerances:

Imperial

Lengths of 45 feet and under:

$$\frac{1}{8}'' \times \frac{\text{Number of feet of test length}}{10} - \text{but not over } \frac{3}{8}''$$

Lengths over 45 feet:

$$\frac{3}{8}'' + \frac{1}{8}'' \frac{(\text{Number of feet of test length} - 45)}{10}$$

Metric

Length of 14 mm and under:

$$\left(\frac{L}{1000} \right) \text{mm} - \text{but not over 10 mm}$$

Length over 14 mm:

$$10 + [(L - 14000) / 1000] \text{ mm}$$

L = mm in test length

Figure 9.3: Dimensional Tolerances

9.4 Dimensional Faults

9.4.1 Incorrect Weld Profiles

Weld deficiencies related to weld profiles are illustrated in **Figures 9.4 & 9.5**.

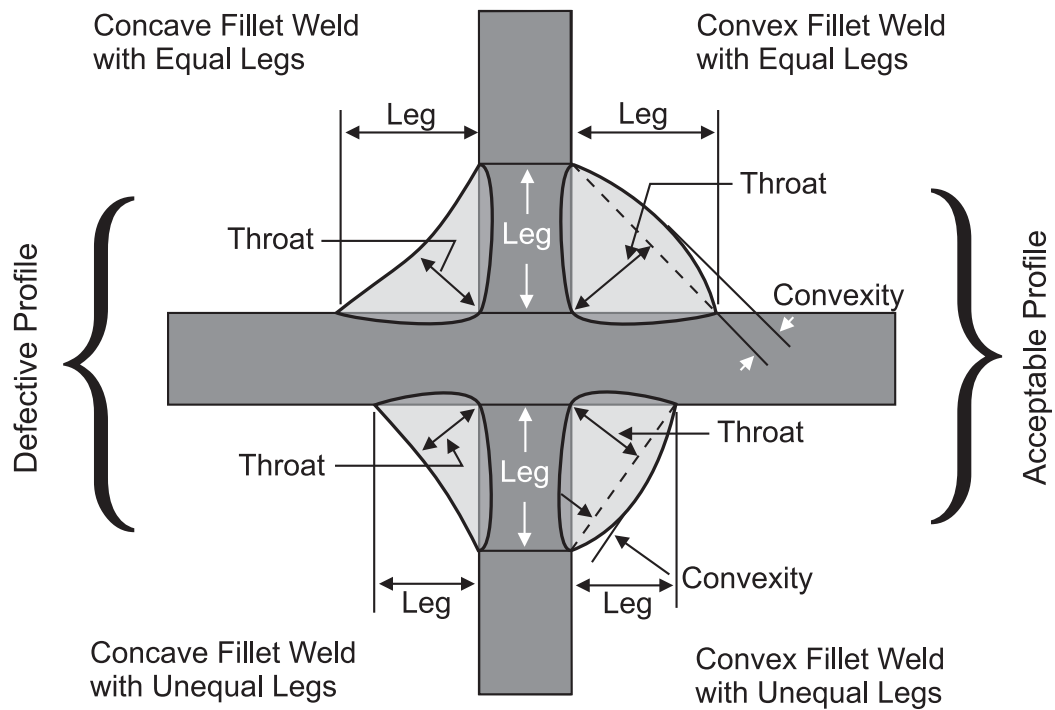


Figure 9.4

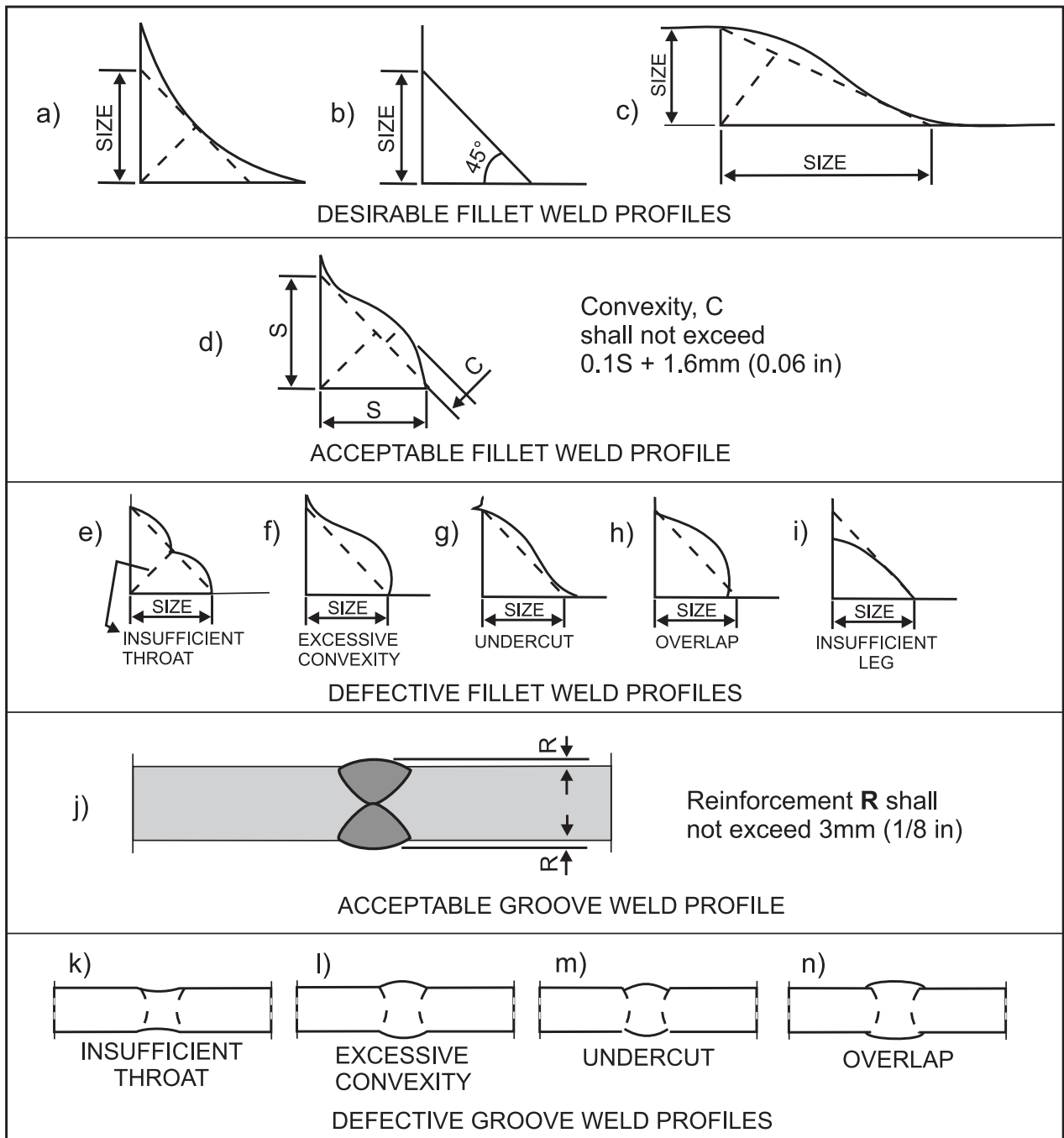


Figure 9.5: Weld profiles - acceptable and defective with various faults illustrated in accordance with CSA Standard W59 (AWS D1.1 is similar).

Overlap is a condition where an excess of weld metal exists at the toe of a weld beyond the limits of fusion and is illustrated in **Figures 9.6 & 9.7**. This condition produces notches, which are harmful due to a resultant stress concentration under load, and, in the case of a fillet weld, may actually reduce its effective size.

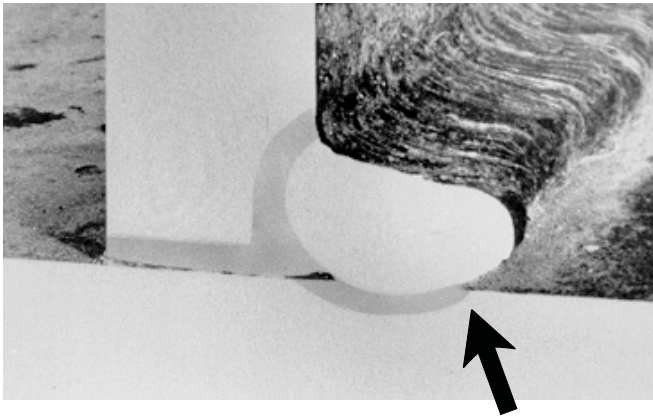


Figure 9.6: Overlap in fillet weld.

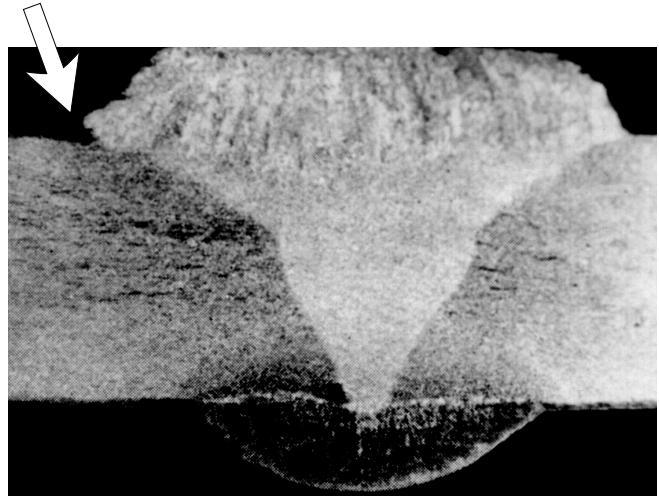


Figure 9.7: Overlap in groove weld.

If the nature of overlap is examined, it will be found that there is a mass of weld metal that is not fused to the parent metal. Overlap is common in fillet and groove welds with various processes, and typical causes of overlap are as follows:

Improper Technique, including

- ◆ travel speed is too slow
- ◆ improper electrode angles
- ◆ improper weave techniques

Essential Variables, including

- ◆ insufficient electrode diameter
- ◆ improper amperage and voltage settings

Joint Preparation Contaminants, including

- ◆ oil
- ◆ paint
- ◆ rust
- ◆ mill scale

Excessive convexity tends to produce notch effects in multipass welds, and may lead to other weld faults, such as slag inclusions, lack of fusion and porosity when depositing subsequent passes.

The term convexity normally refers to the profile of a fillet weld (**Figure 9.8**) whereas excessive weld reinforcement refers to the profile of a groove weld, as illustrated in **Figure 9.9**.

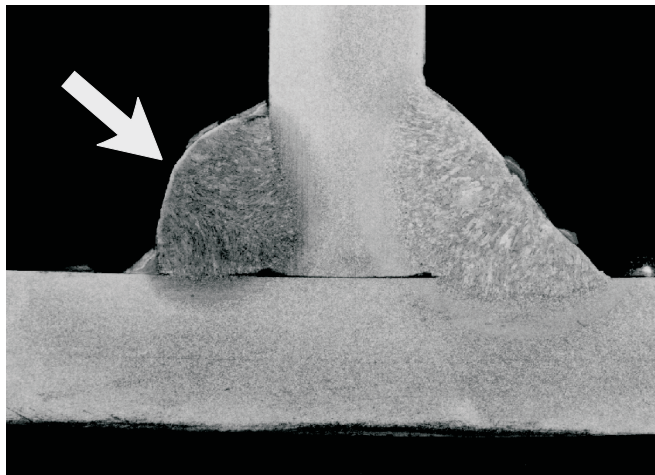


Figure 9.8: Excessive convexity in a fillet weld.

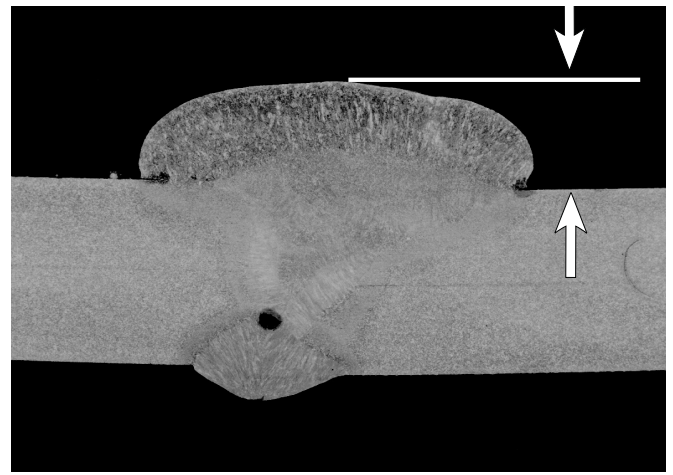


Figure 9.9: Excessive reinforcement in a groove weld.

Excessive convexity, like overlap, may be caused by inhibited weld metal fluidity. Typical causes of convexity may be one, or a combination of the following:

Improper Techniques

- ◆ travel speed too slow
- ◆ incorrect electrode angles
- ◆ incorrect weave techniques

Essential Variables

- ◆ insufficient electrode diameter
- ◆ insufficient amperage and voltage

Joint Preparation Contaminants

- ◆ oil
- ◆ paint
- ◆ rust
- ◆ mill scale

Excessive welding reinforcement is associated with groove welds and is undesirable since it tends to stiffen the section at that point as well as establish notches. This condition results from improper welding technique, or insufficient welding current, and is shown in **Figures 9.10 & 9.11**. This fault is often connected with some irregularity in weld profile and is illustrated in **Figure 9.9**. The opposite of this defect is insufficient reinforcement in the groove weld like that shown in **Figure 9.12**.

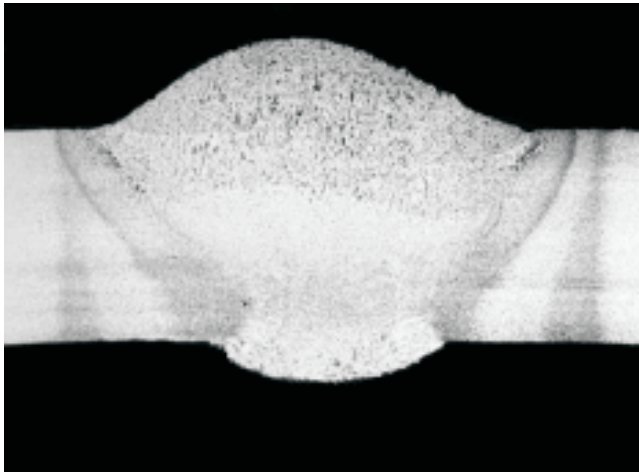


Figure 9.10: Excessive weld reinforcement.

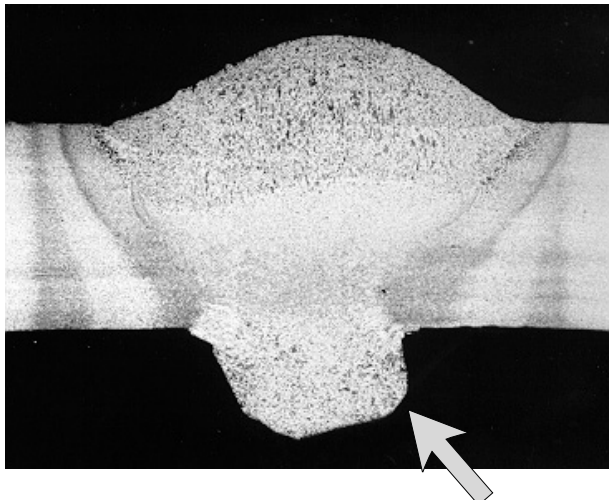


Figure 9.11: Excessive root reinforcement in a single V butt.

Codes, specifications and standards limit the amount of reinforcement on groove welds and should be followed accordingly. The maximum reinforcement permitted by CSA Standard W59 is 1/8" (3 mm) for groove welds (see **Figure 9.5**).

Insufficient weld reinforcement, also associated with groove welds, is considered undesirable. The effective load capacity is reduced considerably if not properly corrected. As illustrated in **Figure 9.13**, additional passes should be added to bring the weld to a proper size, but care should be taken when applying additional passes to:

- ◆ maintain proper profiles
- ◆ not exceed reinforcement requirements
- ◆ blend passes into base material
- ◆ not create additional weld faults

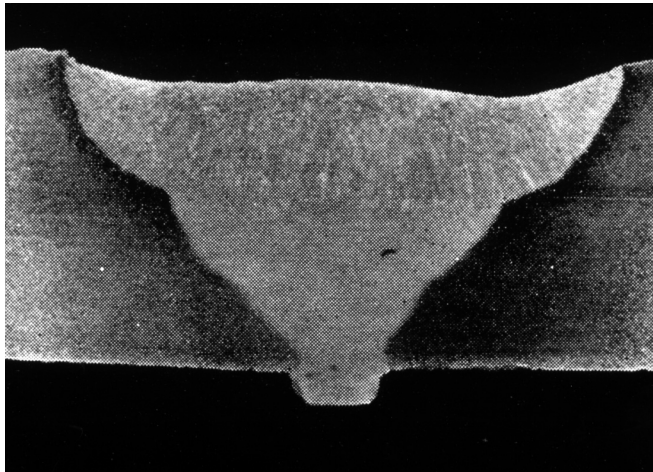


Figure 9.12: Insufficient face reinforcement (underfill).

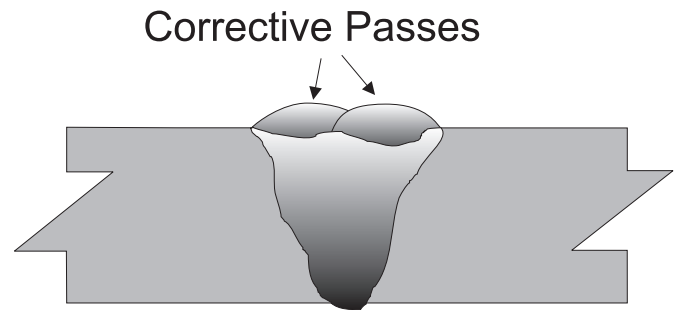


Figure 9.13: Correction for insufficient reinforcement.

Undercut

This term describes the melting away of the parent metal during the welding process. If undercutting is not corrected, it may be detrimental to the component and is, therefore, a fault. Undercut will produce notches and result in stress risers, which can be harmful under load. Limitations for undercut are specified in governing codes and standards and are based on the type of loading that the weld is subjected to (i.e., static, dynamic or cyclic).

Undercut can occur at any stage of the welding process, for example:

- ◆ root undercut in a single V butt weld without back welding (**Figure 9.14**)
- ◆ undercutting of the sidewall of a welding groove at the edge of a layer or bead, thus forming a sharp recess in the sidewall at a point where the next layer or bead must fuse (**Figure 9.15**)
- ◆ reduction in base metal thickness at the line where the last bead is fused to the surface (**Figure 9.16** – external undercut)

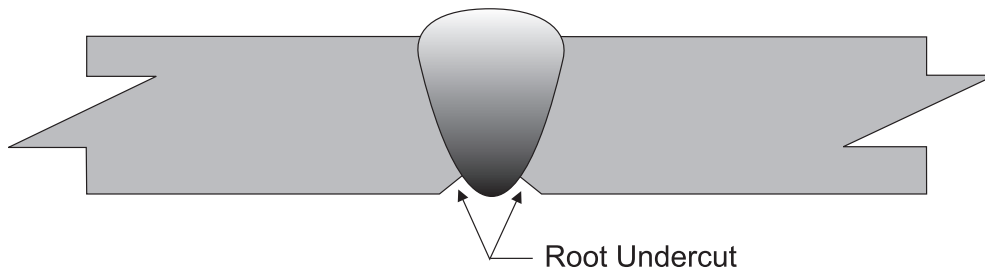


Figure 9.14

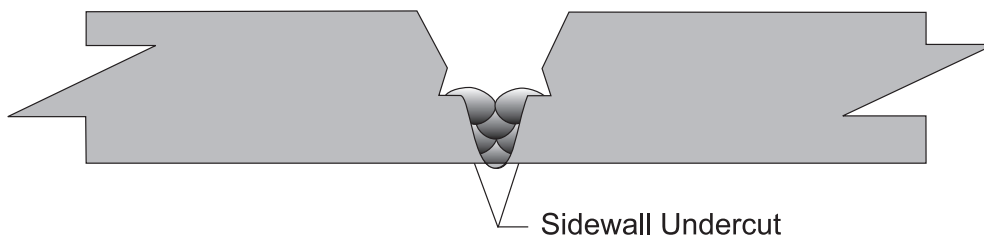


Figure 9.15

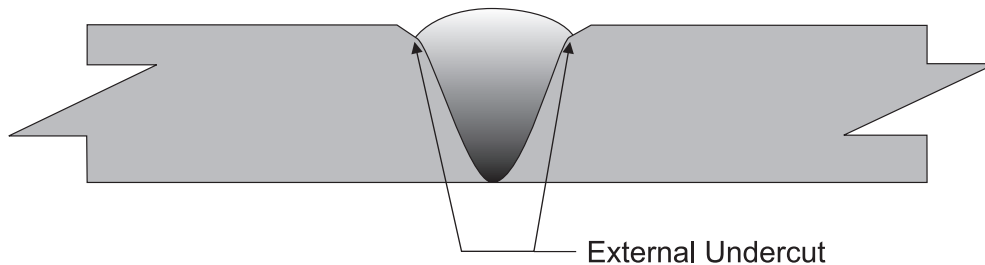


Figure 9.16

Undercutting of the side walls of a groove does not affect the completed weld if sufficient care is taken to correct the condition before depositing the next bead. Failure to correct the condition may lead to slag being trapped in the cavity during the welding of the next pass. Surface undercutting, both internal and external, should be corrected. However, some construction codes and standards allow limited amounts of undercut to remain in the weld. For example, CSA Standard W59 and AWS D1.1 state that undercut for cyclically loaded structures shall not be more than 0.010 inch (0.25 mm) deep when the weld is transverse to the primary stress in the part that is undercut. They further state that undercut shall be no more than 1/32 inch (1 mm) deep when the weld is parallel to the primary stress in the part that is undercut.

On the other hand, the designer or specifier may specifically state in a product specification that undercut in any degree is not allowed.

Some of the probable causes of undercut are as follows:

Operator Technique

- ◆ too much current on too long an arc may increase the tendency to undercut

Electrode

- ◆ different types of electrodes show varying characteristics in this respect

Joint Accessibility and Position

- ◆ with some electrodes the most skilled operator may be unable to avoid undercut under certain conditions such as accessibility and position

Joint Preparation

- ◆ inadequate root face may cause excessive internal undercut (**Figure 9.17**)

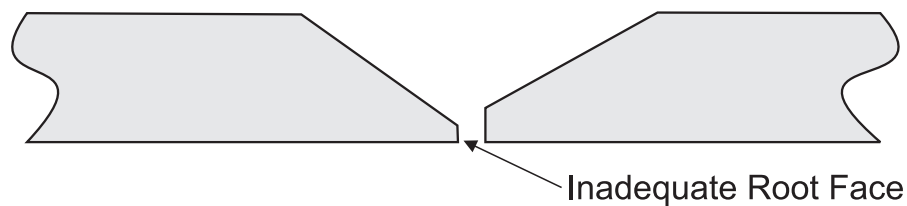


Figure 9.17

Excessive concavity may occur in the root pass of a groove weld (**Figure 9.18**), but is more often associated with fillet welds (**Figure 9.20**). It should be noted that drawings may call for concave fillet welds, in which case it would not be considered a weld fault. The size of a concave fillet weld is determined by its throat size, not the actual measurement of its leg length. A concave fillet profile is dependent on service conditions.

As illustrated in **Figures 9.19 & 9.20**, note that an excessively concave weld profile gives a deceptive appearance as to its actual size. **Figure 9.21** indicates corrective action for concave fillet welds.

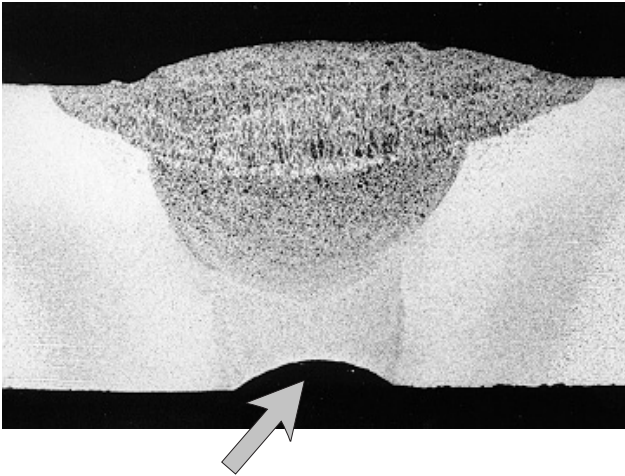


Figure 9.18: Root concavity.

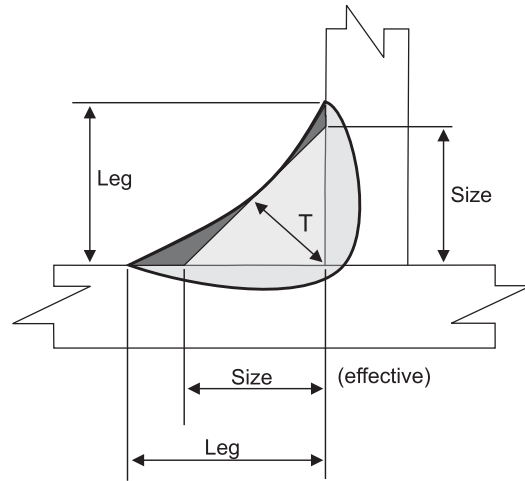
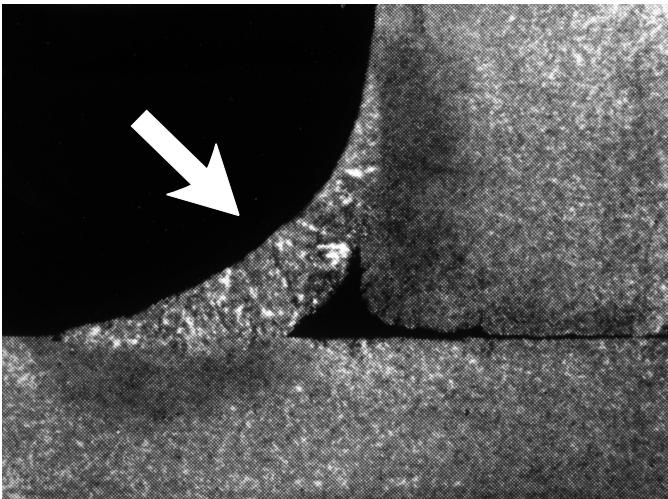
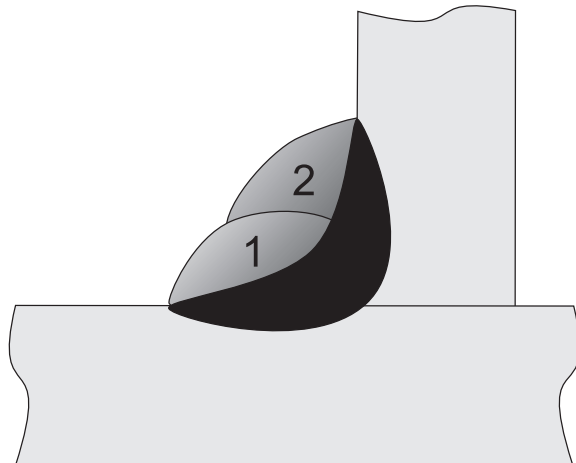


Figure 9.19: Concave fillets.



**Figure 9.20: Excessive concavity.
Lack of root penetration.**

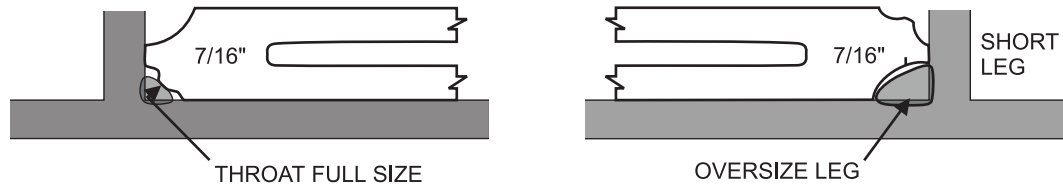


**Figure 9.21: Corrective passes for
a concave fillet.**

Insufficient weld reinforcement may be caused by any one or a combination of the following operator manipulation techniques:

- ◆ travel speed too fast
- ◆ insufficient passes or layers
- ◆ incorrect weave techniques
- ◆ excessive included groove angles

Weld deficiencies due to insufficient or excessive size and poor profile may be detected by visual examination, or by the use of suitable gauges as illustrated in **Figure 9.22**.



Six-bladed pocket size fillet weld gauge and methods of use.

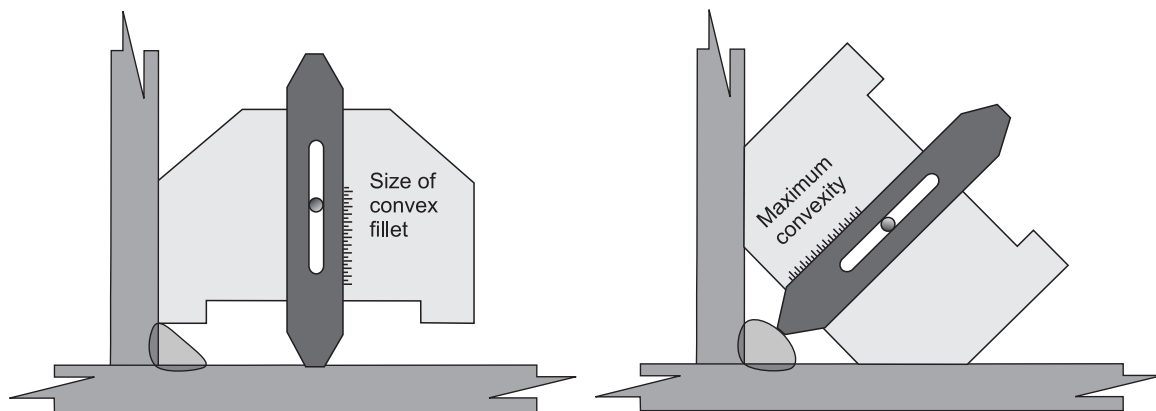


Figure 9.22: Multi-purpose welding gauge.

Typical causes of concavity can be divided into the following categories:

- a) incorrect operator manipulation
- b) change in the essential variables
- c) inadequate joint geometry
- d) position of welding
- e) process behaviour
- f) material type

Each of these categories may be sources contributing to concavity either individually, or in combination.

9.4.2 Incorrect Profile and Size of Lap Weld

The exposed corner of the upper plate is melted off along the length of the weld, reducing the length of the vertical leg and consequently the designed throat size of the weld, as illustrated in **Figures 9.23 & 9.24**.

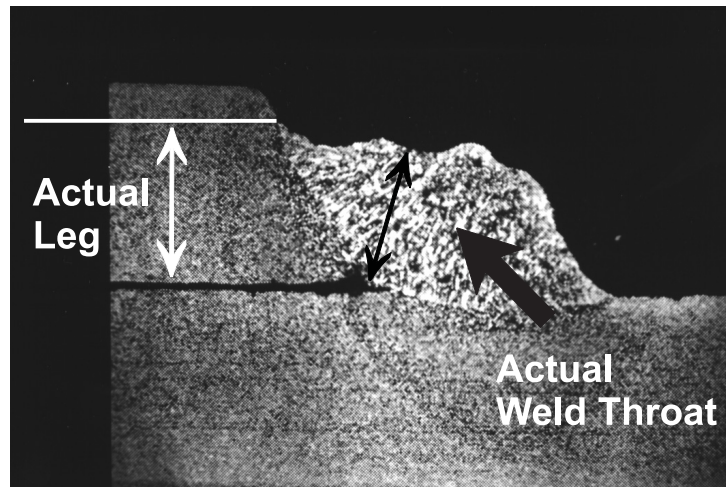


Figure 9.23: Section showing actual weld size with reduced throat thickness.

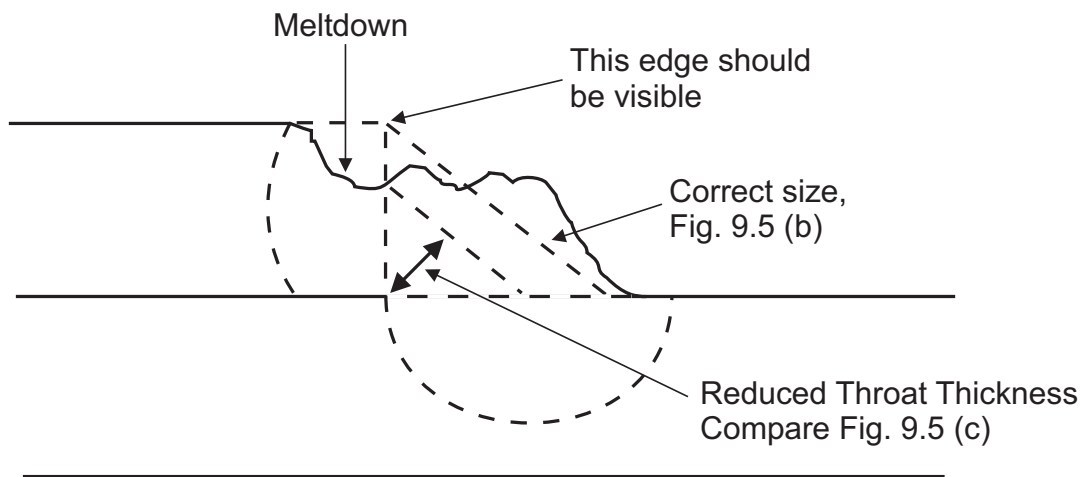


Figure 9.24: Reduction in throat thickness.

The upper edge should just remain visible, or, failing this, the weld fault should be corrected by the addition of another weld pass as illustrated in **Figure 9.25**.

Melting the upper edge may be caused by:

- ◆ inadequate operator manipulation (slow travel speed, wrong electrode angle)
- ◆ process behaviour
- ◆ essential variables (excessive current or voltage)
- ◆ material type
- ◆ position of weld
- ◆ inadequate joint geometry

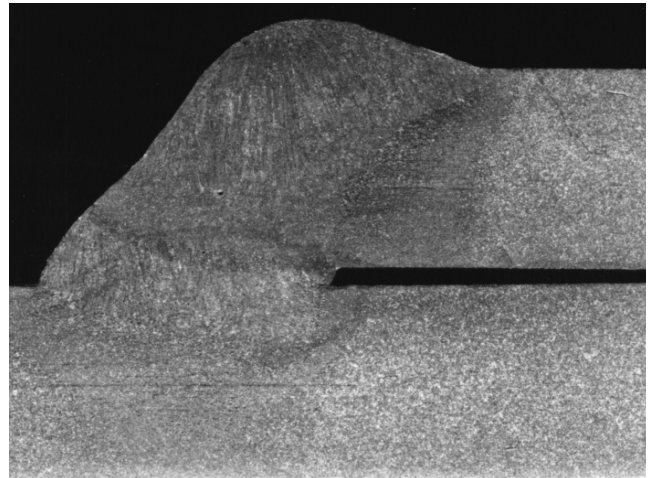


Figure 9.25: Restoration to correct size by addition of a weld pass.

Proper manipulation by the operator is usually determined by the above mentioned categories and may be the cause of the weld fault. Each of the above categories may contribute to the operator technique.

9.4.3 Out-of-Line Weld Beads

Causes

The following causes can lead to misalignment of the weld (**Figure 9.26**):

- ◆ insufficient care in positioning automatic welding machines
- ◆ incorrect bead placement by the welder
- ◆ incorrect edge preparation
- ◆ careless chipping out of the back side of welds

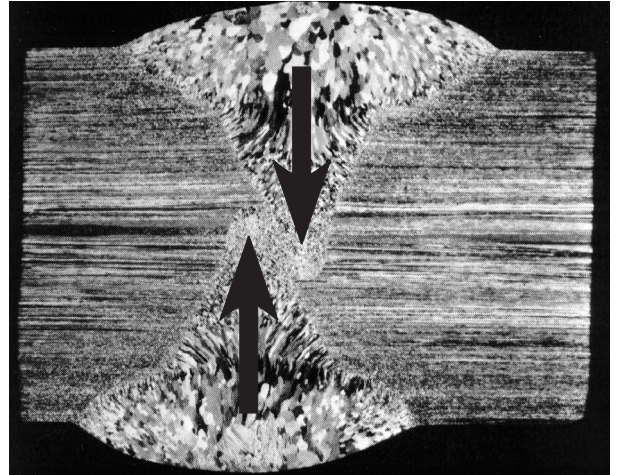


Figure 9.26

9.5 Structural Faults in the Weld Zone

Gas Inclusions (Porosity)

- ◆ isolated gas holes
- ◆ worm holes (elongated gas holes)
- ◆ piping
- ◆ hollow root (suck back)
- ◆ scattered porosity
- ◆ grouped porosity
- ◆ christmas tree porosity

Inclusions

- ◆ isolated slag inclusions
- ◆ slag lines
- ◆ slag entrapment behind backing strip
- ◆ slag inclusions missed by back gouging (double-V weld)
- ◆ tungsten inclusions
- ◆ copper inclusions (from carbon arc-air operations)
- ◆ slag from laminations in parent material

9.5.1 Gas Inclusions

The term porosity is used to describe gas pockets trapped in the solidifying weld metal. Porosity may manifest itself in a variety of patterns, sizes, shapes and quantities. Porosity may be present in any position in the deposited weld metal. Some porosity may appear on the surface of a weld, and therefore, can be detected visually. However, when the porosity is sub-surface, special testing such as radiography or ultrasonics is necessary to disclose it. Examples of porosity are illustrated in **Figures 9.27 – 9.31**.

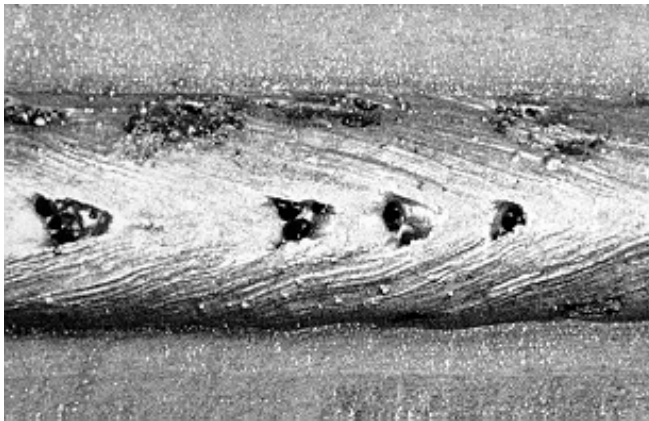


Figure 9.27: Severe surface porosity (sulphur or moisture).

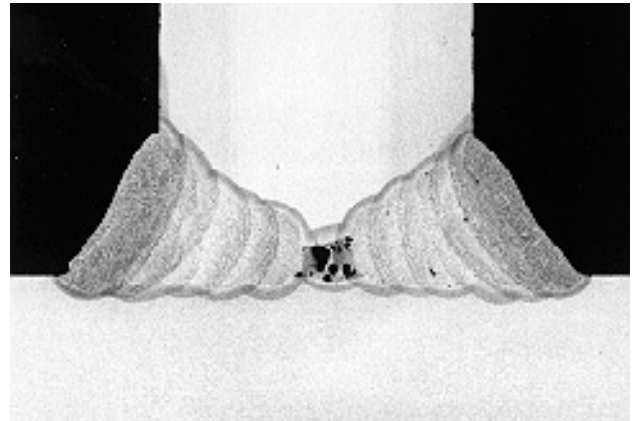


Figure 9.28: Porosity at root of the joint.

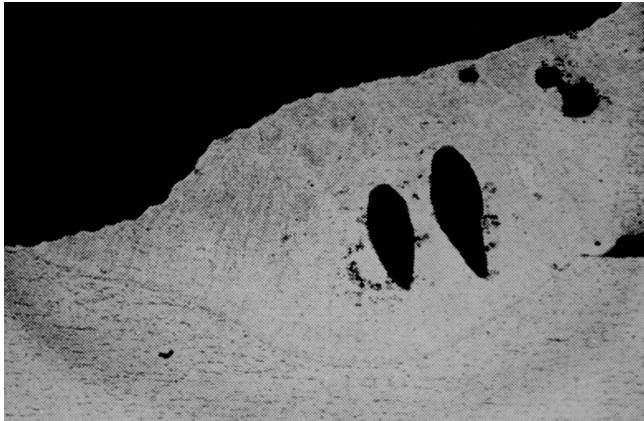


Figure 9.29: Severe piping at lap joint.

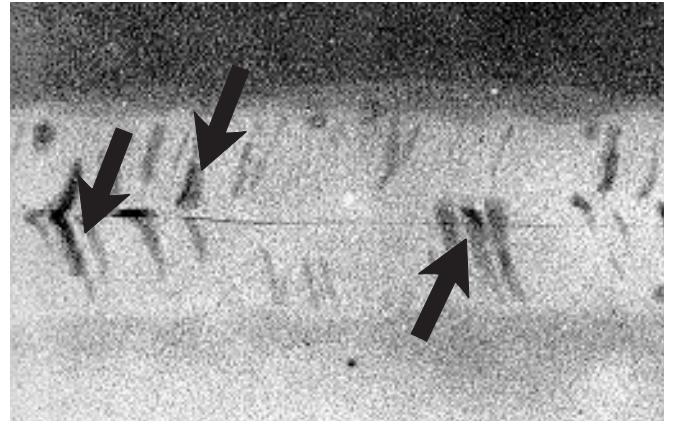


Figure 9.30: Radiographic image of piping porosity resulting from use of wet basic electrodes.

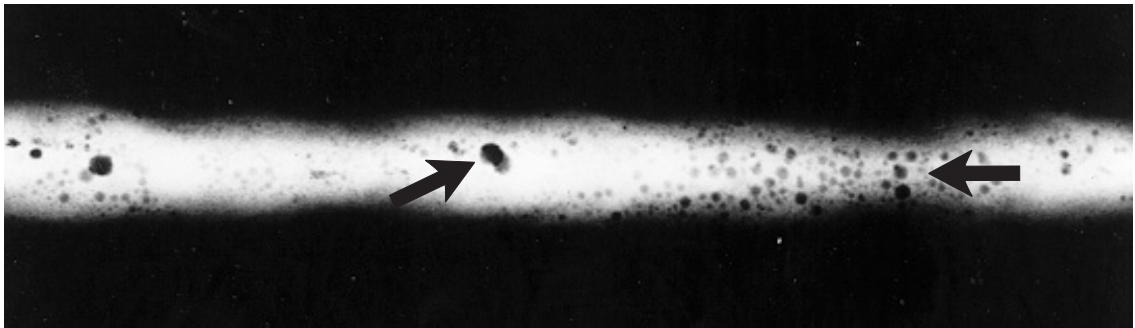


Figure 9.31: Radiographic image of porosity in aluminum weld.

9.5.2 Causes of Porosity

In multi-pass welding, the location of porosity in relation to the depth over the cross-sectional area of the weld may assist in determining the probable cause.

In many cases porosity is cumulative as subsequent passes are deposited. To preclude building up the density of the porosity to a point where a completed weld would be unacceptable, the porosity should be removed entirely prior to the addition of further passes.

The probable causes may be categorized as follows:

- a) Moisture
- b) Chemistry and structure of the parent material
- c) Surface impurities and contaminants
- d) Faulty electrodes, fluxes, shielding gases or slag
- e) Operator techniques

9.5.3 Moisture

Moisture pick-up in flux-coated electrodes or on the surface of flux-coated wire will cause porosity. The same situation pertains to externally applied flux in welding processes such as submerged arc and electroslag.

To avoid moisture, the consumables, including fluxes, should be stored under controlled conditions. Various codes and standards may require procedures for the proper storage of weld consumables, such as CSA Standard W59 and AWS D1.1. Storage conditions will be governed by the type of flux, with basic fluxing systems requiring storage temperatures above 250°F (120°C). This ensures moisture levels are kept at an acceptable level to produce a weld deposit with a low hydrogen designation. For details, see Module 6.

9.5.4 Parent Material

It is important to select the proper filler metal to match the chemistry of the material to be welded. In cases of relatively high sulphur content, porosity is commonly encountered. Other elements, such as zinc in galvanized steels, may also create excessive porosity after welding.

Materials with dense oxides, such as aluminum, should be carefully cleaned. Dense oxide layers can become contaminated with moisture or oils, etc. and cause porosity. Laminations in plate may also be a source of porosity in the welding operation.

9.5.5 Surface Contaminations

When fabricating metals, the surfaces may be in contact with certain contaminants that can cause porosity. Some of these contaminants are as follows:

- ◆ oil
- ◆ grease
- ◆ paint
- ◆ oxide

Rust and mill scale can also absorb contaminants and become a source of porosity.

The method of preparing material for welding often introduces contaminants, and some of these methods are:

- ◆ shears
- ◆ band saws
- ◆ abrasive grinding wheels
- ◆ mechanical nibblers
- ◆ oxy-fuel apparatus

Malfunctioning tools, such as air grinders, air chipping tools or air scaling guns may deposit films of oil, grease or moisture on the surfaces to be welded.

Where aluminum is being welded, tools used on other materials, such as steels, may introduce contaminants that will cause porosity. Care should be taken to use tools designated for aluminum only. These tools, such as stainless steel wire brushes, must be kept clean and separated from general use to reduce the chances of contamination.

Carbon steel wire brushes used on stainless steels may also be a cause of porosity.

Contaminants that cause porosity may be picked up during recovery operations of unused flux during or after submerged arc welding operations.

9.5.6 Insufficient Flux Coverage

Insufficient flux covering in submerged arc welding may be a cause of scattered surface porosity.

9.5.7 Slag Residue

Slag left on the surface of tack welds or internal weld beads may cause porosity.

9.5.8 Shielding Gas

Porosity associated with shielding gases is often caused by poor distribution within the arc and surrounding areas, insufficient or excessive shielding gas flows, or impurities collected in the gas through hoses, connections and the torch or gun assemblies.

When setting up for GMAW of aluminum using pure argon, hoses, regulators and cables (which have been used exclusively for welding steel with CO₂ or CO₂ mixtures) will be a possible source of contamination and subsequent porosity if they are not replaced or cleaned properly.

Loose fittings and connections may allow atmospheric gases to enter the gas hoses and assemblies and cause porosity.

As illustrated in **Figure 9.32**, upon welding an outside corner with GMAW, .035 E70S6 and Ar CO₂ shielding, a gas nozzle inner diameter less than 13 mm (1/2 ") could cause porosity.

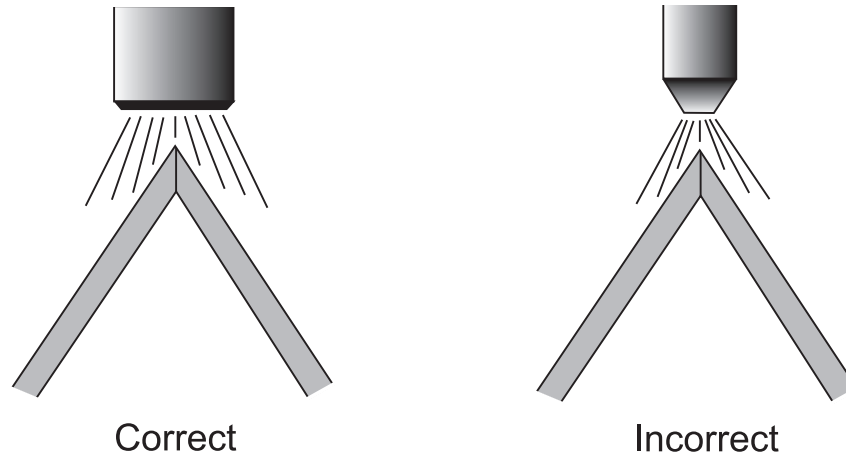


Figure 9.32: Effective shielding for outside corner joint.

If the distance the cup is held from the work is incorrect, it may cause porosity (i.e., 20 mm (3/4") is acceptable and 40 mm (1 1/2") is not).

9.5.9 Welding Techniques

In manual welding applications, the following may cause porosity:

- ◆ faulty manipulation of the electrode
- ◆ excessive arc voltages
- ◆ incorrect electrode angle
- ◆ incorrect weave techniques

9.5.10 Slag Inclusions

This term is used to describe oxides and other non-metallic solids that are sometimes found as elongated or multifaceted inclusions in welds.

Slags are always produced when welding with covered electrodes, and they serve as scavengers of impurities in the molten metal pool. In addition, they form a blanket over the weld to control the cooling rates and exclude atmospheric oxygen from the hot metal surface.

During the welding process, fluxes form slag that is forced below the surface of the molten metal by the stirring action of the arc. Slag may also flow ahead of the arc causing the metal to be deposited over it. In any case, it tends to rise to the surface because of its lower density.

A number of factors may prevent its release and result in the slag being trapped in the weld metal. Some of these factors are:

- ◆ high viscosity (thick) weld metal
- ◆ rapid solidification
- ◆ too low a temperature
- ◆ improper manipulation of the electrode
- ◆ undercut on previous passes

One other potential cause of slag is foreign material entrapped in laminations in the joint preparation.

In multi-pass welding, insufficient cleaning between weld passes can leave portions of the slag coating in place which is then covered by subsequent passes. Such slag inclusions are often characterized by their location at the edge of the underlying metal deposits, where they tend to extend longitudinally along the weld.

In making a root pass the electrode may be so large that the arc strikes the side of the groove instead of the root. The slag will roll down into the root opening and become trapped under the root layer because the arc failed to heat the root area to a sufficiently high temperature to allow the slag to float to the surface.

Slag lines can be either intermittent or continuous. If the prior pass produces a bead that is too convex, or if the arc has undercut the joint surface, it will be difficult to remove the slag between the surface of the groove and the deposited metal. When the slag is left in place it is covered by subsequent passes (**Figure 9.33**).

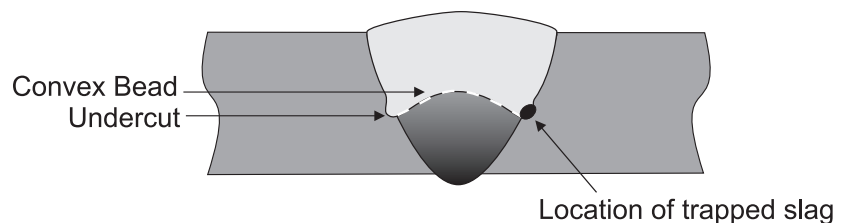


Figure 9.33

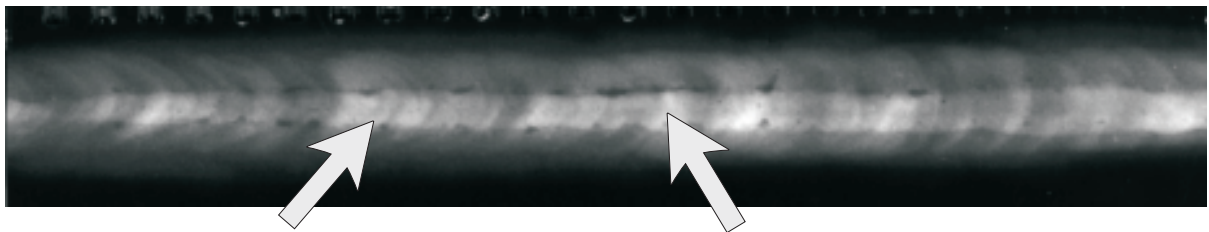


Figure 9.34: Elongated slag inclusions.

The majority of slag inclusions may be prevented by proper preparation of the groove before each bead is deposited (including sufficient cleaning), and using care to correct the contour that would be difficult to penetrate fully with the arc.

9.5.11 Tungsten Inclusions

Tungsten inclusions are characteristic of the inert atmosphere welding methods. If the tungsten electrode comes into contact with the weld metal, tungsten particles can be trapped in the deposited metal. These may be in the form of small pieces of the tungsten wire. Due to its high melting point, fusion of the tungsten to the deposited weld metal does not occur.

9.5.12 Copper Inclusions

This type of inclusion occurs when pieces of the copper sheath of a carbon arc-air electrode fall into the groove and are subsequently welded over. Continuous electrode processes use copper contact tips and copper alloy nozzles. If these parts contact the weld pool, copper inclusions can be created.

Another cause of copper inclusions may occur during magnetic particle testing of welds. The current supplied to create the magnetic field may be passed through copper conductors (prods). If there is poor contact of the prods to the steel when the current is applied, sparking will occur, and copper particles may be melted into the structure. This type of problem should be carefully controlled due to the propensity for crack propagation from the embedded inclusions.

9.5.13 Oxidation

In pipe and tube welding of components for critical service (i.e., nuclear plant) some specifications forbid the presence of oxides on the internal surface of the welds. In these cases, the internal surface of the pipe/tube is purged with a constant supply of inert gas. If the gas flow is inadequate, oxides will form and cause the weld to be rejected. Control of the gas supply is, therefore, an essential operation to produce sound welding.

9.6 Fusion Faults

- ◆ incomplete fusion (inert)
- ◆ incomplete sidewall fusion
- ◆ incomplete root fusion
- ◆ incomplete fusion in fillet welds
- ◆ underbead non-fusion/cold lap
- ◆ incomplete penetration

9.6.1 Incomplete Fusion (Lack of Fusion)

The term “incomplete fusion” is used to describe the failure to fuse weld metal to the base material, or adjacent layers of weld metal to each other. Failure to effect fusion may occur at any point in the welding groove or fillet weld as illustrated in **Figures 9.35 to 9.42**.

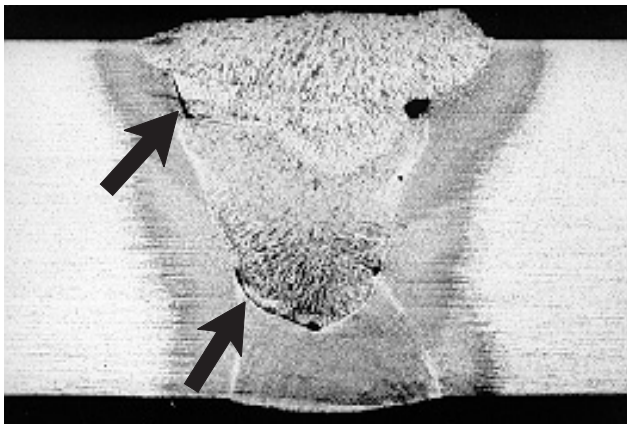


Figure 9.35: Incomplete fusion at root and along joint face.

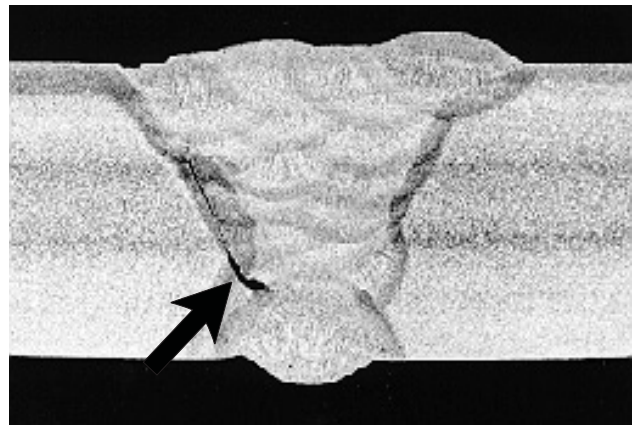


Figure 9.36: Incomplete fusion along joint face.

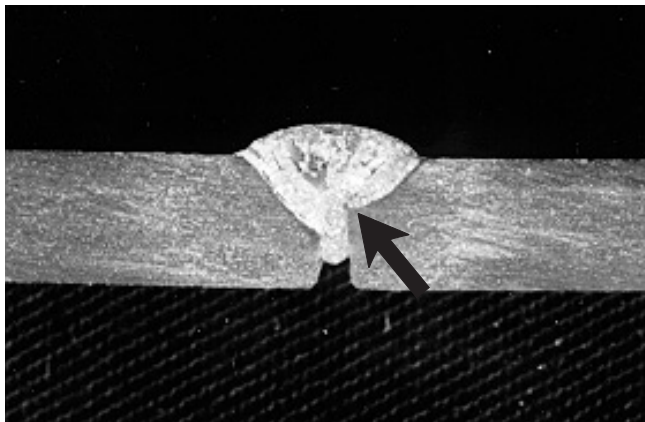


Figure 9.37: Incomplete fusion at root.

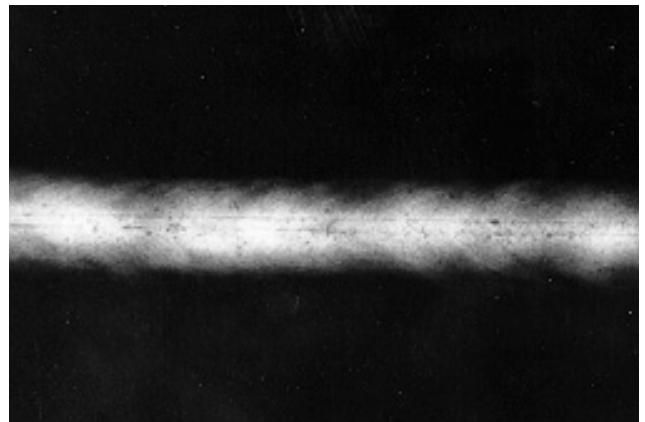
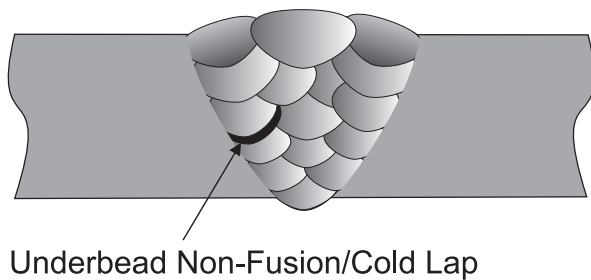
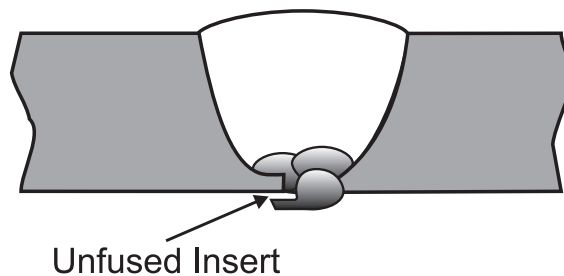


Figure 9.38: X-ray of incomplete fusion at root.



Underbead Non-Fusion/Cold Lap

Figure 9.39



Unfused Insert

Figure 9.40

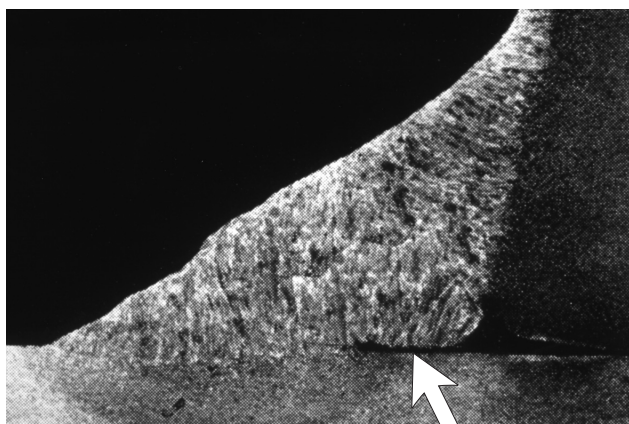


Figure 9.41: Incomplete fusion at root of fillet.

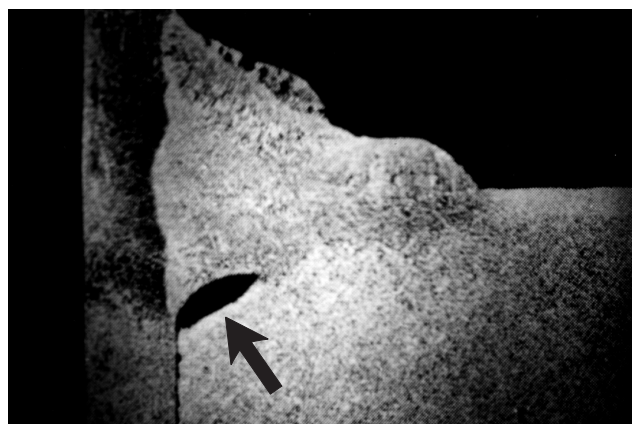


Figure 9.42: Incomplete fusion at root of J-groove weld in thick section.

Incomplete fusion may be caused by a number of factors, either singly or in combination. Some of these factors are listed below:

- a) Using too large an electrode for a narrow preparation
- b) Using the wrong type of electrode
- c) Insufficient welding current, resulting in failure to raise the temperature of an adequate amount of base material to the melting point
- d) Improper manipulation of the electrode
- e) Failure to dissolve, by proper fluxing, the oxides or other foreign materials on the surfaces to which the weld metal must fuse
- f) Poor joint design. As an example, a narrow Vee groove in a thick plate would limit manipulation of the electrode. This would increase the probability of non-fusion of the weld metal to the parent metal (**Figure 9.43**)
- g) Inadequate shielding gas (if used)

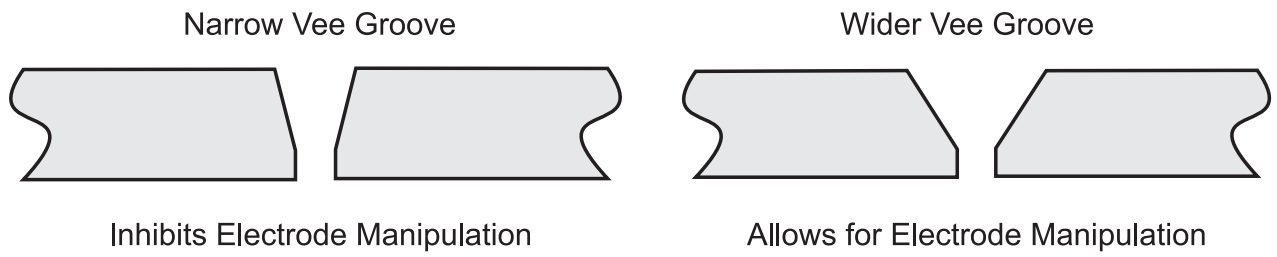


Figure 9.43

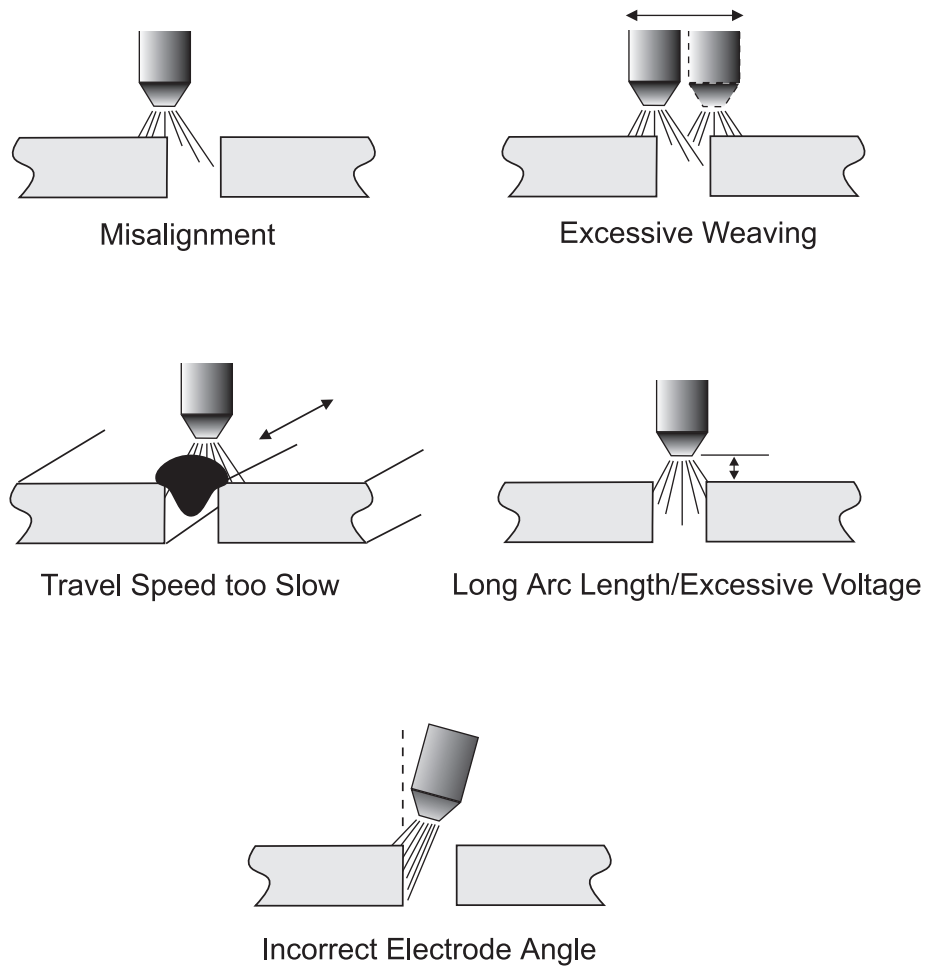


Figure 9.44: Operator techniques.

9.6.2 Incomplete Penetration

The term incomplete penetration describes the failure of the deposited weld metal to fuse integrally with the parent material at the root of the weld joint (see **Figure 9.45**).

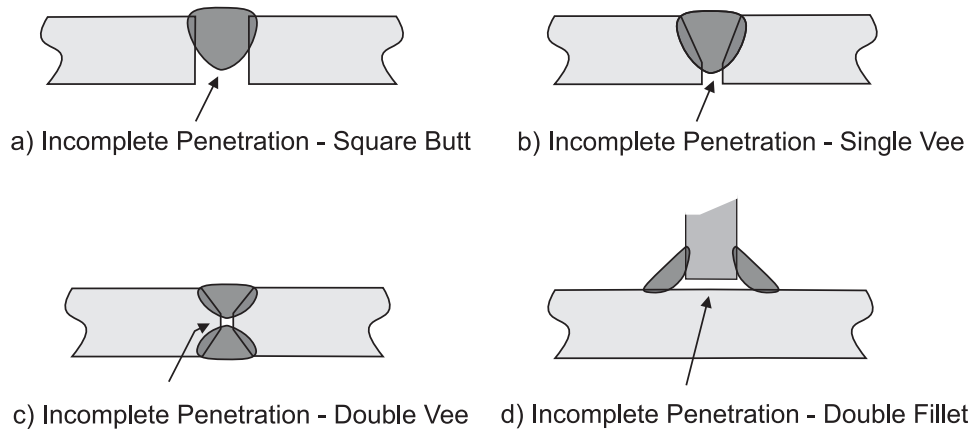


Figure 9.45

It must be noted that incomplete penetration is not necessarily a weld fault. Some welded connections are designed with partial penetration welds. Incomplete penetration becomes a weld fault when the codes, specifications and designs require complete penetration.

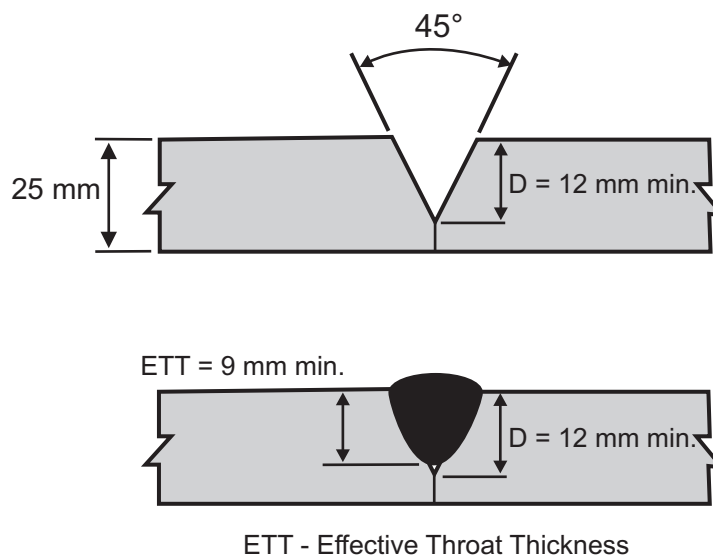


Figure 9.46: Partial penetration groove weld.

The causes of incomplete penetration are very similar to those causing lack of fusion, and are listed below:

- a) Using too large an electrode for a narrow joint
- b) Using the wrong type of electrode
- c) Insufficient welding current, resulting in failure to penetrate and fuse the root faces
- d) Improper manipulation of the electrode (**Figure 9.44**)
- e) Poor joint design
- f) Poor fit up causing inadequate gap between the root faces.

9.7 Cracking

9.7.1 Solidification Cracking

During the solidification of weld metal, grains begin to grow from the fusion boundary towards the central region of the weld pool.

Some alloying elements and impurities are rejected ahead of the growing crystals. Their presence lowers the freezing temperature substantially below that of the first liquid to solidify. As solidification takes place, the weld and surrounding material are progressively cooling, and this gives rise to contraction strains across the weld.

When solidification is almost complete, and grains begin to meet, the low melting point liquid may lead to such low ductility that the contraction strains produce cracking.

Hot Cracks

The development of “hot cracks” in welds results from the combined effects of metallurgical and mechanical factors. Some metals are prone to hot cracking, e.g., high temperature alloys and high sulphur steels.

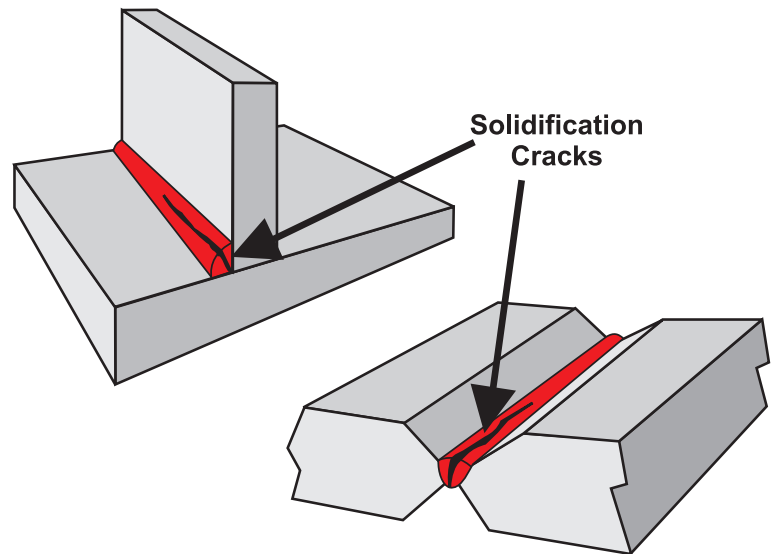


Figure 9.47: Solidification cracks.

9.7.2 Hydrogen-Induced Cold Cracking

Cold cracks may occur in the weld metal or in the heat affected zone. Cold cracks in the weld metal may occur in any orientation with respect to the weld axis, but the commonly observed positions are illustrated in **Figure 9.48**.

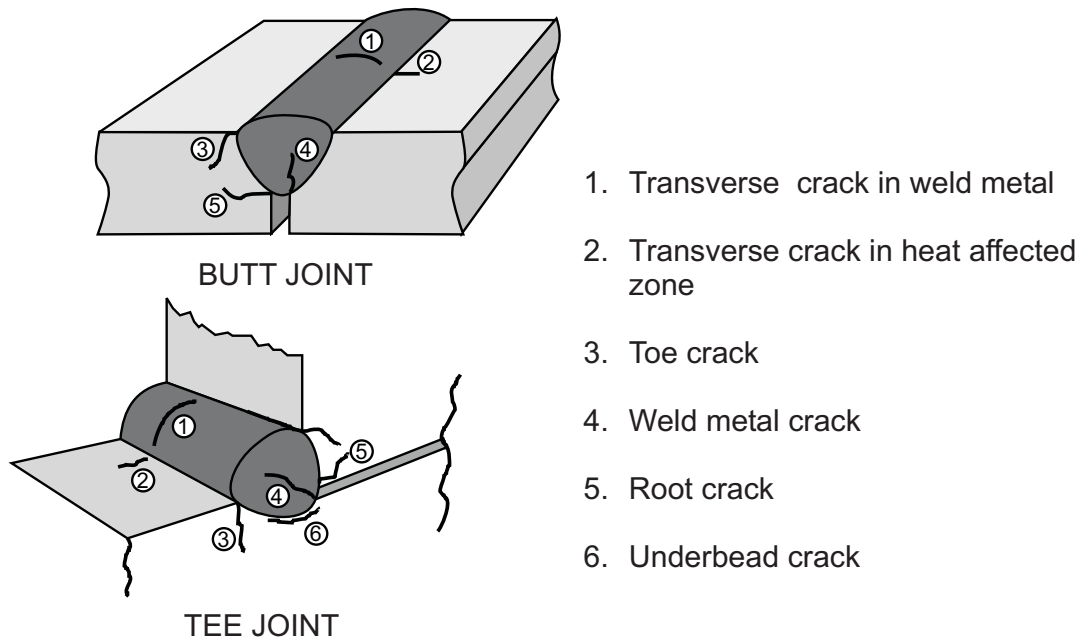


Figure 9.48: Commonly observed positions of cold cracks in butt and fillet welds.

Transverse cracks in the weld metal may extend into the heat affected zone of the parent plate and beyond.

HAZ cracks are usually longitudinal and most often occur at the root or the toes of the welds. Under some conditions, longitudinal cracks may be very long, sometimes running the entire length of the weld.

Cold cracking may also manifest itself as fine micro-cracks that are difficult to detect by normal inspection and non-destructive test methods. The presence of micro-cracks may be symptomatic of a more serious condition (such as high hydrogen level) that could lead to more serious cracking.

Figures 9.49 & 9.50 show typical cold cracking and commonly observed positions. As the name implies, the cracks form at low temperatures – generally below 200°C (390°F). In most cases, cracks occur at room temperature when the weld has completely cooled.

Cold cracks are often delayed. Even after the joint has cooled to room temperature there may be a further lapse of time before cracking occurs. This may be a few minutes or several hours, although in some extreme cases cracks have been observed to form several weeks after welding is complete.

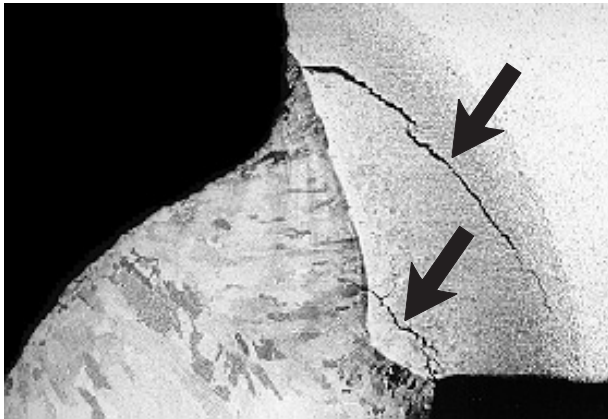


Figure 9.49: Typical cold crack in the heat affected zone.

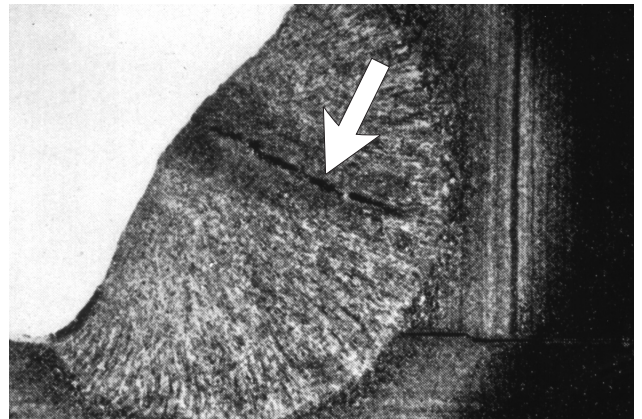


Figure 9.50: Typical cold crack in the weld metal.

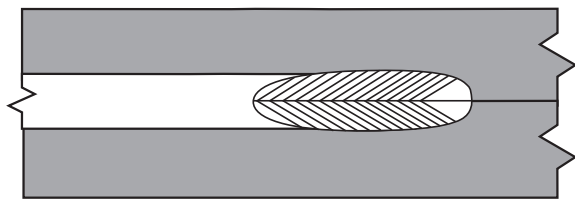
The causes of hydrogen-induced cold cracking are complex and cannot be fully documented in this text, however, a brief list of some of the causes is as follows:

- ◆ hydrogen from coated electrodes
- ◆ hydrogen from external sources in the base material, i.e., hydrogen sulphide
- ◆ insufficient pre- and post-weld heat treatment

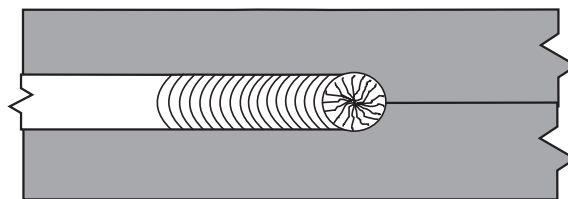
Tack welds left for inclusion in the completed weld may be the cause of cracks. If the tack weld is made on a cold surface of a large mass compared to the size of the tack, the result is a rapid quench. If the tack is badly made or of insufficient size, a crack may readily occur.

Crater cracks occurring during solidification are more likely to form in a long crater, **Figure 9.51 (a)**, where the columnar crystals form from each side of the joint, at right angles to the axis of the weld. This leaves a plane of juncture subject to cleavage as the metal shrinks. A short crater displays columnar crystals radiating from the centre as shown in **Figure 9.51 (b)**.

Figures 9.52 to 9.59 illustrate a variety of weld and HAZ cracks.



(a)



(b)

Figure 9.51

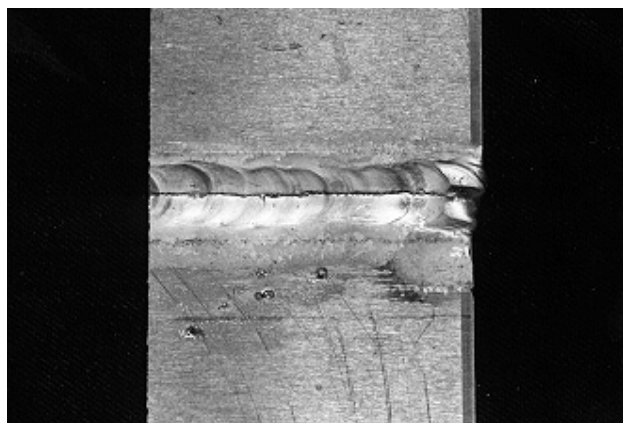


Figure 9.52: Longitudinal crack in butt joint.

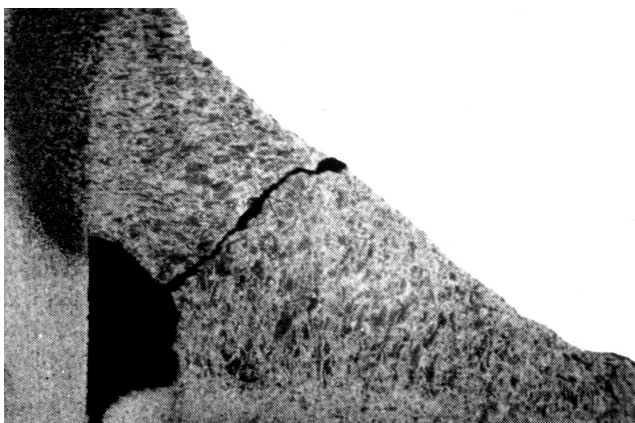


Figure 9.53: Crack in fillet – lack of penetration.

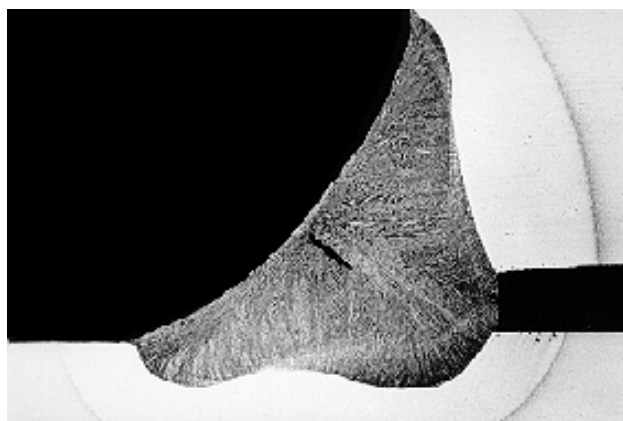


Figure 9.54: Hot crack in deep – penetration fillet.

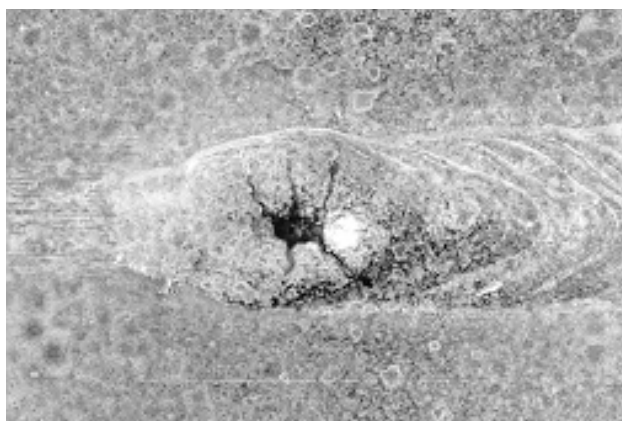


Figure 9.55: Crater cracks.

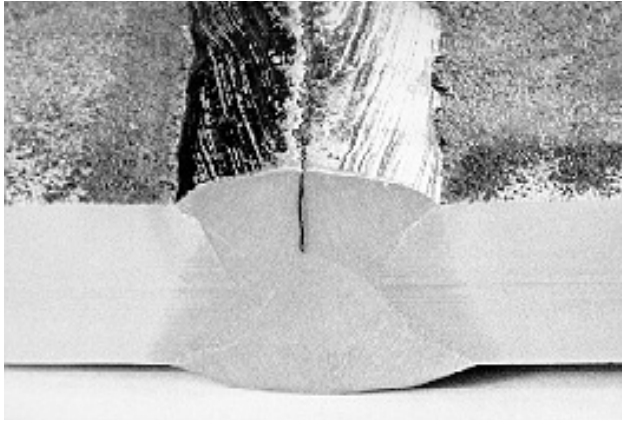


Figure 9.56: Root crack in first pass of double-V butt.



Figure 9.57: Root crack in thick U butt.

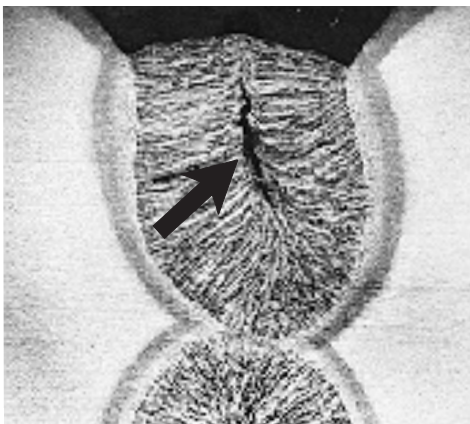


Figure 9.58: Solidification crack.

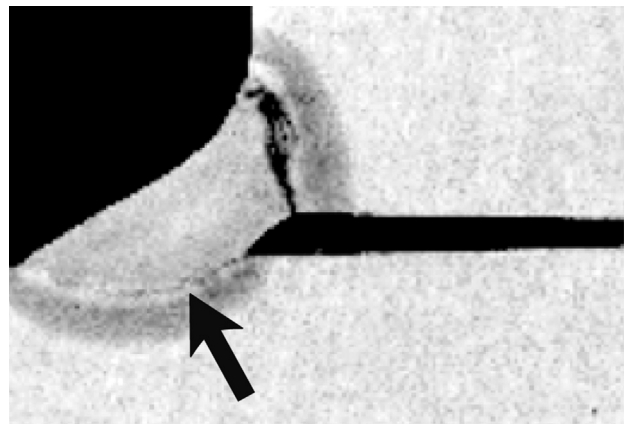


Figure 9.59: Fusion line crack in low-alloy steel (underbead crack).

Some of the causes of cracking are listed below:

- 1) Hydrogen content of electrode
- 2) Hydrogen impregnation of the parent material
- 3) High sulphur or phosphorous content of the base material
- 4) High carbon content of the base material
- 5) High restraint on the joint
- 6) Rapid cooling of hardenable and brittle material
- 7) Welds too small for the size, rigidity and quenching effect of the parts joined
- 8) Poor joint fit up
- 9) Unsuitable electrodes
- 10) Secondary faults such as lack of penetration, porosity, elongated craters, etc.

9.8 Surface Defects (Irregularities)

Sometimes conditions are encountered during the welding which result in holes in the surface of the deposit (**Figure 9.60**). This is generally considered the result of a highly reducing atmosphere. Such a condition is most likely to be encountered at the bottom of a narrow groove where the air is completely excluded and no normal reaction takes place between the arc atmosphere and the surrounding air. The base metal being welded can be a factor (sulphur, moisture in both base metal and electrode, as mentioned before) but leaving this out of consideration, improvement is usually obtained by changing the electrical conditions such as current and polarity. Often an increase of arc length will correct this condition, but it may be necessary to change the type of electrode.

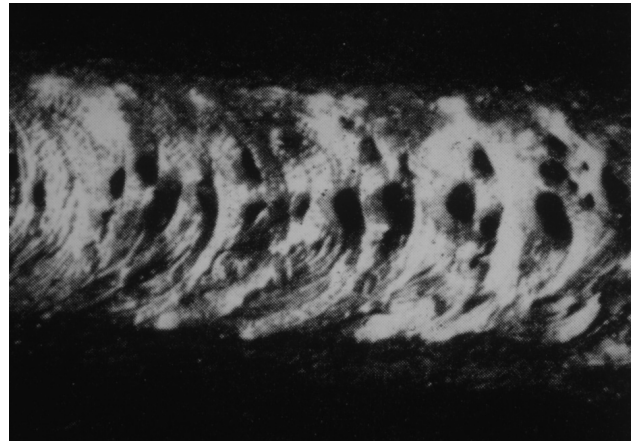


Figure 9.60: Severe surface porosity (sulphur or moisture).

Unsatisfactory Surface Appearance and Spatter

The following illustrated surface irregularities should be noted:

Figure 9.61 – badly shaped surface ripples

Figure 9.62 – badly shaped ripples and excessive spatter

Figure 9.63 – an inadequately filled crater

Figure 9.64 – (a) and (b) – stray flash (accidental striking of arc on plate, adjacent to weld)

The operator is usually directly responsible for these defects as a result of incorrect technique or improper machine settings. Sound welding finished in a poor manner should not be excused even though the adequacy of the joint may be beyond doubt. The ability and integrity of the welder must be questioned.

In some cases, faulty or wet electrodes and unsuitable base material (high sulphur, for example) may cause similar defects and unsatisfactory weld appearance.

Bead requirements are defects in as much as they constitute an abrupt change of section. Spatter in itself is not necessarily a defect, but is quite likely indicative of improper welding and the likelihood of other associated faults.

Stray arc flashes either with the electrode or holder are more serious than might at first be expected. They create a quenched and brittle condition in alloy steels and are inadvisable even on mild steel, where high static or normal fatigue stresses may be encountered. The repair of such damage may be difficult and costly, involving chipping and probably preheating in the case of alloys.

Unsatisfactory Surface Appearance, Spatter, Stray Arc Flash

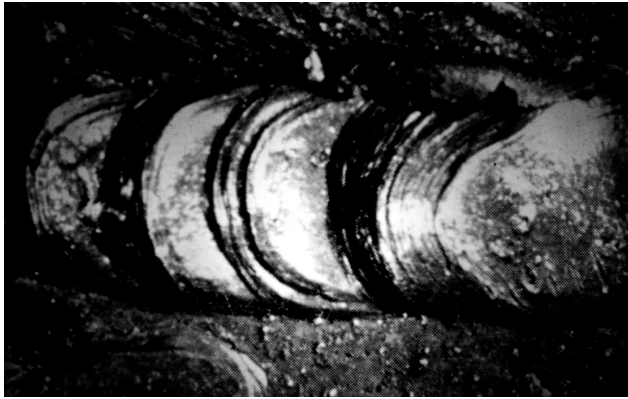


Figure 9.61: Badly shaped ripples.

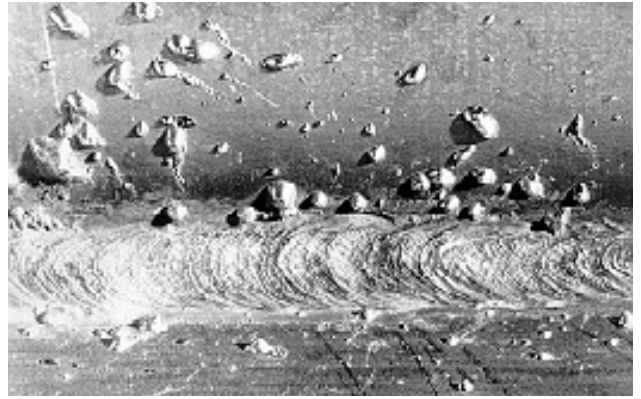


Figure 9.62: Excessive spatter.

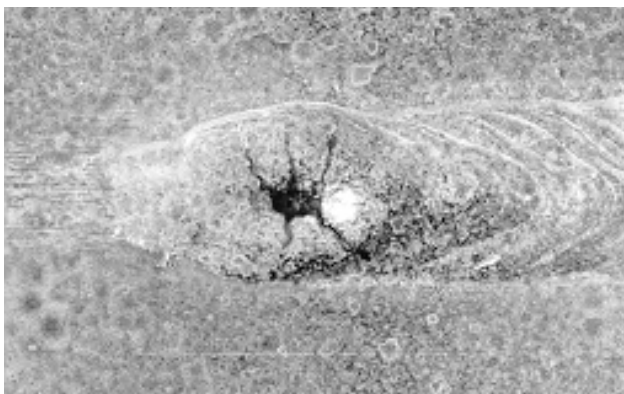


Figure 9.63: Inadequately filled crater.

Danger: cracks in low alloy steels and stress raiser under fatigue loading.

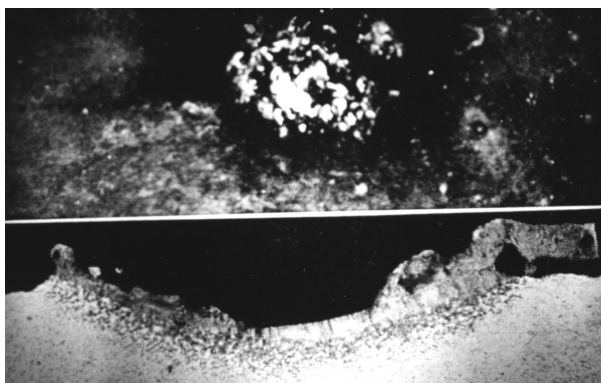


Figure 9.64(a): Electrode holder stray flash – cross section.

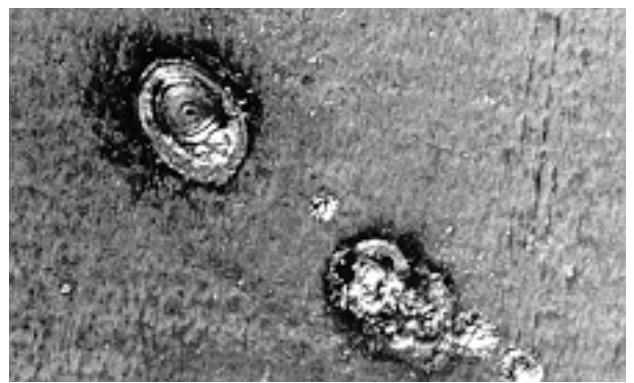


Figure 9.64(b): Electrode holder stray flash – accidental striking of arc on plate, adjacent to weld.

9.9 Defective Properties (Weld Metal and Joint)

Specific mechanical and chemical properties are required of all welds made in any given weldment. These requirements depend on the codes or specifications involved and departure from specified requirements is considered a defect. These properties are generally determined with specially prepared test plates but may be made on sample weldments taken from production. Where test plates are used, the inspector should see that specified procedures are followed, otherwise the results obtained will not necessarily indicate the actual properties of the weldments.

Mechanical properties that may be defective are tensile strength, yield strength, ductility, hardness and impact. Chemical properties may be deficient because of incorrect weld metal composition or welding procedure. Both may result in lack of corrosion resistance.

Not all these defects are due to improper welding conditions since many such difficulties are caused by the base metal. Properties of the base metal that may not meet the requirements are chemical composition, internal conditions (laminations and stringers), surface conditions (mill scale, grease, paint, oil, etc.), mechanical properties and dimensions. All these factors should be kept in mind when considering the causes of welding difficulties.

9.10 Summary of Weld Faults

A good inspector, supervisor or welder can, and will assist greatly in preventing faults in welding. As an aid to competent inspection, **Table 9.2** lists a number of defects that are likely to occur under certain welding conditions.

Table 9.2

Welding Conditions	Effects Likely to Occur
Cold weather	Cracks in weld or base metal
Thick or rigid assemblies	Cracks in weld or fusion line
Hardenable materials	Cracks in either weld or base metal
Base material known or suspected to be high in sulphur content (free machining steels for example)	Cracks and porosity in weld
Rusty, oily or greasy joints	Porosity, inclusions and lack of fusion
Limited access to joint	Undercut, particularly if welding in vertical or overhead position.
Welding in corners, at ends of welds and first passes in deep grooves	Arc blow, resulting in poor fusion, porosity incomplete penetration, spatter and poor appearance.

9.11 Welding Inspection

Practically all areas of welding fabrication involve some form of inspection. To begin with, the welders or welding operators, before the welding operation, will cursorily examine the fit up. During welding, experienced welders would sense if the welding operation was progressing normally. After depositing each weld pass, the welder examines it before laying the next weld pass. After completion of a weld joint, the welding inspector goes over the weldment again. Therefore, the first step of inspection is visual inspection. Other inspection methods will follow depending on the type of joints and type of welds. For example, complete joint penetration of groove weld requires ultrasonic or radiographic examination to see the inside of the weld. Visual or surface examination alone is inadequate. The following inspection methods will be explained:

1. Visual inspection
2. Liquid penetrant inspection
3. Magnetic particle inspection
4. Radiographic inspection
5. Ultrasonic inspection

Inspection of assemblies fabricated by arc welding involves a great many factors that cannot be covered in any code or specification. These factors include not only the fundamental principles of the actual operation of welding and a knowledge of common weld faults, but also related subjects associated with the process, such as basic properties of welds and parent metal, testing methods and interpretation of drawings and specifications.

An inspector acts as a responsible representative of an organization, which may be either the manufacturer, the purchaser or some outside agency. His/her decisions are governed by some form of written lists of requirements that others have drawn up, but which he/she must be able to interpret both as to limitations and intent.

Because of the variety of welded structures requiring inspection, no one class of inspector is expected to be proficient in all types of inspection. A shop inspector employed by a fabricator makes routine checks of materials, dimensions, workmanship, finish and other details to ensure that design requirements are met. Such inspection is as much a part of production as the necessary welding and machine operations.

Independent inspections are on a basis different from that of routine shop inspection. An inspector cannot possibly check all details of each part of the product. Any such checks must be limited to spot checks or random samples, unless the inspector has reason to believe that code or specification requirements are not being met.

As is the case with all other inspection and testing activities, welding inspection should form a part of the planned operations that are set in place to produce a completed fabrication. With the foregoing in mind, it is logical to organize the inspection portions of the fabrication sequence into rational procedures or checklists, which will serve not only to standardize inspection but which will also provide a format for the documentation of inspection activities. The following examples illustrate the foregoing points.

Assume that a pressure vessel is being fabricated and that the first operations consist of preparing, rolling and welding a plate to form a part of the vessel shell. A probable checklist for the inspector would be:

INSPECTION ACTIVITY	ACCEPTABLE	NOT ACCEPTABLE
1) Verify that raw material conforms with that which is specified on the drawing.		
2) Inspect joint preparations to ensure that they conform to drawing requirements.		
3) Inspect joint preparations to ensure they are free from laminations, cracks and other discontinuities which would cause welding problems.		
4) After rolling, check for dimensional accuracy.		
5) Check the weld joint fit-up for gap and misalignment (hi-lo).		
6) Sign-off acceptance of assembly for welding operations to continue.		
Before welding is initiated, the inspector should verify the following:		
a) Welder/operator qualifications.		
b) Check the welder/operator familiarity with the approved procedure.		
c) Verify the consumables in accordance with the requirements of the procedure and the applicable standards.		
	Inspector's Signature	

9.12 Methods of Testing

The methods commonly used in testing and inspecting welds for the defects previously listed are of two types – non-destructive and destructive. The terms in themselves are descriptive and it is obvious that non-destructive testing would include visual, radiographic, ultrasonic, etc. The term destructive might be interpreted erroneously as destructive of the whole weld fabrication by means of an overload test. This, however, is not so, and the word is commonly used to mean some form of mechanical test applied to a typical sample of a weld, or to a section cut from a weld.

9.12.1 Visual Welding Inspection

Visual welding inspection is of great importance because it constitutes the principal basis of acceptance for many types of weldments.

It is one of the most extensively used methods of inspection because it is easy to apply, fast, relatively inexpensive and, provided the inspection report format is properly organized, gives very important information with regard to the welding operator, the weld, and the general conformity of the weldment to specification requirements.

Visual welding inspection should begin prior to the actual fabrication operations. The inspector should examine the drawings, specifications, welding procedures and consumables, condition of the welding equipment, and weld operator qualifications. He should also ensure that the parent metal to be joined conforms to the specification requirements, and that it is free from such defects as laminations, laps, seams, scale or other harmful surface conditions.

When the components are assembled for welding, the inspector should note incorrect root openings, improper edge preparation and alignment, and other features of joint preparation that may affect the quality of the welded joint. The inspector should check the details of the work while welding is in progress. These details may include maintaining pre-heat conditions, welding speed and deposition rate, welding current, etc. In short, the inspector must ensure that the welding operator is working in accordance with an approved welding procedure.

Inspection after welding and heat treatment (where required) completes the inspection cycle. At this time the inspector checks the finished weldment for weld width, bead or weave appearance, surface defects such as crater cracks, porosity, longitudinal and transverse cracks, non-fusion problems and undercut. Reinforcements should be also checked to ensure adherence to specification requirements. Dimensional checks of the welded component should be carried out at this stage to make sure that the welding process has not distorted the finished assembly beyond drawing tolerances.

Visual inspection requires some simple tools, such as measuring tapes, callipers, try squares, plumb bob and fillet weld gauges (see **Figures 9.65 to 9.70**).

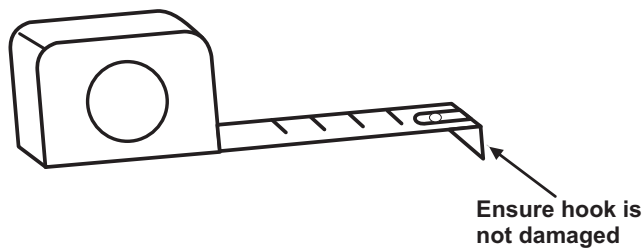


Figure 9.65: The steel tape.

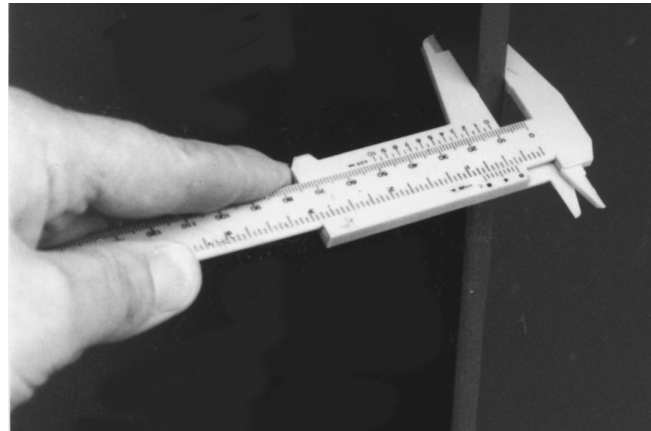


Figure 9.66: Measuring the thickness of a plate with callipers.

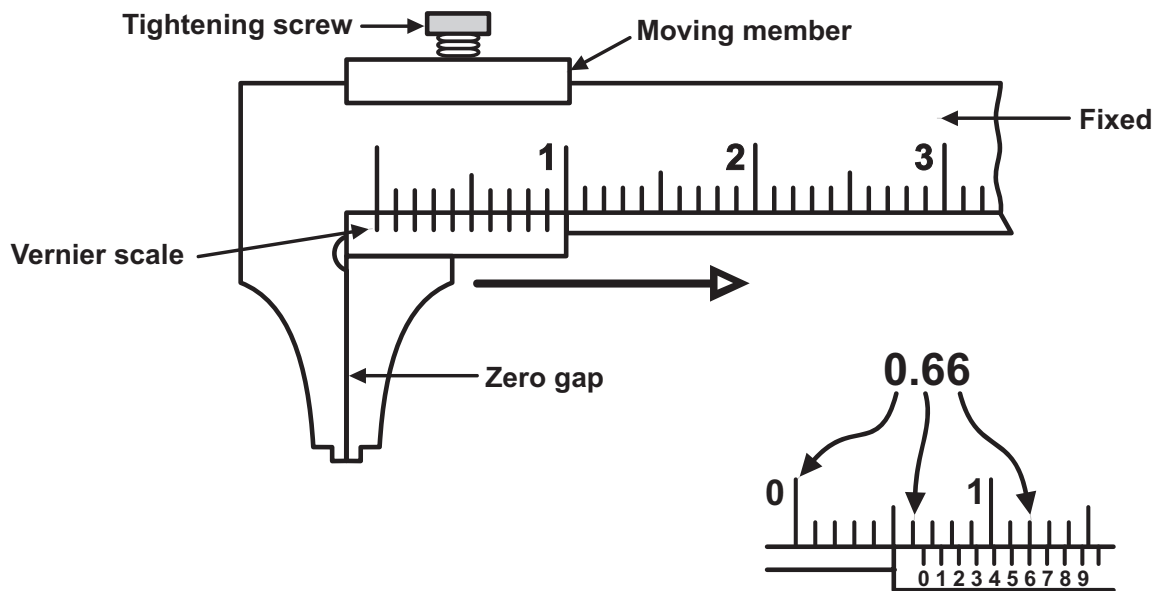


Figure 9.67: Callipers showing the principle of the vernier scale. This simple device increases the precision of measuring instruments.

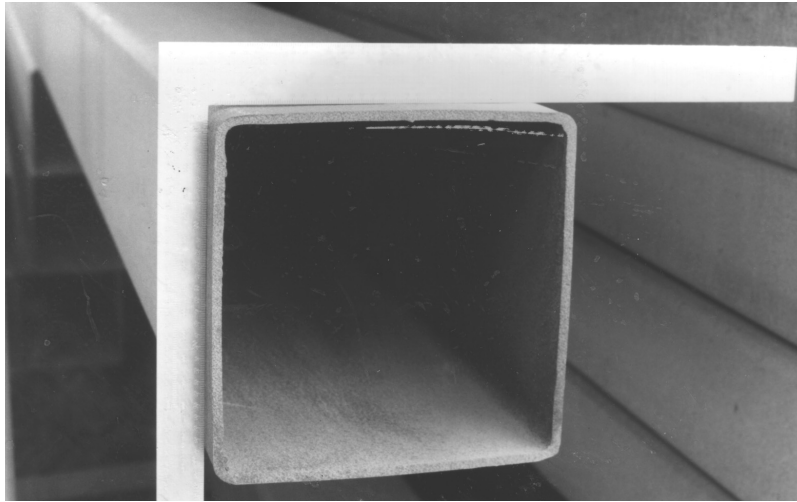


Figure 9.68(a): Using the inside edges of a try square to check squareness and wall flatness on a hollow structural section (HSS).

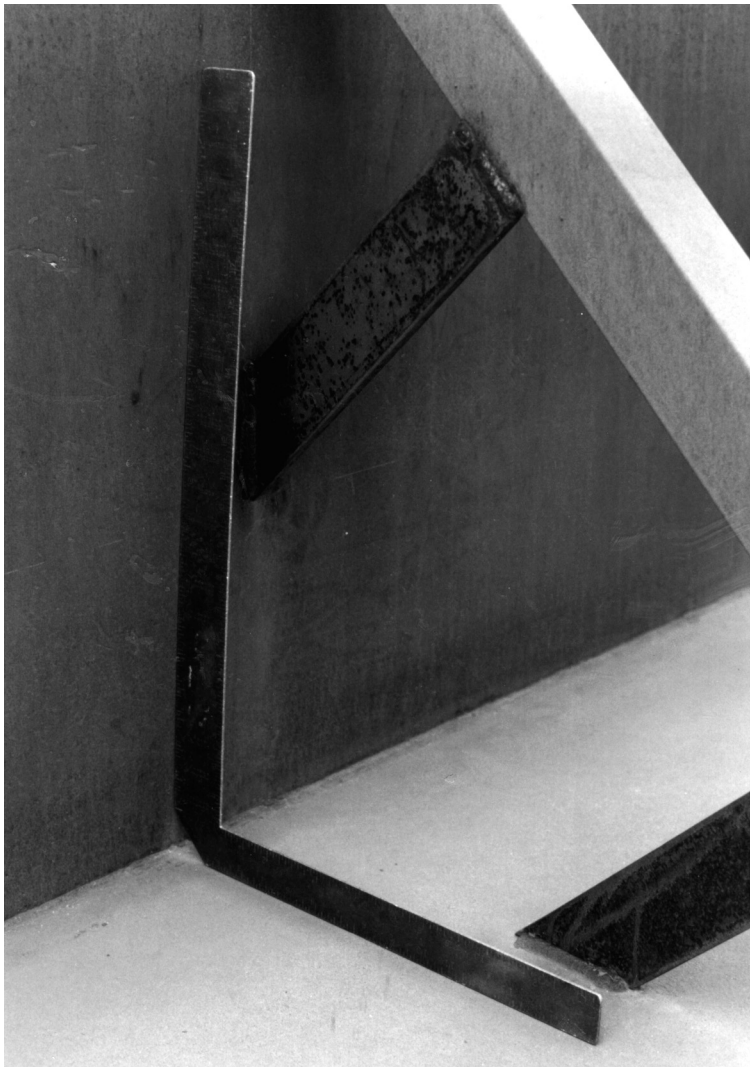


Figure 9.68(b): Application of try square. Note the corner is clipped to clear the fillet weld.

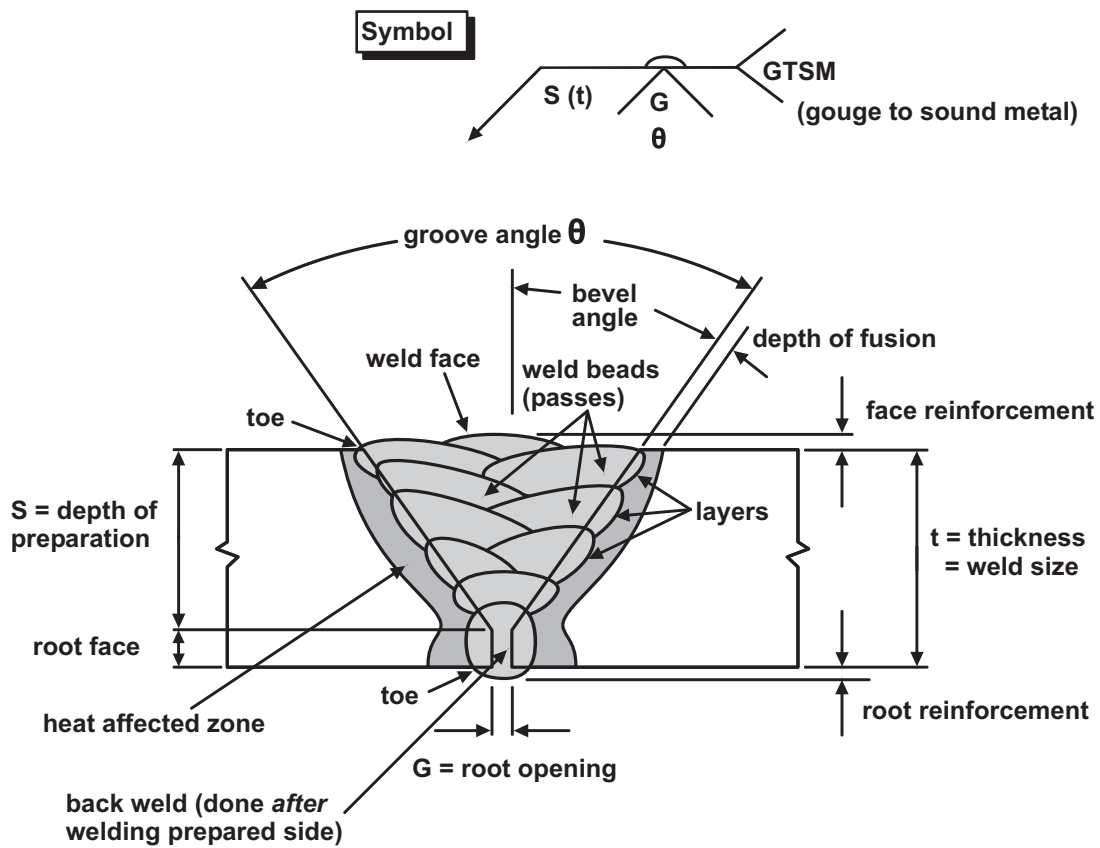


Figure 9.69: Terminology for groove welds.

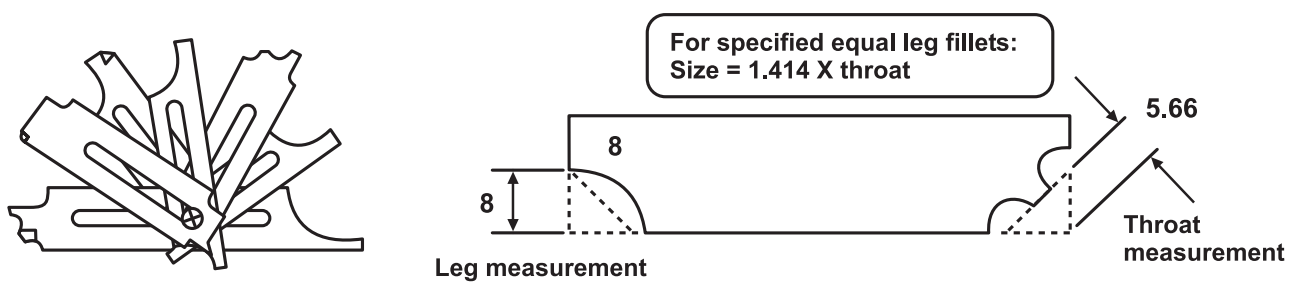


Figure 9.70: Typical gauges for measuring fillet weld sizes.

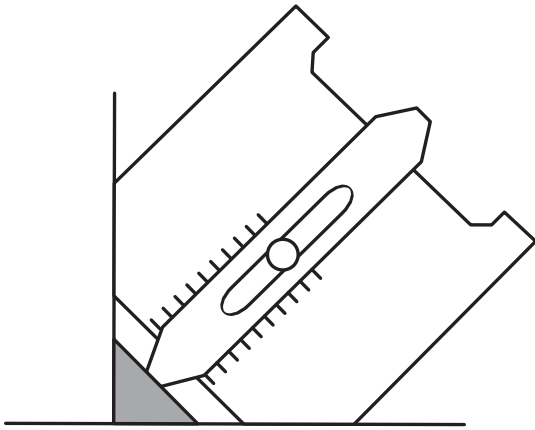
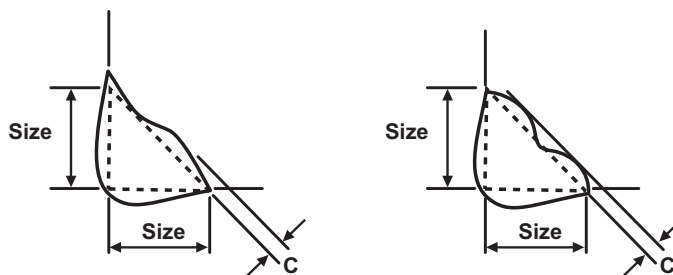
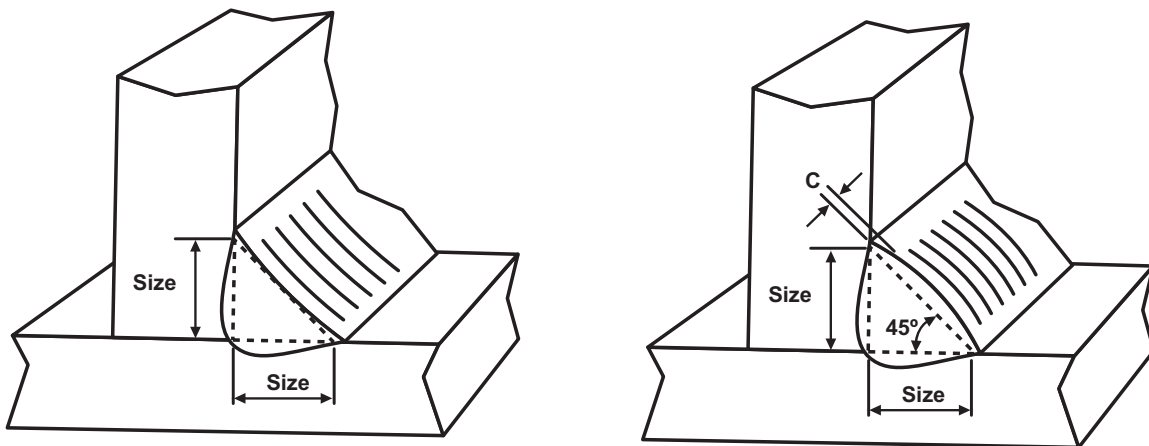


Figure 9.71: This gauge can measure the weld throat, convexity and concavity in a fillet weld.

Fillet weld sizes are measured with welding gauges such as the ones illustrated in **Figure 9.70**, and the sketch on page 461 shows the method of use. Weld profiles are more difficult to measure, but simple convexity and concavity can be determined from the throat measurement (**Figure 9.71**). Acceptable and unacceptable fillet weld profiles as required by CSA W59 are shown in **Figures 9.72 and 9.73**. Unacceptable weld profiles may be corrected by grinding or depositing additional weld metal as shown in **Figure 9.74**.



According to CSA W59, convexity, C , of a weld or individual surface bead shall not exceed 0.07 times the actual width of the weld or individual bead plus 1.5 mm.

Figure 9.72: Fillet welds considered acceptable to CSA W59.

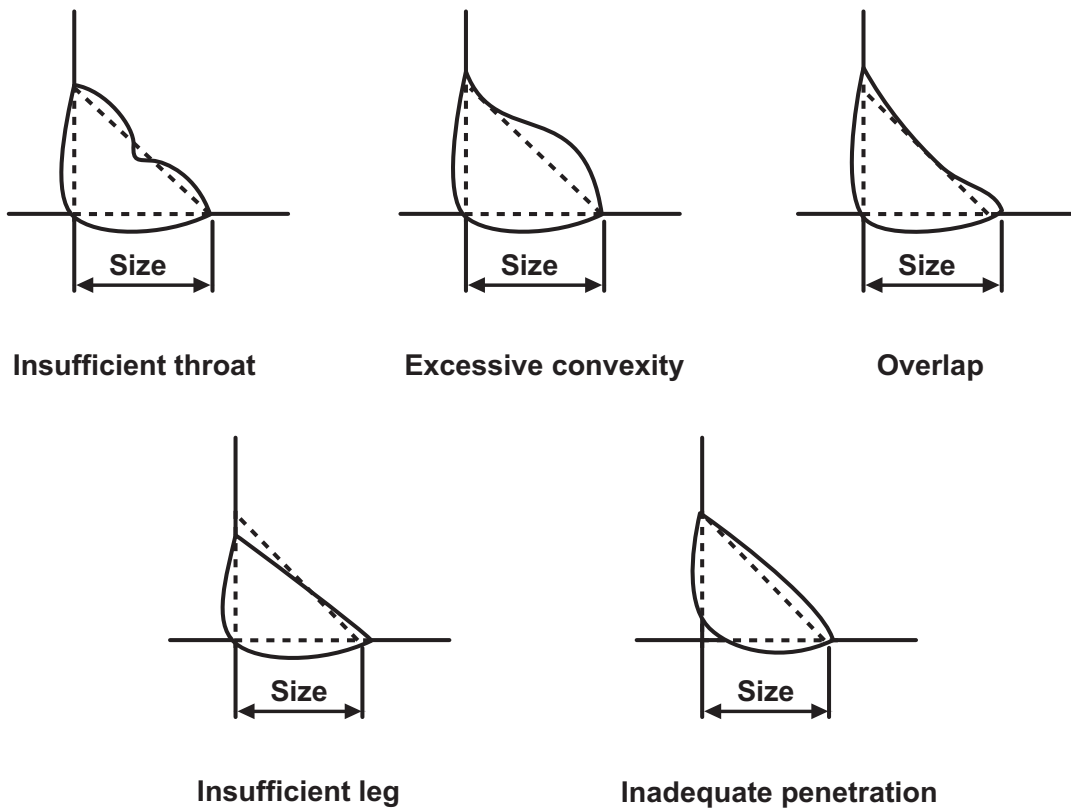


Figure 9.73: Examples of fillet welds considered unacceptable to W59.

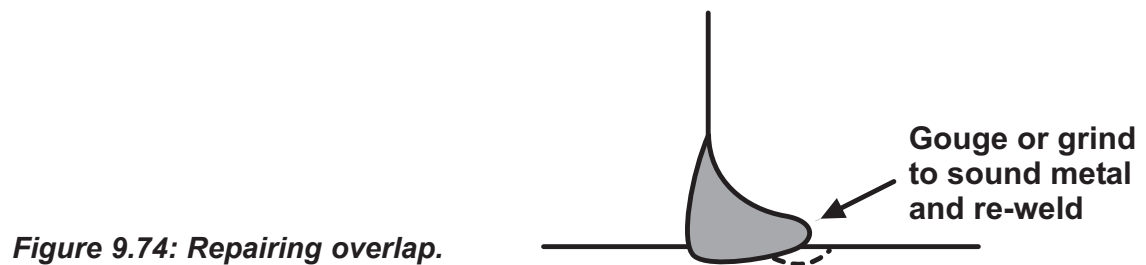
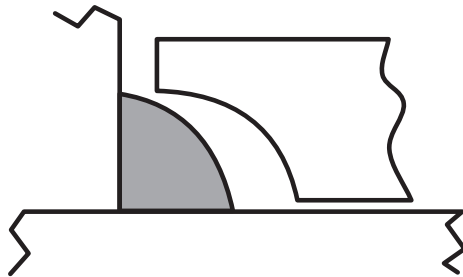
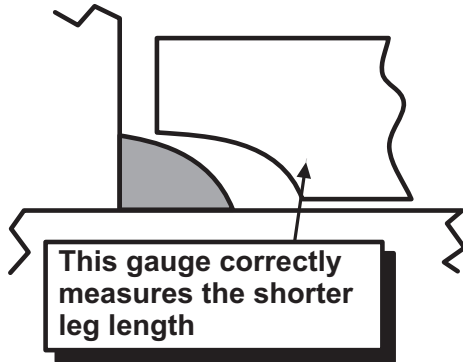


Figure 9.74: Repairing overlap.

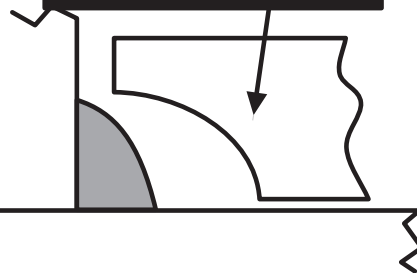
Measuring fillet welds



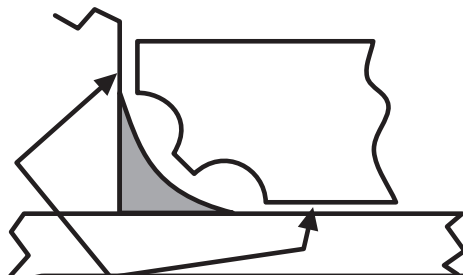
For CONVEX or FLAT fillet welds use gauge to measure leg length.



This gauge incorrectly measures the longer leg length

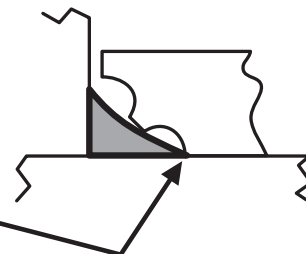


For fillet welds with unequal leg sizes (where an equal leg fillet was specified) always measure the shorter leg length



For CONCAVE fillet welds use gauge to measure the throat.

For concave fillet welds the gauge should touch both sides. For welds of unequal leg size, a concave fillet gauge may give false indication of size. In this case, if equal leg size had been specified, use the special throat gauge shown in Figure 9.71.



9.12.2 Liquid Penetrant Inspection

Liquid penetrant inspection (LPI, also called Penetrant Testing, PT) is a versatile method capable of locating cracks, porosity, laps and folds that are open to the surface. The method is based on the ability of the penetrating liquid to be drawn into a discontinuity. When the object is wiped clean, the liquid remains in the discontinuity but can be drawn out by adding a developer, such as a fine powder, which acts as a blotter. The penetrant shows up against the developer indicating the discontinuity on the surface.

There are six basic steps involved in performing LPI, which are illustrated in **Figure 9.75**.

1. Prepare the surface of the part to be inspected by cleaning and degreasing.
2. Apply the penetrant to the surface.
3. Allow a period of time for it to be drawn into any discontinuities.
4. Remove the excess penetrant in a manner that ensures retention of the penetrant in any discontinuities.
5. Apply a developer to draw the penetrant liquid from the discontinuities out to the surface and thereby provide an enhanced indication of the discontinuities.
6. Examine and assess the discontinuities visually under appropriate viewing conditions. Clean the part and, if necessary, apply a corrosion preventative.

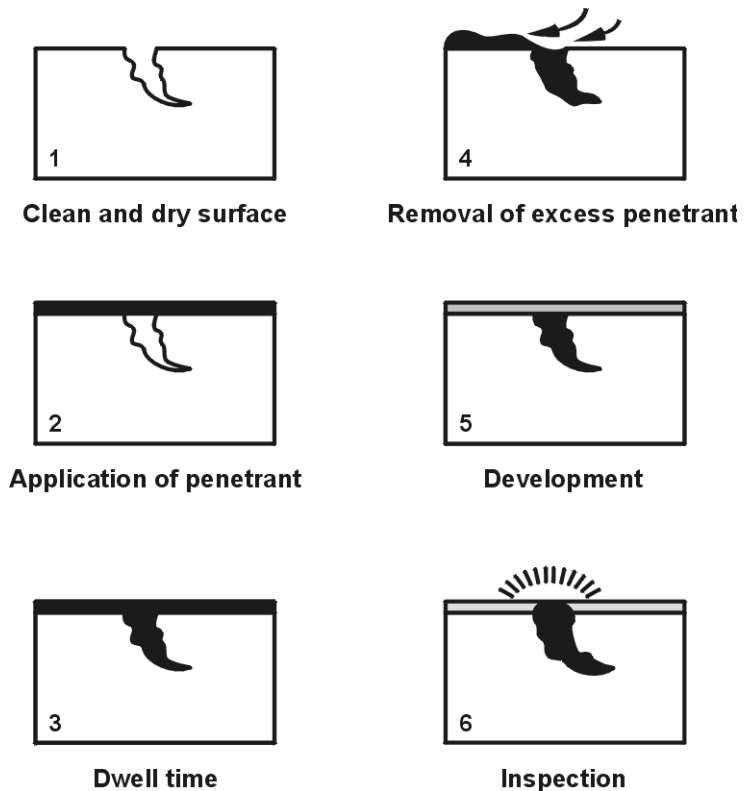


Figure 9.75: The principle of liquid penetrant inspection.

It is a simple, inexpensive method, but a good understanding of how it operates and the correct procedures are necessary to get the best results.

The penetrants used in inspection are commercially available liquids containing visible dyes that have been carefully formulated to combine a large number of desirable properties. The foremost requirement is, of course, the ability to penetrate very small openings, which depends on the surface tension and wetting ability of the penetrant. The rate at which the liquid flows and penetrates openings is influenced by the viscosity. High viscosity liquids penetrate slowly but low viscosity liquids may drain away too rapidly, with a tendency to drain out of shallow defects.

Penetrant should essentially be nonvolatile, although a small amount of evaporation at the defect helps to intensify the dye content and prevent excessive spreading of indications. Rapid evaporation of volatile solvents could imbalance the formula of the penetrant, decrease the ability to spread and cause the penetrant to dry up.

A further desirable property of a penetrant is that it not lead to corrosion of the part being tested. The compatibility of the inspection materials with the metal under test should be checked, particularly when dealing with special alloys (e.g., titanium and nickel alloys) that could be sensitive to specific elements such as sulphur or chlorides (halogens).

There are several methods by which the penetrant principle is used in inspection, and the standards – such as ASTM E-165 – group them in various ways. Penetrant inspection methods can be classified according to the:

- ◆ type of dye
- ◆ method of excess penetrant removal
- ◆ form of developer

For the penetrant to contrast with the developer to reveal the presence of a defect, the penetrant contains a dye. Two types of dyes are used:

- ◆ fluorescent
- ◆ nonfluorescent or visible

Properties of an Ideal Penetrant

- ◆ penetrates very fine openings
- ◆ remains in coarse openings
- ◆ resists evaporation
- ◆ removed easily from the surface
- ◆ has the mobility to re-appear from openings quickly
- ◆ spreads in very thin films
- ◆ resists colour fading
- ◆ non-corrosive
- ◆ non-flammable
- ◆ stable under storage
- ◆ non-toxic
- ◆ inexpensive

9.12.3 Magnetic Particle Inspection

Another method of testing, Magnetic Particle Inspection (MPI), utilizes a magnetic field, which is induced in steel or other magnetic ferrous alloys.

If this field is interrupted by a discontinuity, such as a crack in the material, the field will become distorted at the point, and a north and south pole will form at each point of material separation.

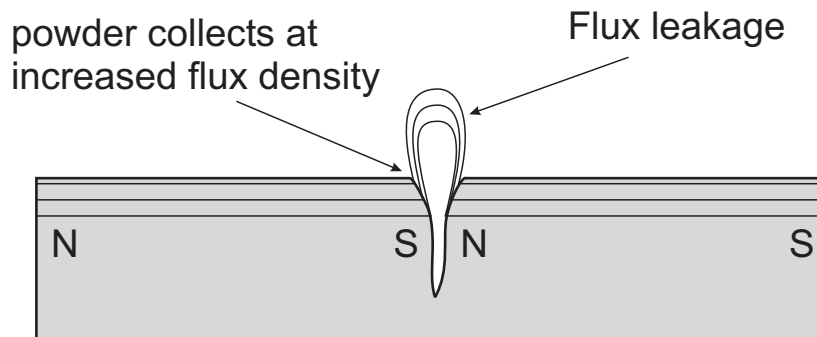
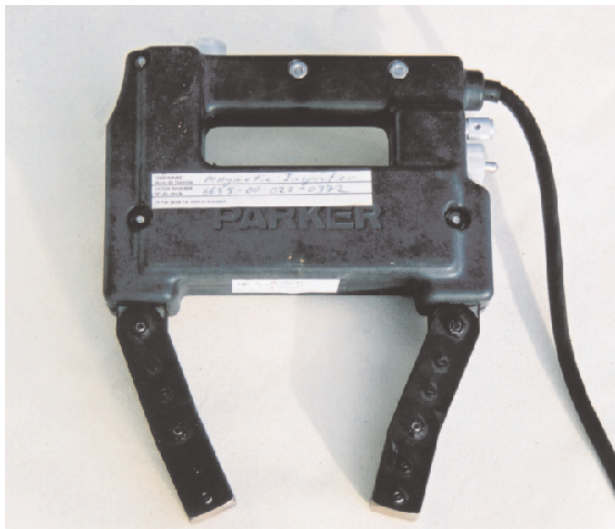
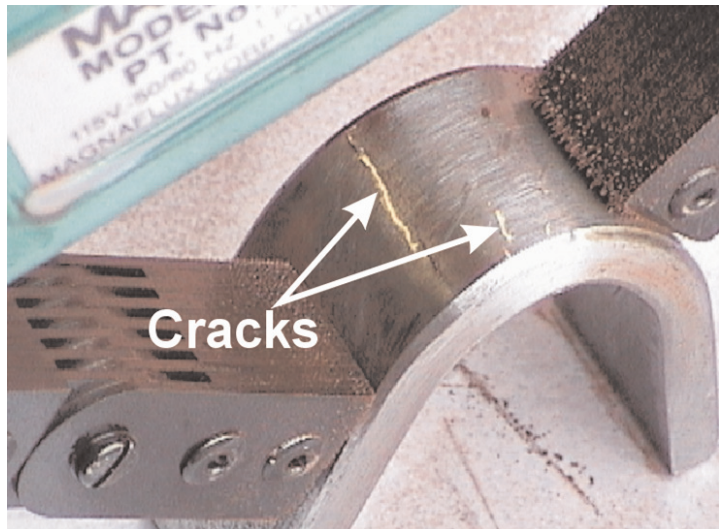


Figure 9.76: Flux leakage at a discontinuity.



(a) AC/DC Yoke



(b) Cracks detected by MPI

Figure 9.77: Magnetic lines of force follow a path around surface defect; leakage field formed at surface of weld attracts and holds magnetic powder in sharp, well-defined build-up.

If fine magnetic particles are applied by spraying or dusting onto the test object, the north and south poles of the crack faces will attract the particles, which will form a visible bridge across the gap. See **Figure 9.76 and 9.77**.

The magnetic field can be induced into the part in a number of ways, depending upon the form and finish of the part.

The most common way to induce the field in the testing of welds is by the prod method using *direct current or alternating current*.

When direct current is used it is possible to detect surface defects as well as linear defects, which are sub-surface and do not break to the surface of the weld.

Alternating current is normally used where defects break the surface of the weld or component under test. The prods are positioned in such a manner that the magnetic field intersects with the defect. For this reason the prods should be placed in two positions to detect linear defects parallel to the direction of weld, as well as linear defects transverse to the direction of weld. See **Figure 9.78**.

The surface roughness of the weld will cause some loss of effectiveness and sensitivity, but even in these circumstances it is an excellent tool to disclose major weld defects, which otherwise would have been missed.

The equipment used in magnetic particle testing of welds can be extremely bulky and awkward to handle, or it can be light and portable. The heavy equipment is used to generate high DC current, which is used where a sub-surface linear defect must be disclosed.

The lighter equipment, such as AC Yokes or permanent magnets, is used when defects penetrate to the surface of the weld, but are still too tightly structured to be detected by normal visual inspection. Magnetic particle testing can be used in all positions including overhead, and semi-skilled persons can be used to perform the actual test. However, the test results must be interpreted by a skilled and qualified magnetic particle operator. **Figure 9.79** illustrates a portable magnetic particle inspection unit.

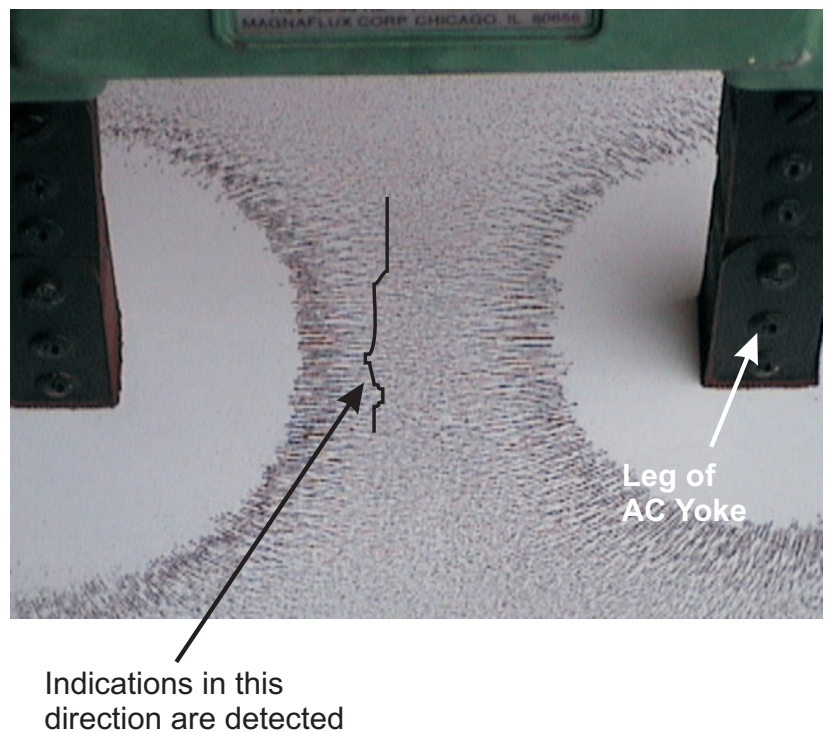


Figure 9.78: AC yoke used to detect linear discontinuities.

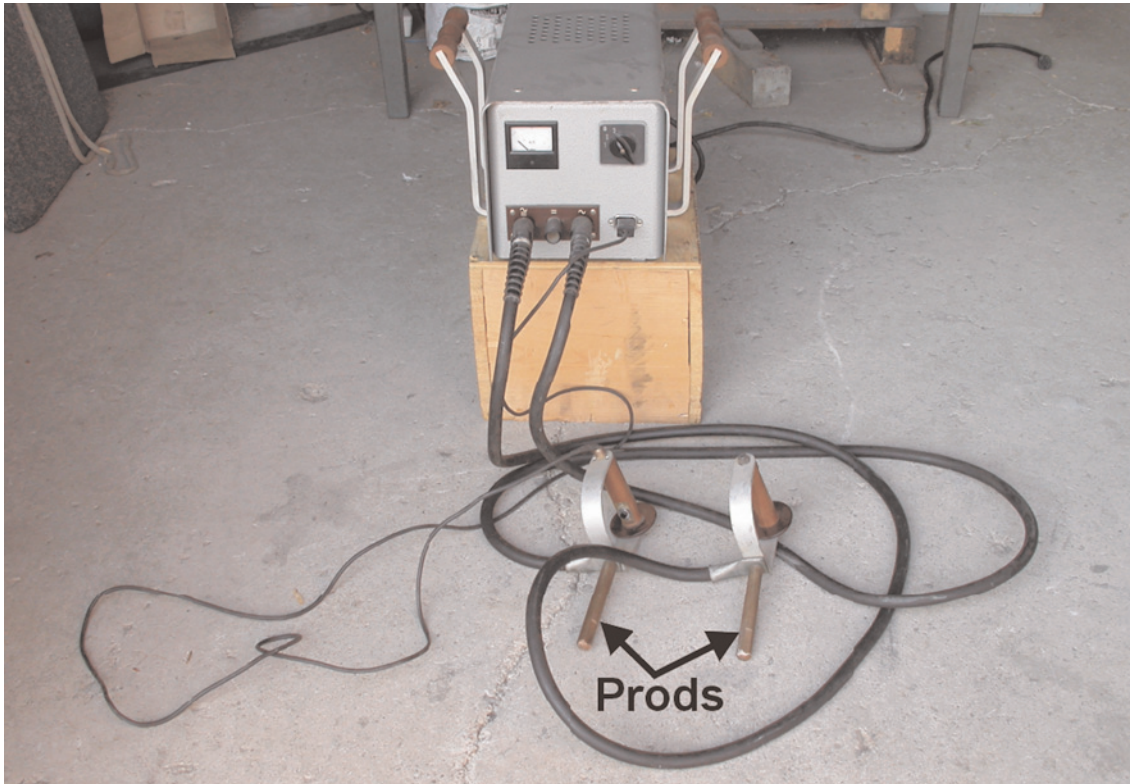


Figure 9.79: Portable magnetic particle inspection unit.

Because the test is a magnetic method it is not applicable to materials that are non-magnetic, such as aluminum, brass, bronze and austenitic stainless steels.

The magnetic particles used as the detection medium are fine iron powders of various colours (to provide a contrast against a given background).

Another type of detecting media is a solution of iron powder and a suspension medium. The iron particles in this method are coated with a fluorescent material that is most brilliant when viewed under a near ultra-violet light (black light). The fluorescent method is not recommended for use on material in the as-welded condition because random fluorescent materials may be retained in the crevices of the weld bead and this may confuse the inspector.

9.12.4 Radiography

Radiography is the most commonly used non-destructive method for the detection of sub-surface volumetric discontinuities in welds.

The radiographic method can be applied to most welded joints, but is largely confined to butt and corner joints.

As with all testing methods, radiography has certain limitations and it is incumbent upon the welding inspector to have some knowledge of both the methods of radiography used in the inspection of welds: X-radiography and gamma radiography. Both X-rays and gamma rays have extremely short wave lengths and it is this characteristic that enables them to penetrate objects opaque to ordinary light. The two types of radiation can affect sensitized photographic film.

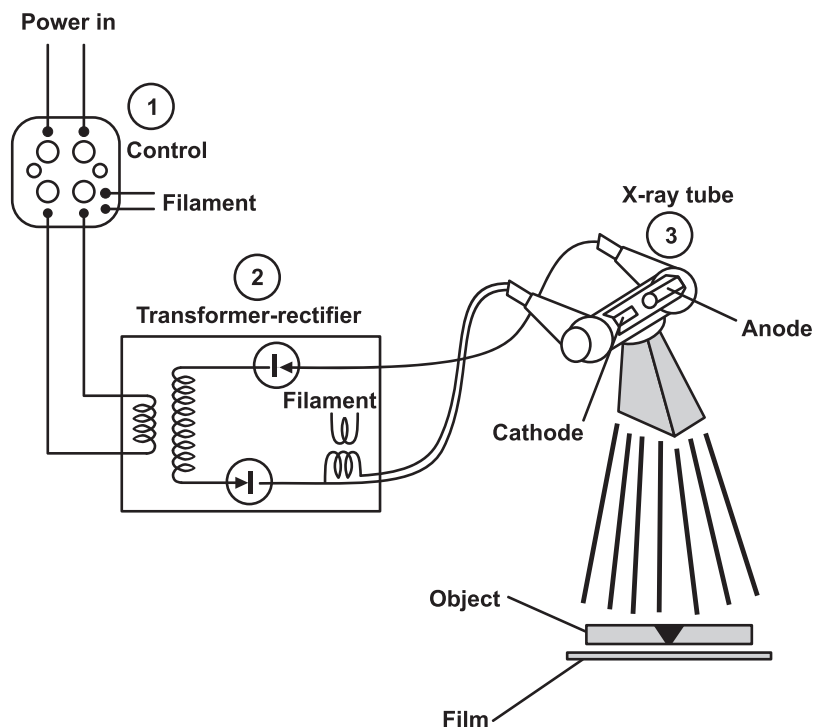


Figure 9.80: Basic circuit of self-rectified X-ray apparatus.

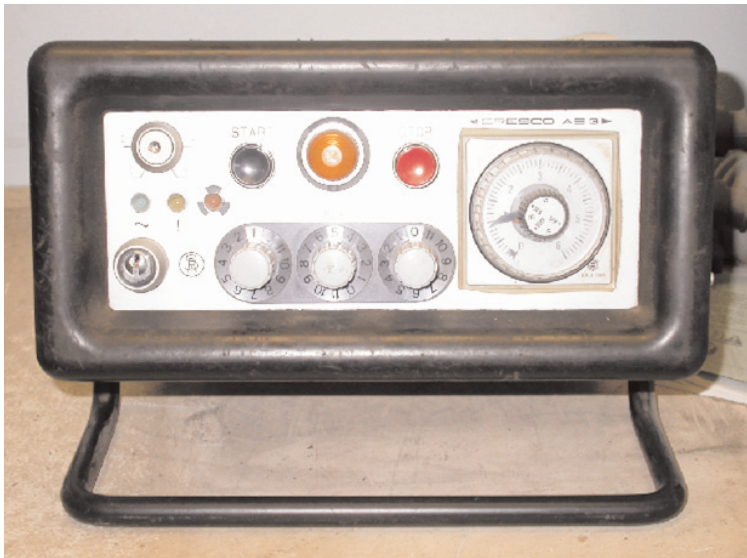
X-rays are generated in an X-ray tube by propelling (at high speed) a stream of electrons against a target, constructed of materials with high atomic numbers and high melting points such as tungsten. The electron stream interacts with the atomic structure of the target material, temporarily dislodging electrons. Energy is generated from this dislodgment action, 99% of which is heat and 1% X-rays. The heat is dissipated by the copper anode and cooling media in the tube housing, and the X-rays are projected (in a cone from the target material) against the weld undergoing test. See **Figure 9.80**.

The density of the electron stream is controlled by the current (M/A) input, and the wave length (and therefore the penetrating ability of the X-rays) is controlled by the high voltage input (kV) across the tube.

The system, as can be seen from the foregoing, is electrical, and no ionizing radiation is generated or retained in the system when it is switched off. In addition, the wave length, and therefore the penetrating power, is adjustable.

The equipment is cumbersome and even the units designed for portability are relatively heavy and awkward to manoeuvre. **Figure 9.81** shows the control box and X-ray unit positioned to radiograph a weld.

Gamma rays, as used in radiography, emanate from a radioisotope.



Control Panel



X-Ray Tube

Figure 9.81

Small amounts of material, such as Cobalt 59 or Iridium 191, are placed in a nuclear reactor and subjected to neutron bombardment. During this time the atomic structure of the Co 59 or Ir 191 captures a neutron. The material is then called Cobalt 60 or Iridium 192 and is in an unstable condition.

In the natural order of things, the structure constantly strives to return to a stable condition and in so doing releases energy in the form of gamma rays.

The wave lengths of the gamma rays are fixed by the type of isotope (Co 60 or Ir 192) that emits them. Co 60 has wave lengths that are much shorter than Ir 192, and therefore have more penetrating ability.

The sources of radiation are constantly emitting ionizing radiation and cannot be shut off. The sources, therefore, are shielded in a protective casing manufactured from extremely dense material such as lead or tungsten. The material absorbs the radiation and protects the operator from exposure (See **Figure 9.82**).

When the source is to be used, it is remotely handled. A drive cable is connected to the source pigtail and projected through a hose called a “nose tube” to a position from which the radiation passes through the weld and onto a film. The drive cable is long enough to allow the radiographer to stay a safe distance away from the source while it is out of the shielded position.

Figure 9.83 shows typical equipment for gamma radiography. **Figure 9.84** shows a typical set-up for gamma radiography. The source is “cranked” out of the safe position and is deployed through the nose tube to a position inside the tubular weldment. The “source” remains in position for a period of time calculated to produce the best image on the film.

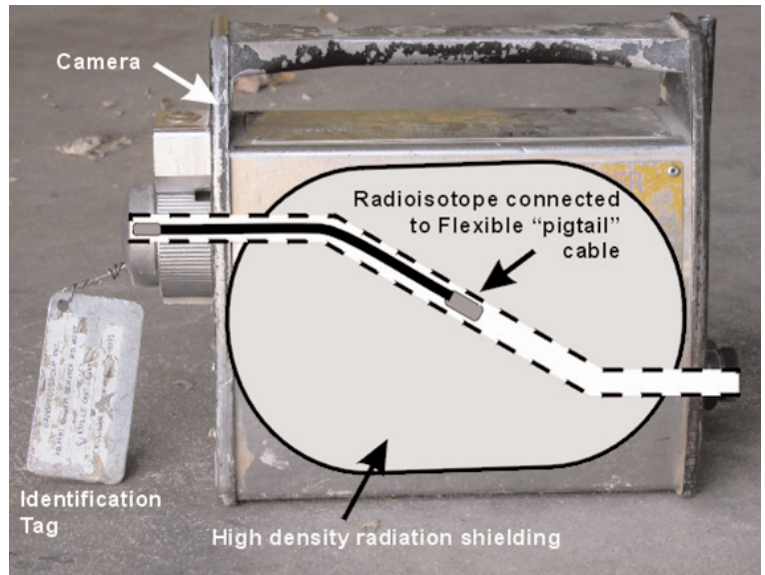


Figure 9.82: Cutaway view of a typical isotope camera.

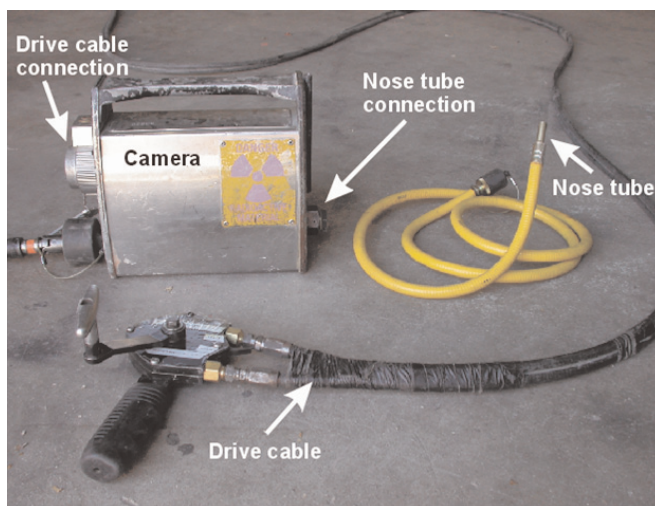


Figure 9.83: Gamma radiography equipment.
(Photo courtesy of Canspec).

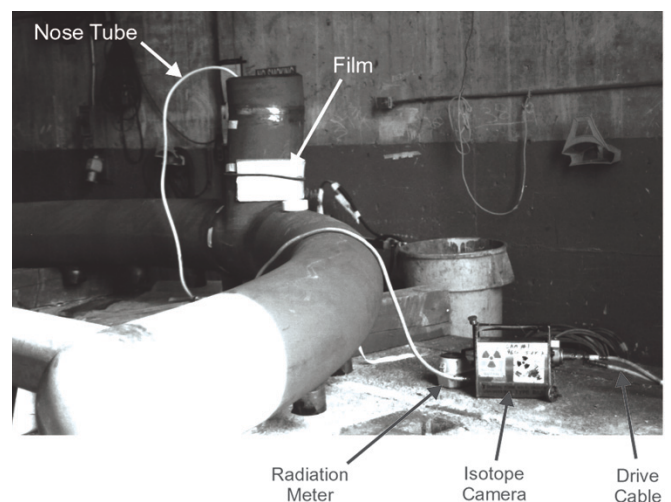


Figure 9.84: Gamma radiography set-up.
(Photo courtesy of Babcock & Wilcox Canada).

As X- or gamma radiation is directed at the weld, a certain amount will be absorbed by the structure of the metal and the remainder will pass through onto a film that has been placed into position. The amount of radiation absorption depends upon the material type and thickness; each material (steel, aluminum, copper, etc.) having a different coefficient of absorption.

When a weld has internal discontinuities such as slag or gas holes, more radiation will reach the film under these areas than in an adjacent area, which has no discontinuities and is therefore absorbing more radiation. In this manner, differential amounts of radiation reach the film and react on the sensitized emulsion in varying degrees. These differences in radiation absorption through a defective weld appear on the developed film as shadows and are interpreted by the shape and density as to what they represent (slag, porosity, gas holes, etc.).

When a defect in a weld does not constitute a relatively substantial difference in the total cross section of the weld, the difference of radiation absorption will be less and therefore the image on the film will not be pronounced. With certain defects such as tight cracks, cold lap, lack of side wall fusion, etc., there is a strong likelihood that no discernable image will appear on the film. Where the beam of radiation is not directed into the plane of defect, **Figure 9.85**, the defect can be completely missed.

When a discontinuity in a weld does not constitute a relatively substantial difference in the total cross section of the weld, the difference of radiation absorption may not be detectable by the density difference it creates. (The image on the film will not be pronounced.) Certain flaws such as tight cracks, cold lap, incomplete fusion, etc., can present little difference in the amount of radiation absorbed such that no discernable image will appear on the film. Where the beam of radiation is not directed into the plane of defect (**Figure 9.85**), the defect can be completely missed. This is the main limitation of radiography.

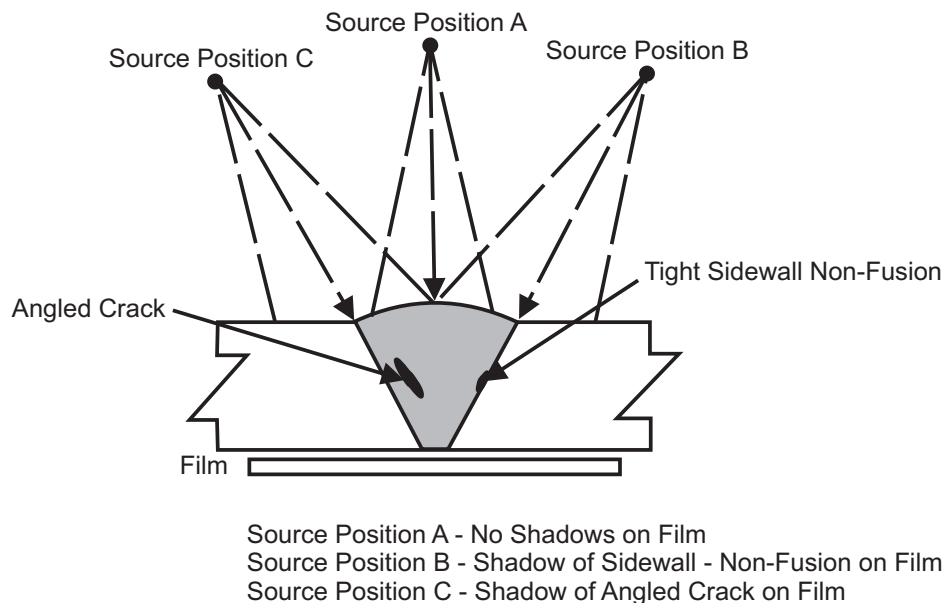
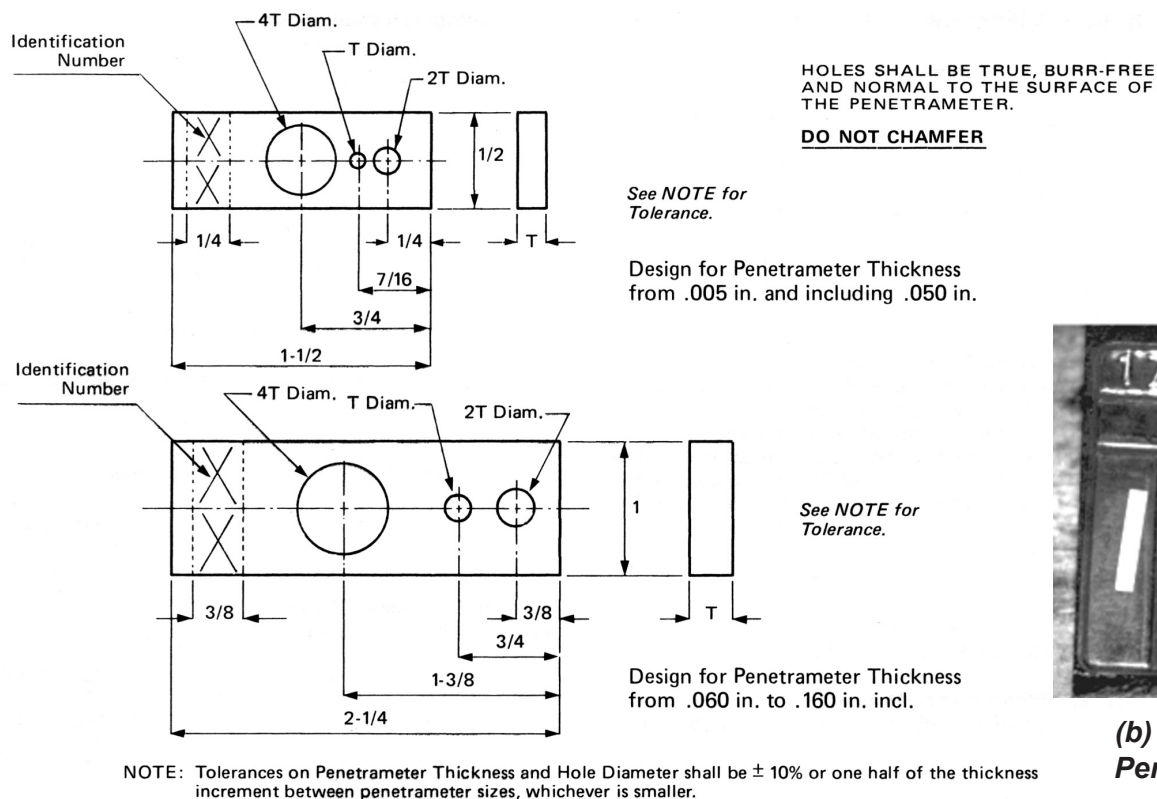


Figure 9.85: Radioisotope projected into position by remote control.

In general, radiographs made with X-rays are superior to those made with gamma rays mainly due to the fact that the penetrating power of the radiation emitted from X-ray equipment can be adjusted. In steel up to 50 mm (2"), this fact is demonstrated by superior radiographic sensitivity and clarity of the defect image. Above 50 mm (2"), the wavelengths necessary to penetrate the steel are of the same order of magnitude to those of gamma radiation so that the radiographic superiority is reduced somewhat.

Construction codes such as ASME Boiler & Pressure Vessel Code, Section VIII, CSA Standard W59 & AWS D1.1, etc. dictate that the way in which a radiograph is produced (procedure) will meet specific requirements. One of these requirements which is important to a welding inspector is the use of a device known as a "penetrameter".

The penetrameter is used to assess the quality of the *radiographic technique* – how good is this film. The penetrameter is an object of known shape size and geometric features. Seeing the image of the penetrameter gives the viewer a sense of how clearly the image of a discontinuity would appear. There are different types of penetrameters. Some have wires of different diameters while others have holes or slots of specific dimensions machined into them. The sizes of the holes are related to the thickness of the penetrameter. A wire type penetrameter is shown in **Figure 9.86(b)**.



(b) Wire Type Penetrameter

(a) Hole Type Penetrameters

Figure 9.86

The penetrameter, also known as the *image quality indicator* (IQI), **Figures 9.87 & 9.88**, is placed on the parent material adjacent to the area of the weld that is to be radiographed, usually on the side of the material that is closest to the source of radiation. **Figure 9.86(a)** indicates the size and placement of ASME Boiler & Pressure Vessel Code penetrameters as shown in **Figure 9.88**. **Figures 9.89(a) & (b)** indicate the placement of penetrameters in accordance with CSA W59 requirements.

In general, construction standards will dictate that a penetrameter thickness shall be 2% of the thickness of the material to be radiographed. Although some schools of thought equate the size of the smallest defect discernable in the weld with the smallest hole discernable in the penetrameter, this is open to serious dispute.

A penetrameter is useful because the image of a discontinuity is affected by the radiographic technique. That is, the geometric set-up of the source in relation to a) the object being examined directly and b) the film, affects the image created on the film. For example, **Figure 9.87** shows the effect of a reduction of source to film distance (D) to image distortion. Penetrameters allow inspectors to factor out the effects of distortion, because the image must be clear enough to enable the interpreter to see the outline and the qualifying holes, and hence factor the image distortion into his/her judgement.

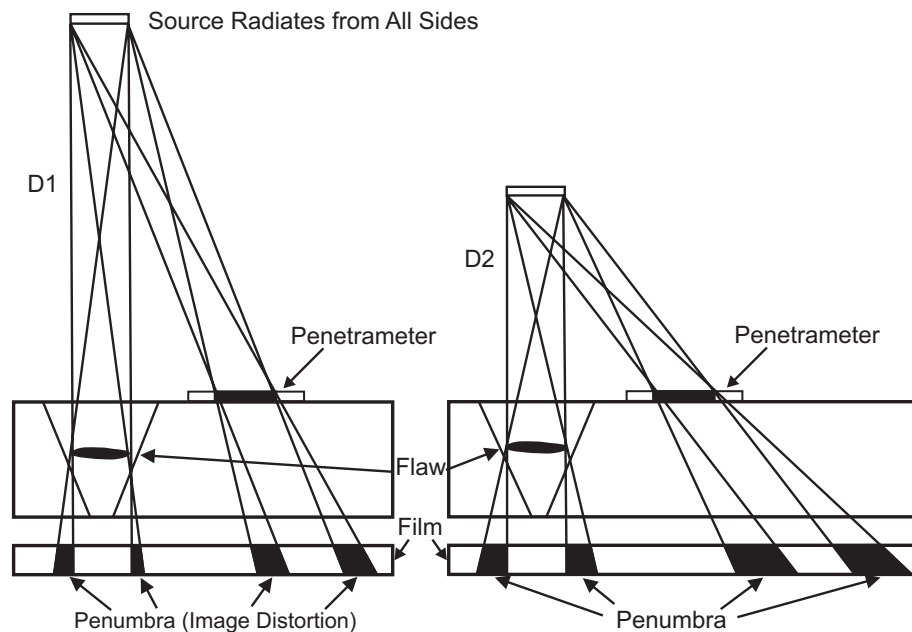


Figure 9.87: Effect of source position.

According to the ASME Boiler and Pressure Vessel Codes, at least one penetrameter shall be used for each exposure, to be placed at one end of the exposed length, parallel and adjacent to the weld seam. Where the source is placed to radiograph a circumferential seam with one 360° exposure, three penetrameters located at 120° intervals shall be used.

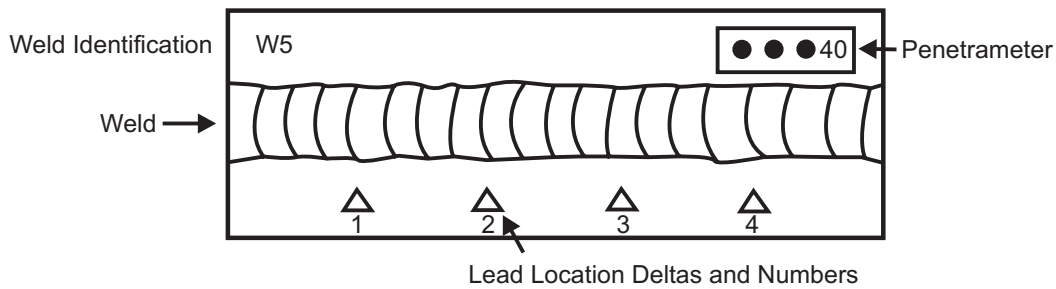


Figure 9.88

The thickness of the penetrameter shall not be more than 2% of the thickness of the plate. In each penetrameter there shall be three holes of diameter equal to one, two and four times the penetrameter thickness, but in no case less than 0.010 ". Tables in the codes indicate which of the holes must appear as images on the radiographs. Each penetrameter has numbers affixed to it identifying the material and minimum thickness of the plate. **Figures 9.86, 9.87 & 9.88** illustrate the ASME Code penetrameter and placement.

In other codes and standards, penetrameter size and hole dimensions may be different, as in CSA Standard W59 (**Figure 9.89**).

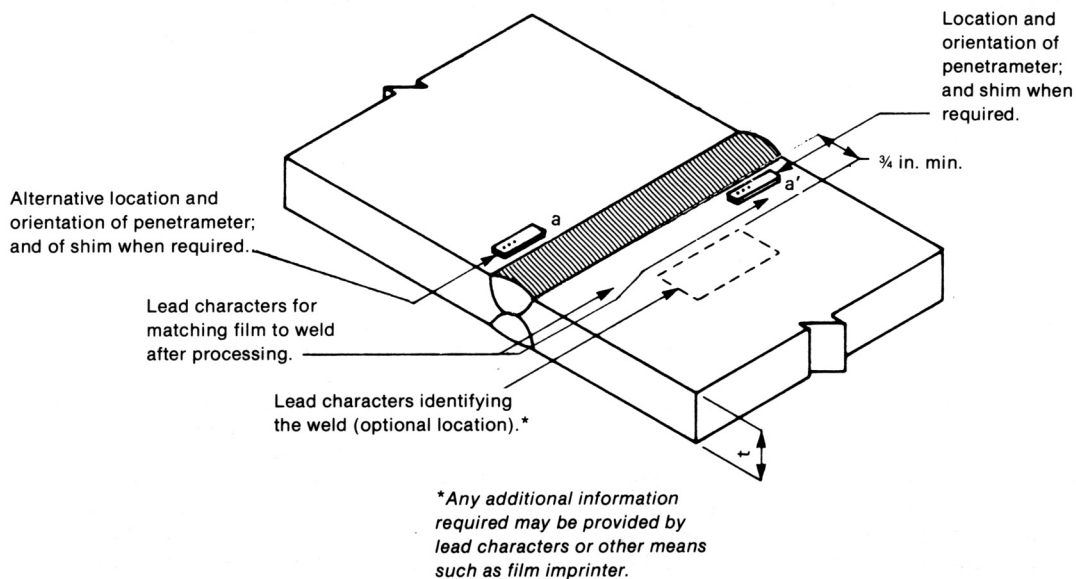


Figure 9.89 (a)
Radiograph Identification and Penetrameter Location on Approximately Equal Thickness Joints
(CSA W59)

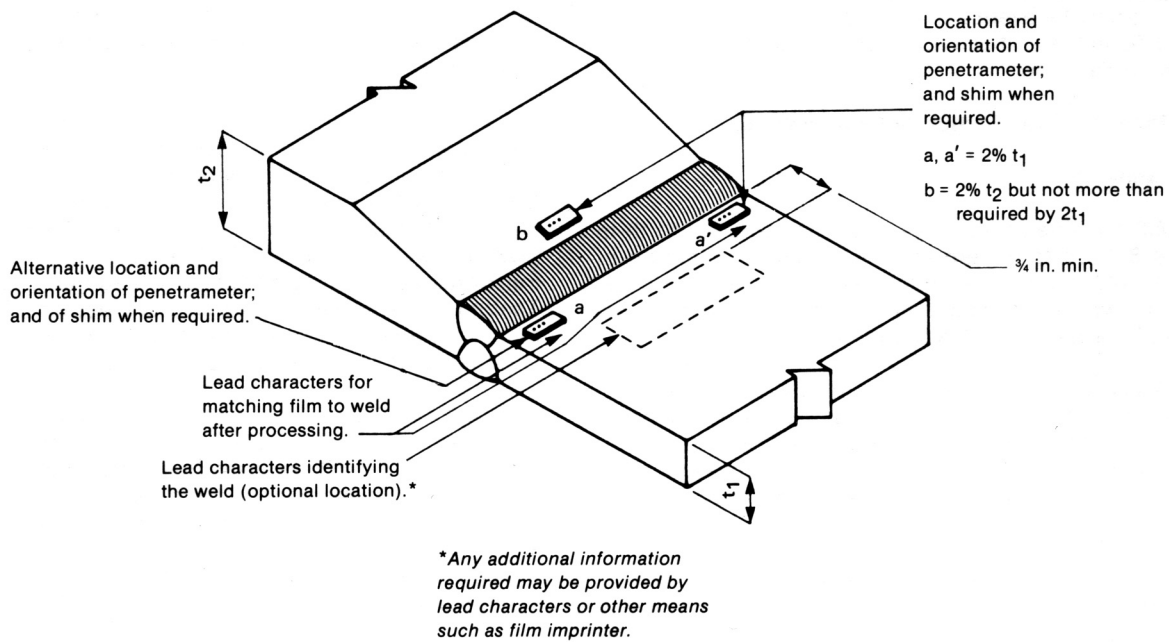


Figure 9.89 (b)
Radiograph Identification and Penetrometer Location on Transition Joints
(CSA W59)

Standards of acceptability for welds subject to radiographic examination have been established by various code committees and are detailed in codes and standards such as ASME Sections I, III and VIII, API 650, CSA Standard W59, ANSI B31.1, etc.

Some fabricators use radiography as a quality assurance tool even when not required by the contract. In this event, acceptance standards are set in an arbitrary manner by company management although usually in reference to a known industry criteria.

When the radiographic report specifies that indications of discontinuities are unacceptable the defective area of the weld is removed and the cavity re-welded. The repair is then radiographed in accordance with the original procedure.

Radiography is the most successful and reliable method for non-destructive testing of welds. There are limitations to the test method, some of which have been pointed out. Where the limits of the method have been defined, it is probable that an alternative test, such as ultrasonic, will serve to complement radiography.

9.12.5 Ultrasonic Testing

For many years railroad wheels and similar items were subjected to hammer tests. The pitch of the sound emanating from the wheel indicated to the inspector whether the wheel was flawed or not. The sound waves emitted during these tests were of frequencies up to 20 kHz, (20,000 cycles per second) that is, they were audible to the human ear.

Ultrasonic examination utilizes sound frequencies between 20 kHz to approximately 10 MHz (10,000,000 cycles per second). When examining welds it is common to use frequencies in the range of 2.5 to 5 MHz.

Ultrasonic sound waves are generated by applying electric pulses to piezoelectric crystals such as quartz or barium titanate. These crystals vibrate, and electrical energy is transferred into mechanical energy. In effect, when the crystal is placed on a material (i.e., steel) *the pulses turn the crystal into a hammer*.

The two main ultrasonic beam modes used in weld testing are;

- ◆ *longitudinal waves*
- ◆ *shear waves*

Longitudinal waves are propagated as pressure waves, that is, the particles of the material under test oscillate in the direction travelled by the ultrasonic waves as shown in **Figure 9.90**.

As can be seen in **Figure 9.91** when shear waves are propagated, the particle motion is transverse to the wave direction.

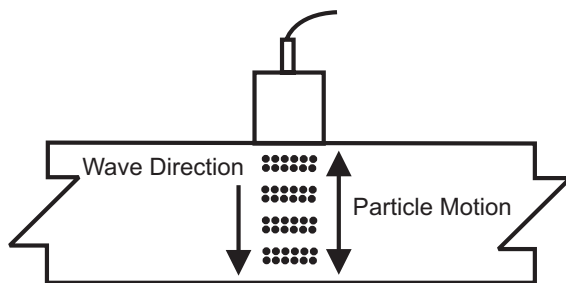


Figure 9.90: Longitudinal wave propagation.

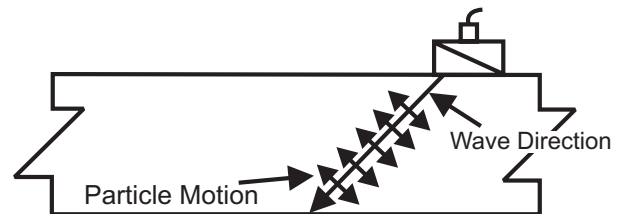


Figure 9.91: Shear wave propagation.

The mechanical energy is transmitted through the particles of the material undergoing test. The velocity at which the ultrasonic beam moves through material is constant for that specific material and for the wave mode (longitudinal wave or shear wave). For example, in carbon steel a longitudinal wave beam moves at a velocity of 0.585 centimetres per microsecond and a shear wave beam at a velocity of 0.323 centimetres per microsecond.

When a change occurs in the material (such as a void caused by a defect), the velocity of the beam changes and what is known as *acoustic mismatch* occurs. When this happens, part of the sound beam is reflected back to the crystal, transformed back into electrical energy and projected onto a screen.

Any flaw in the material will cause acoustic mismatch and reflect the ultrasonic beam. The complete cycle of this action is shown in **Figure 9.92**.

This phenomena of reflection due to acoustic mismatch is the basis of all ultrasonic testing.

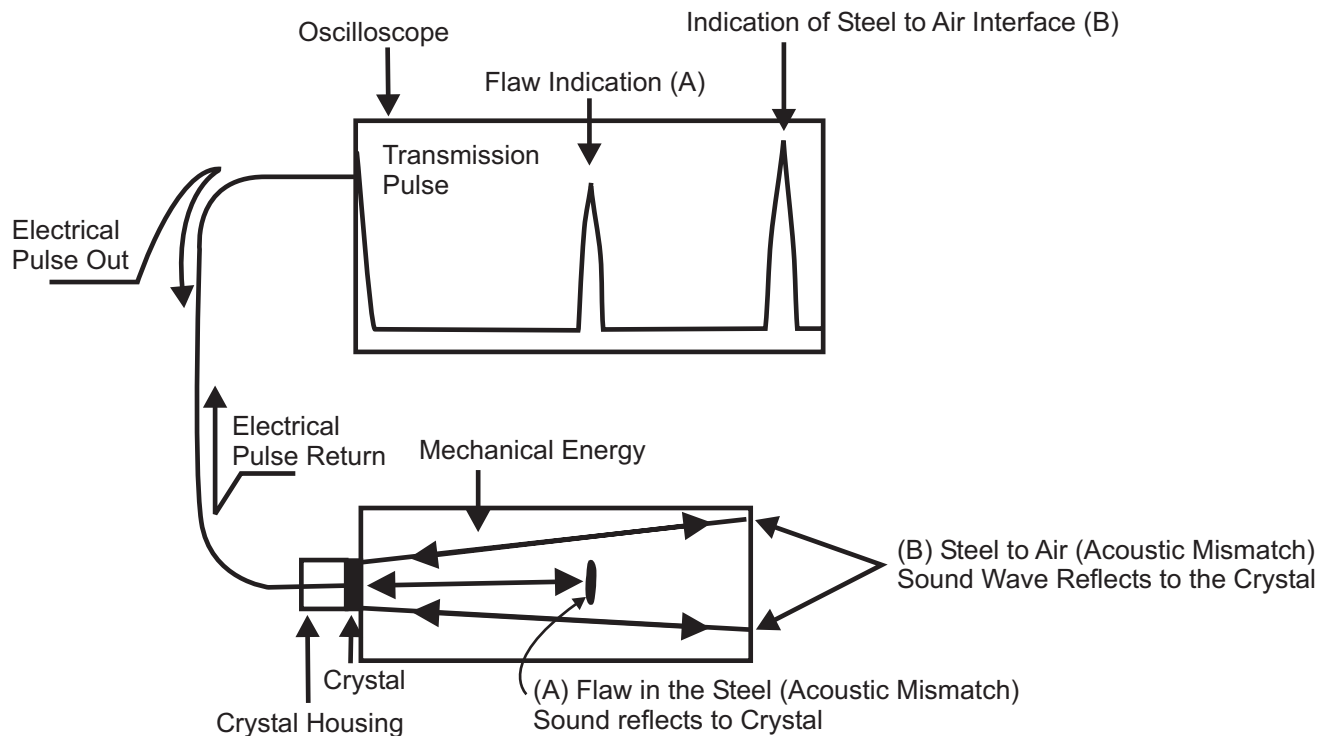


Figure 9.92

Weld testing using ultrasonic methods requires very precise procedures both for calibrating the test equipment and locating and evaluating discontinuities. The capability and qualification of the ultrasonic technician is critical to the accuracy of the test. As indicated previously, both longitudinal and shear wave modes can be generated. In weld testing both modes are used. **Figure 9.93** briefly illustrates the different modes.

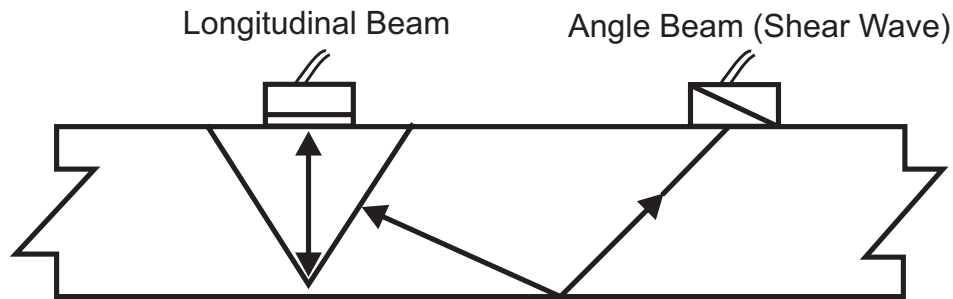


Figure 9.93

The ultrasonic examination system can be used for testing welds in almost any thickness except that under approximately 3 mm (1/8"). Application of ultrasonic methods and interpretation of test results requires special techniques for thin materials.

The system used for weld testing is extremely sensitive, and provided that the wavelength is short enough, can detect extremely small discontinuities.

The system will detect all types of discontinuities. To provide a maximum indication on the oscilloscope, the ultrasonic beam should strike the major face of the defect at 90°. For this reason evaluation of a weld defect is usually done using more than one angle (i.e., 45° and 60°). Its main difficulty is detecting isolated discontinuities such as a single pore or inclusion.

Before an ultrasonic operator can start to test a weld certain information is needed to generate the correct technique. The following describes a few examples:

1. The Welding Method

Reason:

Knowledge of the welding method is important, particularly when the operator is evaluating the type of defect. For example, slag inclusions would not occur in a weld deposited with the gas metal arc process. Tungsten inclusions would not be found in a weld made with the shielded metal arc process.

2. The Type of Material and Condition of Heat Treatment

Reason:

The operator must know the material velocity because it will affect the distance and angle calculations. Heat treatment in some materials affects sound wave velocity slightly and compensates for equipment in set up.

3. The Weld Joint Design

Reason:

The operator must know the angles of the weld preparation because one of the angle beams selected must strike the bevel as closely as possible to 90° , to detect incomplete sidewall fusion. For example, if the weld bevel is 30° one of the probes will be 60° ($60^\circ + 30^\circ = 90^\circ$) and if the bevel is angle 35° , the probe selection would be 55° (**See Figure 9.95**).

Where the weld joint configuration is such that the ultrasonic beam cannot be manipulated so that it will interact with the bevel or other areas of interest at 90° , an alternate method to the single transducer technique may be used (**See Figures 9.96 and 9.97**). This method is known as the “pitch and catch” technique. The ultrasonic beam is projected by the transmitting transducer against the reflecting surface, and is reflected by that surface to a receiving transducer.

If an ultrasonic test operator does not have detailed knowledge of the test subject, he/she cannot perform an adequate test.

Most of the ultrasonic test systems used in shop or field conditions do not provide for a permanent record of test results. Permanent records can be produced through the use of fully automated, electronically controlled systems. **Figure 9.94** shows a fully automatic system for checking plate quality prior to fabrication and welding. The equipment comprises a series of probes mounted on a motorized fixture. The X and Y axis of movement is controlled by the technologist and a 3-dimensional “map” of the object under test is created and stored in a computer.



Figure 9.94: Fully automatic ultrasonic testing machine.
(Photo Courtesy of Babcock & Wilcox Canada)

The interpretation is usually made by the operator. From this it can be seen that the inspector must be reliable and a person of integrity, as well as being highly trained, and that his written reports must be accurate and reliable.

Once a technique has been detailed, the actual test is completed in a relatively short time.

The nature, size and orientation of a specific fault is not easy to plot. This evaluation process requires considerable experience and judgment.

Radiography can be used to complement the ultrasonic tests by first using ultrasonics to rapidly locate the fault, and then radiographing the area to both define the problem and have a permanent record. Conversely, ultrasonics complements radiography due to its ability to define tight incomplete fusion and cracks much more satisfactorily than radiography. It can also be used to locate the depth of a defect disclosed by radiography. This information is extremely valuable in welds that are accessible from two sides, to determine from which side a repair should be made.

Figures 9.95, 9.96 and 9.97 illustrate a number of techniques used to detect straight sided defects, both perpendicular, and angled.

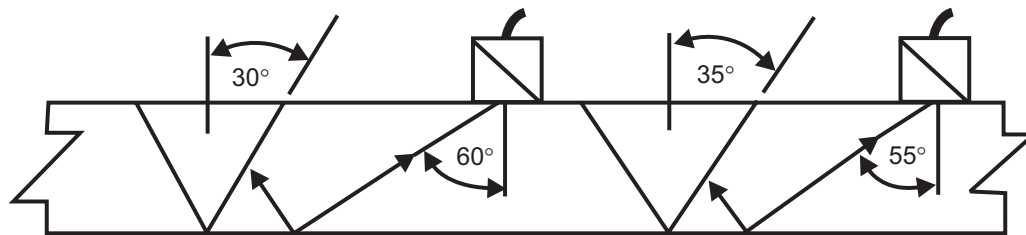


Figure 9.95: Single V groove weld, lack of side wall fusion - probe selection predicated on bevel angle.

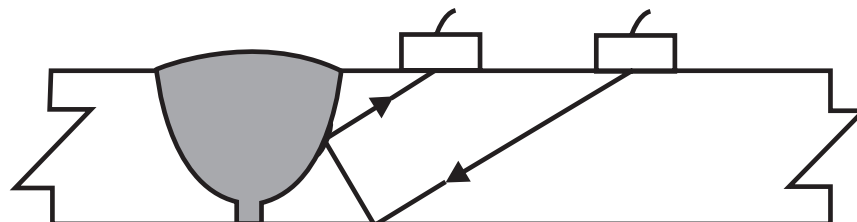


Figure 9.96: Double J groove weld, incomplete fusion - side wall - pitch and catch method - weld preparation almost perpendicular to sound path.

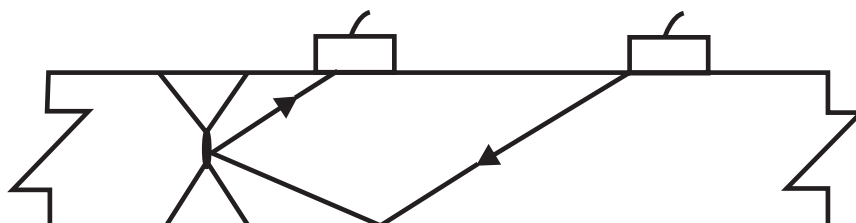


Figure 9.97: Double V groove weld in butt joint, incomplete penetration - pitch and catch method - reflecting surface near perpendicular to sound path.

Figure 9.98 illustrates an ultrasonic unit with a single probe, **Figure 9.99** shows a technique using an angle probe to detect lack of penetration in butt welds welded from one side.

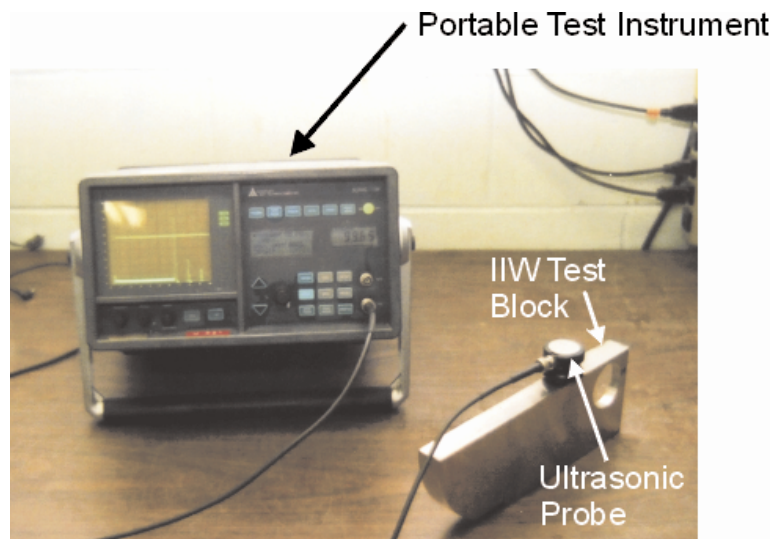


Figure 9.98: Portable ultrasonic instrument.
(Photo Courtesy of Babcock & Wilcox Canada)

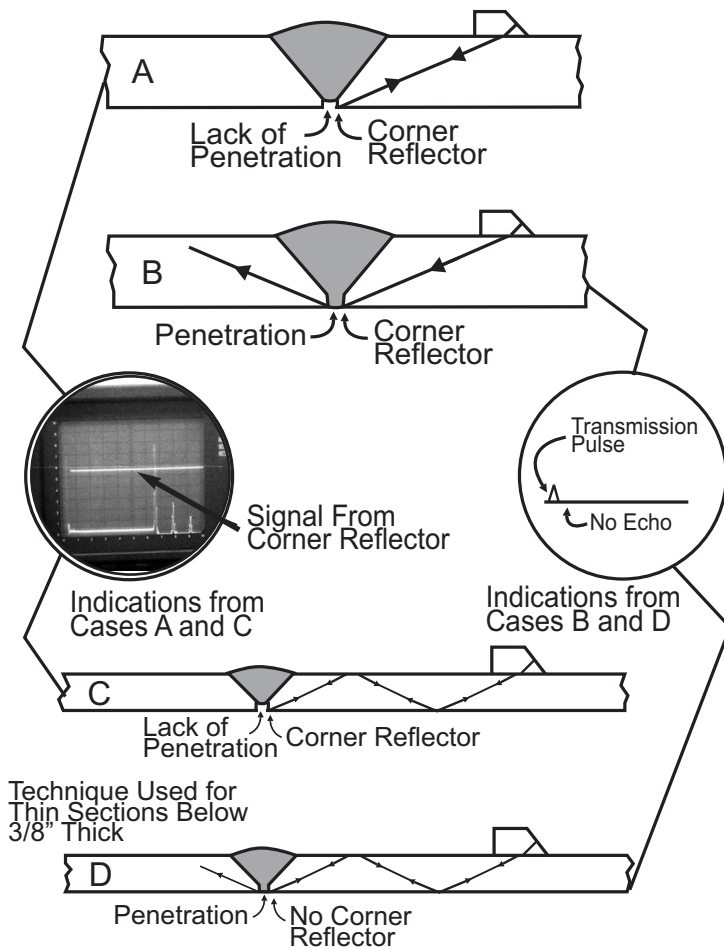


Figure 9.99: Incomplete penetration indicated by reflected signal on ultrasonic oscilloscope, schematic diagram.

Chapter 10

Weld Cost Estimating

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10.1 Introduction

The costs of any industrial process can be accurately estimated. A process such as welding will involve factors such as:

- ◆ labour
- ◆ welding consumables
- ◆ overhead

A cost analysis is needed prior to bidding on a contract involving welding, and it may be done at any time during the course of a project for verification of actual cost. The following methods may be used to determine the welding costs of any welding process, but only the most common processes are used as examples.

Weld cost estimating involves many aspects of the fabrication process. Formulas have been developed to calculate welding costs that contain factors that can vary widely depending upon the welding process, the manner in which the process is applied, and shop practices and efficiencies. The process of evaluating welding costs begins with an assessment of “How much weld is to be made?” and “What type of welds are to be made?” All other decisions flow from these first assessments. The rate at which weld metal is deposited varies significantly from process to process. The manner in which that process is applied (welding procedure) effects the potential deposition rate.

Mathematical formulas have long been in place that predict the time necessary to complete a weld. These formulas are relatively simple and are based upon the ability of a welding process to produce metal at a certain rate. The variation in the use of these formulas comes from two areas:

- ◆ consistent application of welding methods
- ◆ operating factor

10.2 Consistent Application of Welding Methods

The costs of welding are based upon the amount of weld metal that must be deposited. Knowing the amount of weld metal to be made, we then select the process that best suits the application. Each process in a given application has the potential to produce a certain number of kilogram/hour (pounds/hour). The critical issue for the estimator is to know shop practices and welding procedures. Properly documented and applied welding procedures (recipes) offer the estimator hard data on potential deposition rate.

10.3 Cross-Sectional Area of Weld (At)

To determine the amount of weld metal that must be made we start with calculating the weld's cross-sectional area. The areas of welds are usually simple geometric shapes either alone or in combinations. Their cross-sectional area is calculated from standard formulas. Tables have been provided here to aid in area determination.

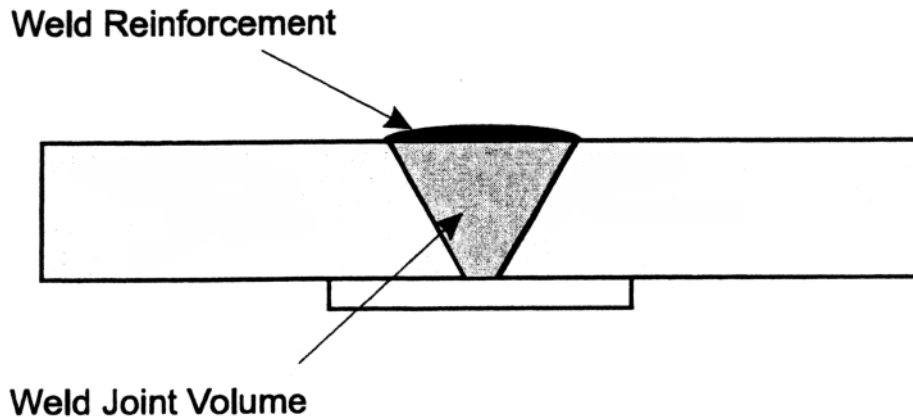


Figure 10.1: Joint Volume

The actual area of the weld will be the total of the theoretical joint volume plus the area of reinforcement.

$$A_t = A \times \frac{(100 + X)}{100}$$

A = Theoretical cross-section area of weld size

A_t = Total cross-section area of deposited weld (includes excess weld)

Table 10.8 lists the joint areas for many common joint designs. The column under single bevel, 45° bevel angle can be used for determining the volume of fillet welds.

10.4 Excess Weld (X)

The amount of weld metal deposited will exceed the theoretical amount due to oversize welds, additional weld surface reinforcement, and fit-up tolerances. This amount is called overwelding and must be considered in predicting realistic cost estimates. It is largely due to two reasons.

The first reason involves errors in weld size judgment by the welder (or intentional overwelding). Most welding is done either manually or semi-automatically. An experienced welder will try to slightly overweld, knowing how difficult it is to add a small amount of metal to a slightly undersize weld. The important issue is to control overwelding to within reasonable limits and to account for these costs in the estimating process. In some operations it has been found to represent 30% of the total welding cost. Obviously, this is an area where immediate savings can be made.

The second reason for overwelding is related to the joint itself. The fit-up of the joint influences the amount of welding necessary to complete it. The accuracy of the fabrication processes tremendously influences welding costs. Obviously joints that have wide gaps require more metal to fill. They also are difficult to fit and cause large amounts of distortion, which may make the assembly unsuitable for service.

In the case of complete penetration weld joints that are to be backgouged, the root pass technique has a tremendous effect on the cost of producing the joint.

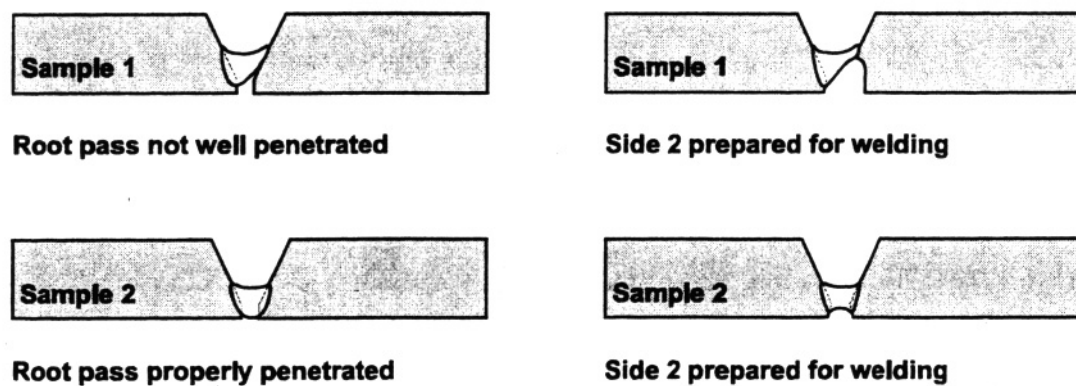


Figure 10.2: Effect of improper root bead welding.

In **Figure 10.2**, the root pass in Sample 1 penetrates only partly through the joint and will require a large amount of gouging to reach sound metal. In contrast, Sample 2 requires only minimal clean up to reach sound metal. Therefore the total cost of producing identical joints will vary significantly.

10.5 Unit Weight of Weld (M)

For mild steel welds the density equals:

$$M = 7850 \text{ kg/m}^3$$

$$M = 0.283 \text{ lb/in}^3$$

For copper welds the density equals:

$$M = 8925 \text{ kg/m}^3$$

$$M = 0.34 \text{ lb/in}^3$$

For stainless steel welds the density equals:

$$M = 7880 \text{ kg/m}^3$$

$$M = 0.286 \text{ lb/in}^3$$

For magnesium welds the density equals:

$$M = 1740 \text{ kg/m}^3$$

$$M = 0.063 \text{ lb/in}^3$$

For aluminum welds the density equals:

$$M = 2700 \text{ kg/m}^3$$

$$M = 0.098 \text{ lb/in}^3$$

10.6 Weight of Weld Metal

$$\begin{aligned} W &= A_t \times L \times M \\ &= V \times M \end{aligned}$$

W = weight of deposited weld metal (total weight for length L)

A_t = total cross-section area of deposited weld (includes excess weld)

L = length of weld (or total length of similar welds under consideration)

V = volume of deposited weld metal (includes excess weld)

M = unit weight of weld metal (per unit volume)

10.7 Weld Metal Deposition Rate (D)

The weld metal deposition rate is defined as the weight of deposited weld metal per welding arc hour. The deposition rate is very much dependent upon the welding procedure, i.e., welding process, electrode size and welding current. If the welding process is not known when the estimate is made, then certain assumptions must be made by the estimator. These assumptions become very important and will have an influence on the weld cost estimate.

If it is known that a fabricator's specific welding procedure data sheets will be used, they should be used as a basis for the estimator's information.

The following examples explain how widely the weld metal deposition rate can vary:

SMAW Process

E4910 x 3.2 mm	@	110 A ...	...	1.27 kg/hr (2.8 lb/hr)
E4912 x 3.2 mm	@	110 A ...	...	1.00 kg/hr (2.2 lb/hr)
E4914 x 4.0 mm	@	180 A ...	...	1.82 kg/hr (4.0 lb/hr)
E4918 x 4.0 mm	@	180 A ...	...	1.82 kg/hr (4.0 lb/hr)
E4924 x 3.2 mm	@	140 A ...	...	1.41 kg/hr (3.1 lb/hr)
E4924 x 4.0 mm	@	210 A ...	...	2.09 kg/hr (4.6 lb/hr)

FCAW Process

E491T-9-CH x 1.6 mm	@	275 A ...	...	5.00 kg/hr (11 lb/hr)
E491T-9-CH x 2.4 mm	@	400 A ...	...	5.46 kg/hr (12 lb/hr)

GMAW Process

ER49S-6 x 0.9 mm	@	175 A ...	...	2.05 kg/hr (4.5 lb/hr)
ER49S-6 x 1.2 mm	@	175 A ...	...	1.68 kg/hr (3.7 lb/hr)
ER49S-6 x 1.2 mm	@	225 A ...	...	2.36 kg/hr (5.2 lb/hr)
ER49S-6 x 1.2 mm	@	270 A ...	...	3.73 kg/hr (8.2 lb/hr)

SAW Process

Wire Diameter (mm)	Amperage	Current Type	Deposition Rate (lb/hr)	
			Electrode Stick-Out	
4.0	400	DC+	7.9	9.2
4.0	600	DC+	14.7	16.7
4.8	500	AC	-	10.4
4.8	500	DC+	-	9.4
4.8	700	AC	-	16.7
4.8	700	DC+	-	15.0
4.8	400	AC	-	7.1
4.8	400	DC+	-	6.4

10.8 Shielding Gas (G)

Shielding gases are used with the FCAW and GMAW welding processes, except when a FCAW electrode is self shielding and does not require shielding gas coverage. Self shielding electrodes are usually employed in field welding. Shielding gas costs are specific to the company and are usually a reflection of the total amount of gas used by the company. These costs will have to be taken from actual accounting information.

It is important to note that control of the amount of shielding gas consumed is in the hands of the welder. Many welders do not realize that high shielding gas flow rates do not necessarily improve the soundness of the weld. It is common to find wide variances in flow rate settings, even through the use of pressure gauges in place of flow meters.

Pressure gauges do not control flow; rather they supply gas at a given pressure not flow rate. Education of the welder and welding supervision is the key to controlling excessive gas consumption.

For Estimating Shielding Gas Consumption: cubic foot per hour (cfh), or liter per minute (ℓ/min)

Steel: 30 cfh – 40 cfh or 15 ℓ/min - 18 ℓ/min

Aluminum: 40 cfh – 55 cfh or 18 ℓ/min – 25 ℓ/min

10.9 Flux for SAW Process (F)

SAW flux is consumed by a portion of it being melted in the welding arc, then fused to form slag over the SAW weld. The unfused flux is usually vacuumed and returned to the flux hopper. Literature suggests that the weight of flux consumed is approximately the same as the weight of SAW weld deposited. The cost per pound of flux can be found in actual accounting information.

10.10 Process Deposition Factor (Dp)

The weight of electrode consumed is always greater than the weight of weld metal deposited. The electrode loss is caused by weld spatter, formation of flux and electrode end loss (stub ends in SMAW). Each electrode manufacturer publishes deposition efficiencies for their products so this information is readily available.

Following are typical values for deposition rates for the stated welding processes:

Dp (SMAW)	= 65%
Dp (FCAW)	= 85% (Not for metal core wire)
Dp (FCAW)	= 95% (Metal core wire)
Dp (GMAW)	= 95%
Dp (SAW)	= 98% - 100%

10.11 Welder/Operator Work Efficiency Factor (Dw)

This is a factor for the average arc time per welder manhour while the welder works on welding and welding related functions. In other words, this is the total number of minutes out of an hour during which welding is actually taking place. This is an important factor, which is often difficult to establish. It will have a significant influence on the weld cost estimate so one should make a careful decision on selecting Dw. The Dw factor is weld-shop specific, influenced by shop supervision, shop layout, and the welder's ability to work efficiently.

10.11.1 Operator Factor

In any operation there are down times. Any time the arc is not operating, the joining process is not in progress. This can be attributed to many reasons; changing electrodes, fitting parts, replacing components in a jig, turning assemblies over, personal down time, equipment repair or maintenance and so on. Each company operates somewhat differently. However, these factors can be brought together and accounted for in an estimate. Evidence for this comes from the ability of experienced supervisors to accurately predict the time to complete a job. The supervisor knows from first-hand observation how long it will take his welders to complete the task. The estimator can often draw on this type of data from historical information.

Welding procedures provide the starting point in establishing welding costs. Since the welding procedure is a recipe for making a weld, it will include all the information necessary to determine the rate at which metal can be made. Let's take an example of a typical welding procedure for making a fillet weld with the FCAW process.

Layer	Pass	Wire Feed Speed	Current	Voltage	Travel Speed
1	1	5.9 m/min (230 in/min)	300	26	430 mm/min (17 in/min)

From the information above we see that the welder, when following this procedure completes the 6 mm fillet weld at 430 mm/min (17 in/min). Logically then, if the part contains 10 m (395 in) of 6 mm fillet weld it should take about 23 minutes to complete.

$$10 \text{ m divided by travel speed of } 0.43 \text{ m/min} = 23.3 \text{ minutes}$$

An experienced estimator will know not to bid on this basis. There are great differences between what is theoretically possible and actual performance. These differences are related to real "arc-on time" (operating factor) and whether the procedure is actually used by the welder.

We know that a welder following the procedure needs no less than 23 minutes of “arc-on time” to make this much metal. If the welder sets the equipment to lower parameters the weld will take longer. If the equipment is in poor condition, time will be lost to continuously adjusting the setup in an attempt to improve the operation of the process. If the welder is assigned other tasks than just continuously welding, operating factor is reduced again. There are many reasons why 100% operating factor is never achieved, even when using robots.

The data taken from a welding procedure is used to represent 100% operating factor. The welding procedure data represents how much weld metal can be made when using the procedure, if welding was continuous.

The following are examples of typical Operating Factors for the most common welding processes. They should be used as a baseline from which to start, and compared against the experiences of the shop.

a) *SMAW Process*

- ◆ Dw could typically be 10% - 20%. This will provide 6 to 12 minutes arc time per hour.

b) *FCAW Process*

- ◆ This is a continuous wire feed process so the efficiency factor will be higher than for SMAW.
- ◆ If applied semi-automatically on long joints, the welder will stop every 2 to 3 minutes to change position. When applied to short welds, the stops will be more frequent.
- ◆ Assume the welder stops each minute for ½ minute, and takes 5 minute breaks each hour.
- ◆ Dw could typically be 20% - 40%. This will provide 12 to 24 minutes arc time per hour.

c) *GMAW Process*

This process is similar to the FCAW, with the exception that there is no slag covering the weld.

- ◆ Dw could typically be 20% - 40%. This will provide 12 to 24 minutes arc time per hour.

d) *SAW Process*

SAW process is usually employed on long weld runs, and often on a production basis. The longer and/or thicker the joints, the less material handling is involved and higher operating factors can be expected. For these reasons, the range of operating factor is very wide.

- ◆ Dw Could typically be 30% - 70%.

Note: The above Dw factors are approximations, and the estimator should consult the fabricator for realistic values before proceeding with the estimate. The estimator can correlate welds of similar type and welding process, then choose a Dw factor that is suited to the specific shop operation.

10.12 Weld Cost Estimating Procedure

Summary of symbols used throughout this discussion and weld estimate formulae:

- A = Theoretical cross-section area of weld size
- X = Excess weld due to oversize and weld surface reinforcement (in %)
- At = Total cross-section area of deposited weld (includes excess weld)
- L = Length of weld (or total length of similar welds under consideration)
- V = Volume of deposited weld metal (includes excess weld)
- W = Weight of deposited weld metal (total weight for length L)
- M = Unit weight of weld metal (per unit volume)
- D = Weld metal deposition rate (weight per hour)
- Dp = Weld process deposition factor {(wt. of metal deposited) / (wt. of electrode used)}
(expressed in decimal format)
- Dw = Welder/Operator work efficiency factor (arc time per hour expressed in decimal format)
- E = Weight of electrode used for length L
- Tw = Person hours unfactored to weld length L
- Tt = Total person hours (factored) to weld length L (Tt will be greater than Tw)
- G = Shielding gas consumed (cubic content)
- F = Flux consumed (weight)
- OH = Overhead cost on labour

1. Assume joint geometry for each type of joint.
2. Make a weld take-off of the various types of welds.
3. For each type of weld, choose the “excess weld factor” (X%). (One may wish to group welds by size).
4. Determine the “Weld Metal Deposition Rate” (D) by knowing the welding process, electrode, and some average current range (knowing welding procedures will help).
5. Determine the “Welder/Operator Work Efficiency Factor” (Dw) (this factor can be weld-shop specific).
6. Determine “Weld Process Deposition Factor” (Dp).
7. Calculate total cross-section area for the various welds:

$$A_t = A \times \frac{(100 + X)}{100}$$

8. Calculate volume of weld deposited:

$$V = At \times L$$

9. Calculate weight of weld:

$$W = V \times M$$

10. Calculate unfactored person-hours (for gas consumption if required)

$$T_w = \frac{W}{D}$$

11. Calculated factored person-hours:

$$T_t = \frac{W}{D \times D_w}$$

12. Calculate electrode weight:

$$E = \frac{W}{D_p}$$

13. Calculate gas consumption:

$$G = T_w \times (\text{cu volume/hour})^*$$

*Approximately 35 ft³/hr or 1000 ℓ³/hr

14. Calculate weight of SAW flux.

$$F = W$$

10.12.1 Summary

$$A_t = A \times \frac{(100 + x)}{100};$$

$$V = A_t \times L;$$

$$W = V \times M$$

$$T_w = \frac{W}{D};$$

$$T_t = \frac{W}{D \times D_w};$$

$$E = \frac{W}{D_p}$$

$$G = T_w \times (\text{volume/hour});$$

$$F = W$$

Labour Cost:

Direct Labour	$T_t \times \text{Rate}$	= _____
Overhead	$T_t \times \text{OH}$	= _____
	Total	= _____

Material Costs:

SMAW Electrode	=	W (SMAW)	x	\$/Unit Wt.	_____
FCAW Electrode	=	W (FCAW)	x	\$/Unit Wt.	_____
GMAW Electrode	=	W (GMAW)	x	\$/Unit Wt.	_____
SAW Electrode	=	W (SAW)	x	\$/Unit Wt.	_____
Flux	=	W (Flux)	x	\$/Unit Wt.	_____
Gas	=	Volume	x	\$/Unit Vol.	_____
				Total	_____

Table 10.1**Fillet Welds**

Assume:

- a) 1/8" and 3/16" welds increased by 1/64" in size
- b) Welds > 3/16" increase 1/32" in size
- c) Weld reinforcing is convex by 1/16" (parabolic)

Fillet		Actual Fillet		Reinforcement Area (1/16")	%
Size (in)	Area (sq. in)	Size (in)	Area (sq. in)	(sq. in)	Excess Weld Area
1/8	.0078	9/64	.0099	.0083	133
1/4	.0313	9/32	.0396	.0166	80
1/2	.1250	17/32	.1411	.0313	38
3/4	.2813	25/32	.3052	.0460	25
1	.5000	1 1/32	.5317	.0608	19
1 1/2	1.125	1 17/32	1.1724	.0902	12
2	2.0000	2 1/32	2.0630	.1197	9

Table 10.2**45° Bevel Weld with Backing:**

Assume:

- a) Weld reinforcement of 1/16" and 1/8" (parabolic)
- b) Weld reinforcement overlaps the top edge of the joint by 1/8" each side.
- c) Root opening = 1/4"

Thickness T (in)	Area (sq. in)	Reinforcement (Area sq. in)		% Excess Weld		
		Size (in)	Area (sq. in)	1/16" Reinf.	1/8" Reinf.	Avg.
3/16	.0645	.0286	.0573	44	89	67
1/4	.0938	.0313	.0625	33	67	50
1/2	.2500	.0417	.0833	17	33	25
3/4	.4688	.0521	.1042	11	22	17
1	.7500	.0625	.1250	8	17	13
1 1/4	1.0938	.0729	.1458	7	13	10
1 1/2	1.5000	.0833	.1667	6	11	9
1 3/4	1.9688	.0938	.1875	5	10	8
2	2.5000	.1042	.2083	4	8	6

Table 10.3

45° V-Grooves:

Assume:

- a) Weld metal to root of groove (zero root opening)
- b) Reinforcing overlaps top edge of groove by 1/8" each side
- c) Calculate for 1/16" and 1/8" reinforcing

45°-V Groove Depth (in)	Area (sq. in)	Reinforcement (Area sq. in)		% Excess Weld		
		1/16" Reinf.	1/8" Reinf.	1/16" Reinf.	1/8" Reinf.	Avg.
1/8	.006	.015	.029	250%	483%	367%
1/4	.026	.019	.038	73%	146%	110%
1/2	.104	.028	.056	27%	53%	40%
3/4	.233	.037	.073	16%	31%	24%
1	.414	.045	.090	11%	22%	17%
1 1/4	.647	.054	.107	8%	17%	13%
1 1/2	.932	.063	.124	7%	13%	10%
1 3/4	1.268	.071	.142	6%	11%	9%
2	1.657	.080	.159	5%	9%	7%

Table 10.4

60° V-Groove:

Assume:

- a) Weld metal to root of groove (zero root opening)
- b) Reinforcing overlaps edges of groove by 1/8" each side
- c) Calculate for 1/16" and 1/8" reinforcing

60°-V Groove Depth (in)	Area (sq. in)	Reinforcement (Area sq. in)		% Excess Weld		
		1/16" Reinf.	1/8" Reinf.	1/16" Reinf.	1/8" Reinf.	Avg.
1/8	.009	.017	.033	188%	367	278
1/4	.036	.023	.045	64%	125	94
1/2	.145	.035	.069	24%	48	36
3/4	.325	.047	.093	14%	29	22
1	.577	.059	.117	10%	20	15
1 1/4	.902	.071	.141	8%	16	10
1 1/2	1.299	.083	.165	6%	13	10
1 3/4	1.768	.095	.189	5%	11	8
2	2.310	.108	.213	5%	9	7

Table 10.5**45° Bevel Groove:**

Assume:

- a) Weld metal to root of groove (zero root opening)
- b) Reinforcing overlaps edges of groove by 1/8" each side
- c) Calculate for 1/16" and 1/8" reinforcing

45° Bevel Depth (in)	Area (sq. in)	Reinforcement (Area sq. in)		% Excess Weld		
		1/16" Reinf.	1/8" Reinf.	1/16" Reinf.	1/8" Reinf.	Avg.
1/8	.008	.016	.031	200	388	294
1/4	.031	.021	.042	68	135	102
1/2	.125	.032	.063	26	50	38
3/4	.281	.042	.083	15	30	23
1	.500	.053	.104	11	21	16
1 1/4	.781	.063	.125	8	16	12
1 1/2	1.125	.074	.146	7	13	10
1 3/4	1.531	.084	.167	5	11	8
2	2.000	.095	.188	5	9	7

Table 10.6**60° Bevel Groove**

Assume:

- a) Weld metal to root of groove (zero root opening)
- b) Reinforcing overlaps edge of groove by 1/8" each side
- c) Calculate for 1/16" and 1/8" reinforcing

60° Bevel Depth (in)	Area (sq. in)	Reinforcement (Area sq. in)		% Excess Weld		
		1/16" Reinf.	1/8" Reinf.	1/16" Reinf.	1/8" Reinf.	Avg.
1/8	.014	.020	.039	142	279	211
1/4	.054	.029	.057	54	106	80
1/2	.217	.047	.093	22	43	33
3/4	.487	.065	.129	13	26	20
1	.866	.083	.165	10	19	15
1 1/4	1.353	.101	.201	7	15	11
1 1/2	1.949	.120	.237	6	12	9
1 3/4	2.652	.138	.273	5	10	8
2	3.464	.156	.310	5	9	7

Table 10.7

Backgouged Groove - 45° V-Groove:

Assume:

- a) 45° groove angle
- b) 3/16" root radius
- c) use 50% of root circle
- d) use 3/8" wedge in middle
- e) two side triangles

Gouged Depth		Areas (sq. in)				Reinforcement (Area sq. in)		% Extra Weld		
		R=3/16"	3/8"xD	2@22.5°	Total	1/16" Reinf.	1/8" Reinf.	1/16" Reinf.	1/8" Reinf.	Avg.
Total (T)	D = T - R									
¼	1/16	.055	.023	.002	.080	.028	.056	35	70	53
½	5/16	.055	.117	.040	.212	.037	.074	17	35	26
¾	9/16	.055	.211	.131	.397	.045	.091	11	23	17
1	13/16	.055	.305	.273	.633	.054	.108	9	17	13
1 ¼	17/16	.055	.398	.468	.921	.063	.125	7	14	11
1 ½	21/16	.055	.492	.714	1.288	.071	.143	6	11	9
1 ¾	25/16	.055	.586	1.011	1.652	.080	.160	5	10	8
2	29/32	.055	.680	1.361	2.096	.089	.177	4	8	6

Table 10.8: Cross-section Areas for Joint Size “S”

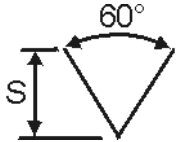
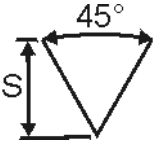
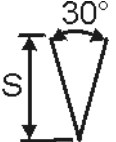
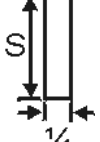
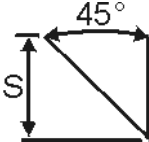
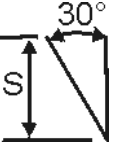
Butt Size “S”						
1/4	.036	.026	.017	.063	.031	.018
5/16 (.31)	.056	.040	.026	.078	.048	.028
3/8	.081	.058	.038	.094	.070	
7/16 (.44)	.111	.080	.052	.110	.097	.056
1/2	.145	.104	.067	.125	.125	.072
9/16 (.56)	.183	.130	.084	.140	.157	.091
5/8	.226	.162	.105	.156	.195	.113
11/16 (.69)	.273	.197	.127	.173	.238	.137
3/4	.325	.233	.151	.188	.281	.162
13/16 (.94)	.379	.272	.176	.203	.328	.189
7/8	.442	.317	.205	.219	.383	.221
15/16 (.94)	.510	.366	.237	.235	.442	.255
1	.588	.414	.268	.250	.500	.289
1 1/8	.731	.524	.339	.281	.633	.365
1 1/4	.902	.647	.418	.313	.781	.361
1 3/8	1.092	.783	.506	.344	.945	.546
1 1/2	1.299	.932	.603	.375	1.125	.650
1 5/8	1.525	1.094	.708	.406	1.320	.762
1 3/4	1.768	1.268	.820	.438	1.531	.884
1 7/8	2.030	1.456	.942	.469	1.758	1.015
2	2.310	1.657	1.072	.500	2.000	1.155
2 1/4	2.923	2.097	1.356	.563	2.531	1.461
2 1/2	3.609	2.589	1.675	.625	3.125	1.804
2 3/4	4.367	3.132	2.026	.688	3.781	2.183
3	5.197	3.728	2.411	.750	4.500	2

Table 10.9: Weight Per Length of Electrode

Wire Diameter		Inches Per Pound of Filler Alloy						
Decimal Inches	Fraction Inches	Aluminum	Copper (deox.)	Nickel	Carbon Steel	Stainless Steel	Magnesium	Silicon Bronze
0.020		32,400	9800	9900	11,100	10,950	50,500	10,300
0.025		22,300	6750	6820	7,680	7,550	34,700	7,100
0.030		14,420	4360	4400	4,960	4,880	22,400	4,600
0.035		10,600	3200	3240	3,650	3,590	16,500	3,380
0.040		8,120	2450	2480	2,790	2,750	12,600	2,580
0.045	3/64	6,410	1940	1960	2,210	2,170	9,990	2,040
0.062	1/16	3,382	1020	1030	1,160	1,140	5,270	1,070
0.078	5/64	2,120	640	647	730	718	3,300	675
0.093	3/32	1,510	455	460	519	510	2,350	510
0.125	1/8	825	249	252	284	279	1,280	263
0.156	5/32	530	160	162	182	179	825	169
0.187	3/16	377	114	115	130	127	587	120
0.250	¼	206	62	63	71	70	320	66

10.13 Computer Estimating

There are several computer software programs on weld cost estimating. Knowing all the factors involved, you will be in better control when using computers to do the estimating for you.

Weld_IT is an excellent program designed by welding experts of the Canadian Welding Bureau. It can be obtained through the CWB office.

Welding for Design Engineers

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Additional Resources

Welding Health and Safety

CWB/Gooderham Centre - *Module 1*, Canadian Welding Bureau, 7250 West Credit Ave., Mississauga, ON, Canada, L5N 5N1.

CAN/CSA - W117.2. *Safety in Welding, Cutting, and Allied Processes*, Canadian Standards Association, 178 Rexdale Blvd., Rexdale, ON, Canada, M9W 1R3. Page 12 of this standard lists other CSA standards relevant to safety in welding.

CAN/CSA-Z94.2. *Hearing Protectors*, Canadian Standards Association, 178 Rexdale Blvd., Rexdale, ON, Canada, M9W 1R3.

ANSI/ASC Z49.1-94. *Safety in Welding and Cutting*, American Welding Society, 550 N.W. LeJeune Rd., Miami, FL 33135, U.S.A.

ANSI/AWS F4.1. *Recommended Safe Practices for the Preparation for Welding and Cutting of Containers That Have Held Hazardous Substances*, (AWS publishes a *Safety and Health Information Packet* that includes these two standards).

Structure and Properties of Metals

CWB/Gooderham Centre - *Modules 8, 20*, Canadian Welding Bureau, 7250 West Credit Ave., Mississauga, ON, Canada, L5N 5N1

Physical Metallurgy Principles, Reed-Hill, R.E., D.Van Nostrand Company, Inc.

Welding Handbook, Eighth Edition, Vol 1, American Welding Society, 550 N.W. LeJeune Rd., Miami, FL 33126, U.S.A.

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