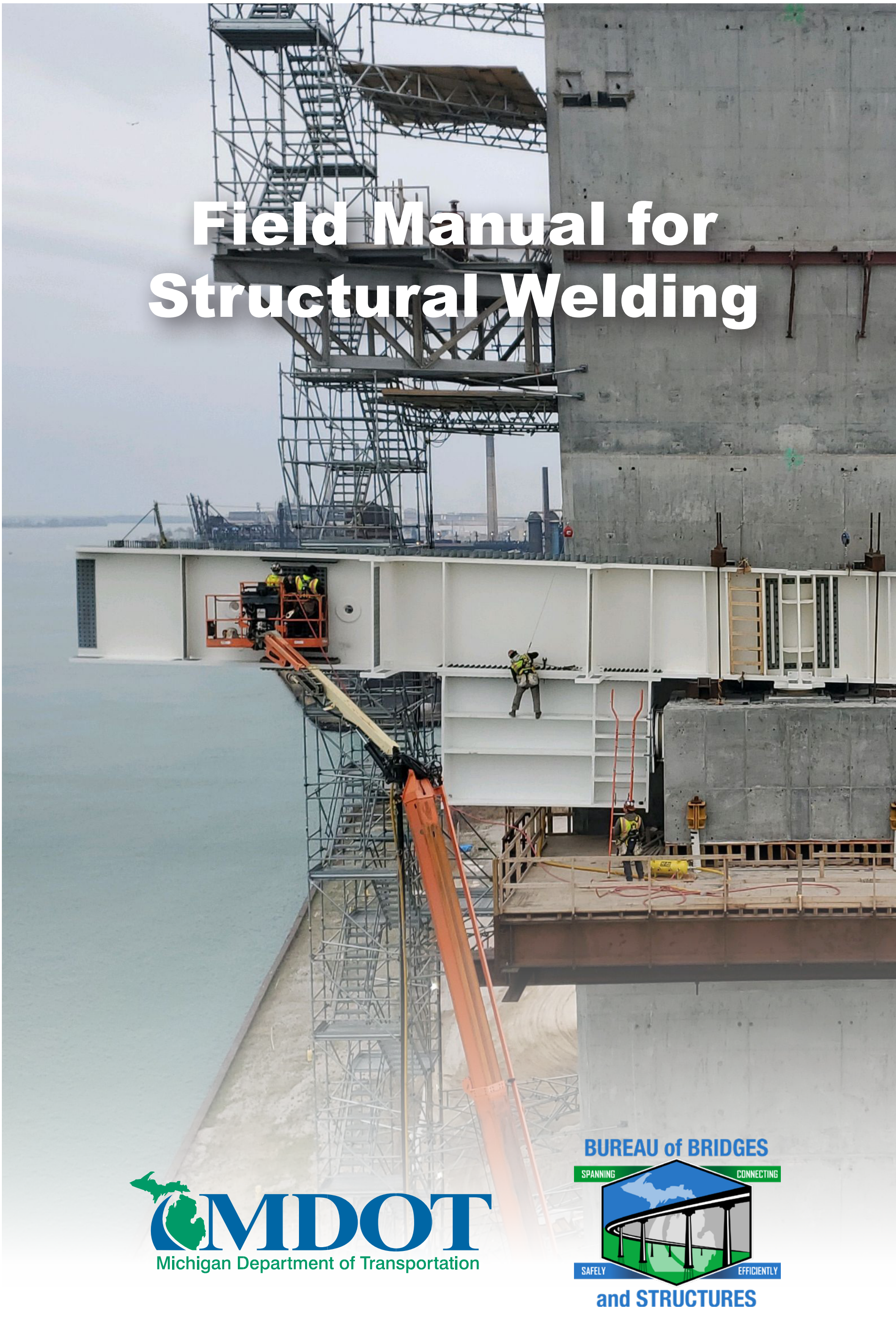
Michigan Department of Transportation

Field Manual for Structural Welding



MDOT
Michigan Department of Transportation

BUREAU of BRIDGES and STRUCTURES
SPANNING CONNECTING SAFELY EFFICIENTLY

2nd Edition – May 2022

Cover photo courtesy of Windsor-Detroit Bridge Authority and Bridging North America.

Glossary

arc welding – A welding process that produces a coalescence of metals by heating them with an electric arc.

arc welding electrode – A part of the welding system that conducts current and ends at the arc.

back gouging – The removal of weld and base metal from the other side of a partially welded joint. The objective is to assure complete penetration upon subsequent welding from that side.

backing – A piece of material placed at the root of a weld joint for the purpose of supporting molten weld metal.

base metal – The metal to be welded.

bevel – An angled edge preparation.

butt joint – A joint between two members lying in the same plane.

complete fusion – Fusion over the entire fusion faces and between all adjoining weld beads.

CJP (complete joint penetration) – A groove weld condition in which weld metal extends through the joint thickness.

defect – A discontinuity that, by nature or accumulated effect (for example, total crack length or amount of porosity), renders a part or product unable to meet minimum applicable acceptance standards or specifications.

depth of fusion – The distance that fusion extends into the base metal or previous bead from the surface melted during welding.

facing surface – The surfaces of materials in contact with each other and joined or about to be joined together.

filler material – The material to be added in making a welded, brazed, or soldered joint.

fillet weld – A weld of approximately triangular cross section that joins two surfaces approximately at right angles to each other in a lap joint, T-joint, or corner joint.

flat welding position – A welding position where the weld axis is approximately horizontal, and the weld face lies in an approximately horizontal plane.

flux – Material used to prevent, dissolve, or facilitate removal of oxides and other undesirable surface substances.

FCAW (flux cored arc welding) – An arc welding process that produces coalescence of metals by means of a tubular electrode. Shielding gas may or may not be used.

FCAW-S (self-shielded flux cored arc welding) – A flux-cored arc welding process variation in which shielding gas is obtained exclusively from the flux within the electrode.

fusion – The melting together of filler metal and base metal, or of base metal only, to produce a weld.

GMAW (gas metal arc welding) – An arc welding process where the arc is between a continuous filler metal electrode and the weld pool. Shielding from an externally supplied gas source is required.

GTAW (gas tungsten arc welding) – An arc welding process where the arc is between a tungsten electrode (non-consumable) and the weld pool. The process is used with an externally supplied shielding gas.

groove weld – A weld made in a groove between two members.

HAZ (heat-affected zone) – That section of the base metal, generally adjacent to the weld zone, whose mechanical properties or microstructure have been altered by the heat of welding.

hot crack – A crack formed at temperatures near the completion of weld solidification.

incomplete fusion – A weld discontinuity where fusion did not occur between weld metal and the joint or adjoining weld beads.

incomplete joint penetration – A condition in a groove weld where weld metal does not extend through the joint thickness.

interpass temperature – In a multi-pass weld, the temperature of the weld area between passes.

joint – The junction of the edges of members that are to be joined or have been joined.

lap joint – A joint type in which the non butting ends of one or more workpieces overlap approximately parallel to one another.

leg of fillet weld – The distance from the root of the joint to the toe of the fillet weld.

MCAW (metal cored arc welding) – An arc welding process with a tubular electrode where the hollow electrode contains alloying materials.

metal cored electrode – A composite tubular electrode consisting of a metal sheath and a core of various powdered materials, producing no more than slag islands on the face of the weld bead. External shielding is required.

peening – The mechanical working of metals using impact blows.

PJP (partial joint penetration) – A groove weld condition in which weld metal extends partially through the joint thickness.

plug weld – A circular weld made through a hole in one member of a lap or T-joint.

porosity – A hole-like discontinuity formed by gas entrapment during solidification.

PWHT (post weld heat treatment) – Any heat treatment subsequent to welding.

preheating – The application of heat to the base metal immediately before welding, brazing, soldering, thermal spraying, or cutting.

preheat temperature – The temperature of the base metal immediately before welding is started.

PQR (procedure qualification record) – The demonstration that the use of prescribed joining processes, materials, and techniques will result in a joint exhibiting specified soundness and mechanical properties.

reinforcement – Weld metal, at the face or root, in excess of the metal necessary to fill the joint.

root opening – A separation at the joint root between the work pieces.

root crack – A crack at the root of a weld.

SMAW (shielded metal arc welding) – A process that welds by heat from an electric arc between a flux-covered metal electrode and the work. Shielding comes from the decomposition of the electrode covering.

shielding gas – Protective gas used to prevent atmospheric contamination.

SAW (submerged arc welding) – A process that welds with the heat produced by an electric arc between a bare metal electrode and the work. A blanket of granular fusible flux shields the arc.

tack weld – A temporary weld used to hold parts in place while more extensive, final welds are made.

tensile strength – The maximum stress a material subjected to a stretching load can withstand without tearing.

weld bead – The metal deposited in the joint by the process and filler wire used.

welding leads – The work piece lead and electrode lead of an arc welding circuit.

weld metal – The portion of a fusion weld that has been completely melted during welding.

weld pass – A single progression of welding along a joint. The result of a pass is a weld bead or layer.

weld pool – The localized volume of molten metal in a weld prior to its solidification as weld metal.

weld puddle – A nonstandard term for weld pool.

welding sequence – The order in which weld beads are deposited in a weldment.

Acknowledgement

The material presented herein was put together by Sherif El-Tawil and Jason McCormick of the Department of Civil and Environmental Engineering at the University of Michigan (UM) under the auspices of the Michigan Department of Transportation (MDOT)-funded UM Bridges and Structures Research Center of Excellence. The UM Center is directed by Sherif El-Tawil and managed by MDOT's Steve Kahl and Michael Townley. Matt Filcek, Peter Jansson, and Jeff Weiler, who were members of MDOT's Bridge Field Services team, provided content and reviewed the material for the first edition. Cole Christy, Rick Liptak, Bob Otremba, and Matt Filcek, who are members of MDOT's Bureau of Bridges and Structures team, provided changes for the second edition.

Content was taken from several sources, including:

- AASHTO Design: AASHTO LRFD Bridge Design Specifications, Customary U.S. Units, 7th Edition, with 2015 and 2016 Interim Revisions.
- AASHTO Construction: AASHTO LRFD Bridge Construction Specifications, 3rd Edition, with 2010, 2011, 2012, 2014, 2015 and 2016 Interim Revisions.
- MDOT BDM: Michigan Department of Transportation Bridge Design Manual, 2016 Revisions.
- MDOT SSC: 2020 Michigan Department of Transportation Standard Specifications for Construction, 2016 Revisions.
- AWS A2.4: AWS A2.4:2012, Standard Symbols for Welding, Brazing, Nondestructive Examination.
- AWS A3.0: AWS A3.0:2010, Standard Welding Terms and Definitions.
- AWS D1.1: AWS D1.1:2020, Structural Welding Code - Steel.
- AWS D1.5: AASHTO/AWS D1.5:2020, Bridge Welding Code. Additional content was adapted from:
  - American Institute of Steel Construction (AISC) Steel Design Guide 21: Welded Connections - A Primer for Engineers by Duane Miller.
  - AISC Bolting and Welding Primer, Part 1: Welded Connection Design by Duane Miller (***https://www.aisc.org/content.aspx?id=2174***).
  - AISC Bolting and Welding Course (***https://www.aisc.org/WorkArea/showcontent.aspx?id=37216***).

Introduction and Purpose

The purpose of this Field Manual for Structural Welding is to summarize basic definitions, concepts, and procedures for welded joints. The manual addresses general considerations for welding, welder certification, and inspection procedures. The intent of the manual is to assist engineers, construction workers, and inspectors with designing, constructing, and inspecting welded joints to meet current specifications, respectively.

Welding is the process of fusing multiple pieces of metal together by heating the filler metal to a liquid state. Welds create a load path, known as a joint, between two pieces of metal. A properly welded joint is stronger than the base metal. Welding can be performed in the shop or in the field.

Welded joints are critical components of any structure. For many types of structural systems, failure of a welded joint can lead to collapse or extensive systemwide damage. Therefore, current design specifications and construction procedures impose rigorous design, construction, and inspection practices to ensure that such joints can perform their function safely.

Governing Specifications

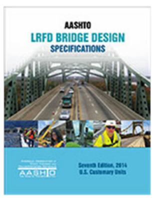
The design of highway bridges in Michigan is based on AASHTO Design. The construction and fabrication of highway bridges is based on AASHTO Construction. In some cases, the AASHTO Design specifications are vague or leave a decision to the judgment of the engineer. Guidelines in the MDOT BDM are provided as clarification and thus supplement the AASHTO Design specifications. Some minimum requirements in the AASHTO Design specifications have been found through experience to be insufficient. In these instances, the MDOT BDM supersedes AASHTO Design with more rigorous controls. Likewise, minimum requirements in AASHTO Construction have been found through experience to be insufficient. In these instances, the MDOT SSC and other contract documents supersede AASHTO Construction with more rigorous controls.

The American Welding Society (AWS) prepares specifications and documents related to welding. AWS has two documents that are relevant: AWS D1.1 and AWS D1.5. These documents are similar, but the latter is specifically focused on bridges and is also an AASHTO document. Therefore, MDOT BDM supersedes AWS documents.

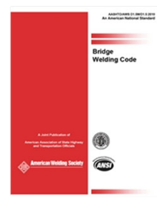
The MDOT SSC is the standard for basic requirements governing materials, equipment and methods used in construction contracts administered by MDOT. MDOT BDM will primarily reference AASHTO specifications. MDOT SSC is for construction and does not reference the MDOT BDM. Any references within MDOT SSC usually pertain to ASTM or AASHTO material specifications and other subsections within itself. MDOT Special Provision for Structural Steel and Aluminum Construction [20SP-707(A)] contains specifications required by MDOT that modify the AWS requirements. It supersedes MDOT SSC.

Figure 1 shows some of the standards mentioned.

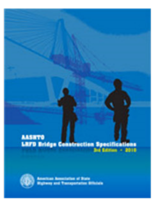
AASHTO LRFD Bridge Design Specifications **(AASHTO Design)**



AASHTO/AWS D1.5M/D1.5 Bridge Welding Code **(AWS D1.5)**



AASHTO LRFD Bridge Construction Specifications **(AASHTO Construction)**



D1.1/D1.1M Structural Welding Code-Steel (**AWS D1.1**)

MDOT's Michigan Bridge Design Manual **(MDOT BDM)**

MDOT's Standard Specifications for Construction **(MDOT SSC)**

Figure 1: Standards used for preparation of this manual.

Arc Welding Processes

Arc welding processes are based on fusion. Fusion requires closeness and cleanliness at the atomic level, both of which can be achieved by shielding the molten puddle with gas or slag. There are several types of arc welding processes as follows:

Shielded Metal Arc Welding (SMAW)

An electric arc is produced between the end of a coated metal electrode and the steel components to be welded (Figure 2). The electrode is a filler metal covered with a coating. The electrode's coating has two purposes: 1) It forms a gas shield to prevent impurities in the atmosphere from getting into the weld, and 2) It contains a flux that purifies the molten metal.

SMAW is almost exclusively a manual arc welding process. Because of its versatility and simplicity, it is particularly dominant in the maintenance and repair industry. The most common quality problems associated with SMAW include weld spatter, porosity, poor fusion, shallow penetration, and cracking.

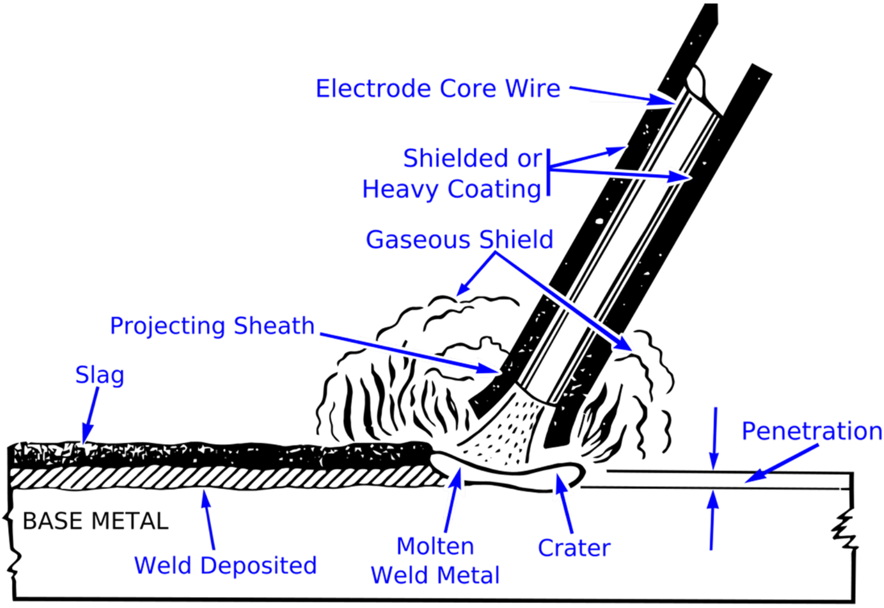


Figure 2: Shielded Metal Arc Welding (SMAW).

Gas Metal Arc Welding (GMAW)

Gas Metal Arc Welding (GMAW) is fast and economical. As shown in Figure 3, a continuous wire is fed into the welding gun. The wire melts and combines with the base metal to form the weld. The molten weld metal is protected from the atmosphere by a gas shield that is fed through a conduit to the tip of the welding gun. The process may be semiautomatic or automatic. It cannot be used in a windy environment because the loss of the shielding gas from air flow will produce porosity in the weld. **As such, MDOT does not allow GMAW in the field.**

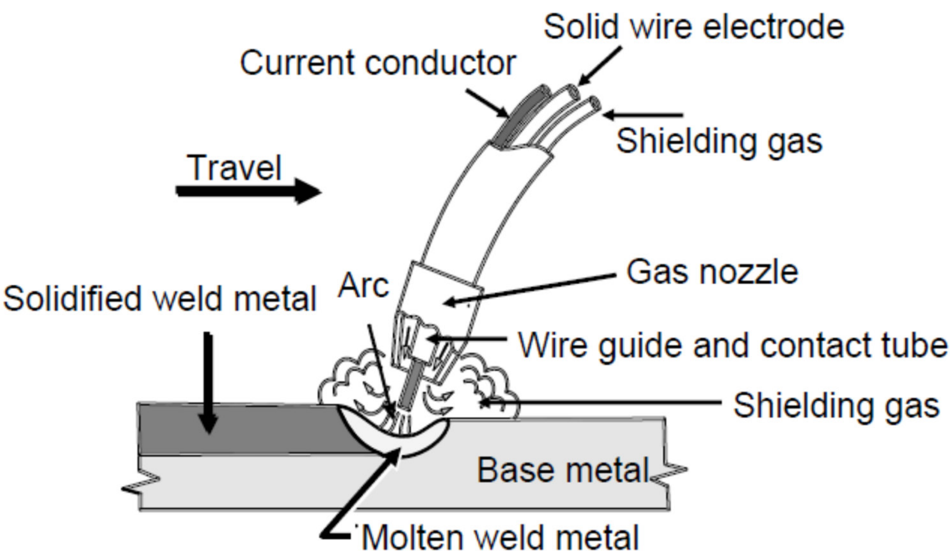


Figure 3: Gas Metal Arc Welding (GMAW).

Flux Cored Arc Welding (FCAW)

Flux Cored Arc Welding (FCAW) is similar to the GMAW process and is usually performed by semi/fully automatic methods. The difference is the filler wire has a center core that contains flux (see Figure 4). With this process, it is possible to weld with or without a shielding gas, which makes it useful for exposed conditions where a shielding gas may be affected by the wind.

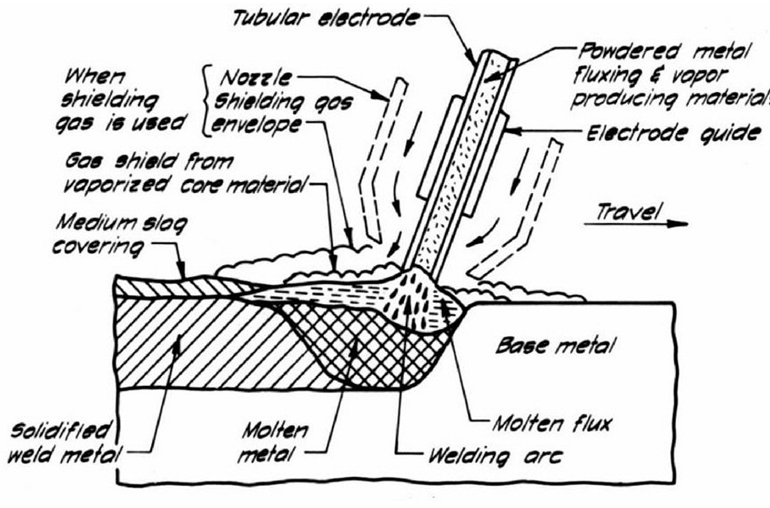


Figure 4: Flux Cored Arc Welding (FCAW).

Submerged Arc Welding (SAW)

Submerged Arc Welding (SAW) is usually performed by semi/fully automatic or handheld methods. As shown in Figure 5, it uses a continuously fed filler metal electrode. The weld pool is protected from the surrounding atmosphere by a blanket of granular flux fed at the welding gun. It results in a deeper weld penetration than the other processes. **However, only flat or horizontal positions may be used.**

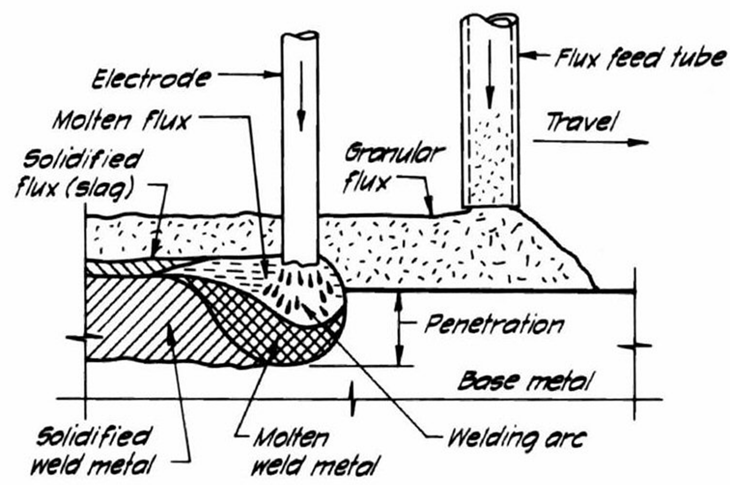


Figure 5: Submerged Arc Welding (SAW).

Process Selection

Selection of the welding process is typically left to the contractor. The characteristics of the various processes are:

- SAW: long, big, semi/fully automatic, or handheld methods.
- FCAW: semi/fully automatic methods.
- SMAW: small, miscellaneous, repair, tack welds, and handheld methods.
- GMAW: semi/fully automatic methods in shop.

Field welding is not permitted by MDOT unless otherwise shown on the plans or approved by the engineer. MDOT permits structural field welding by the SMAW process using E7018 low hydrogen electrodes for low carbon and high strength, low alloy steels provided the filler metal matches the base metal strength.

Welded Structural Connections

A welded structural connection transmits loads between members. Members are attached to the connection using welded joints, which transmit loads between the members and the connection. Figure 6 shows a connection where multiple members are connected through gusset plates.

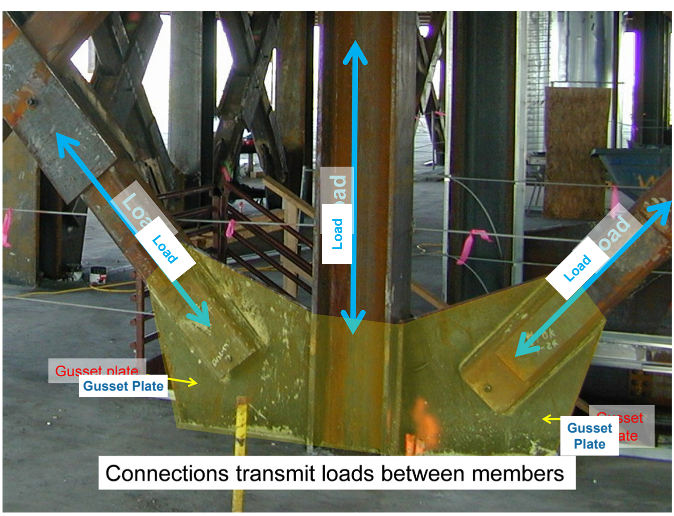


Figure 6: Welded connection.

Joint Types

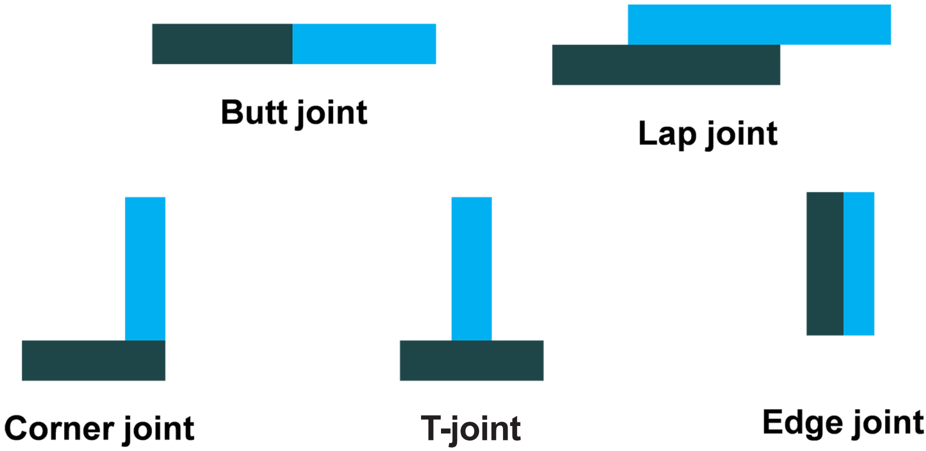


Figure 7. Various types of joints.

Weld Types

There are several types of welds. The most important are groove welds and fillet welds.

Groove Welds

As shown in Figure 8, groove welds can be complete joint penetration (CJP), also called full penetration or full pen welds, or partial joint penetration (PJP), also called partial penetration or partial pen welds. Each groove weld type can have many possible configurations.

Preparation is needed because the welding process typically cannot penetrate the necessary depth of fusion. As shown in Figure 8, a variety of preparations are possible. Sections with thickness up to 3/8 inches can be square edge prepared using prequalified welding procedure specification (WPS) as permitted by AWS.

In general:

- V- and bevel groove preparations are easiest.
- U- and J groove preparations are more costly because they require machining or air arc gouging.

All preparations yield equal strength (because they have the same effective throat).

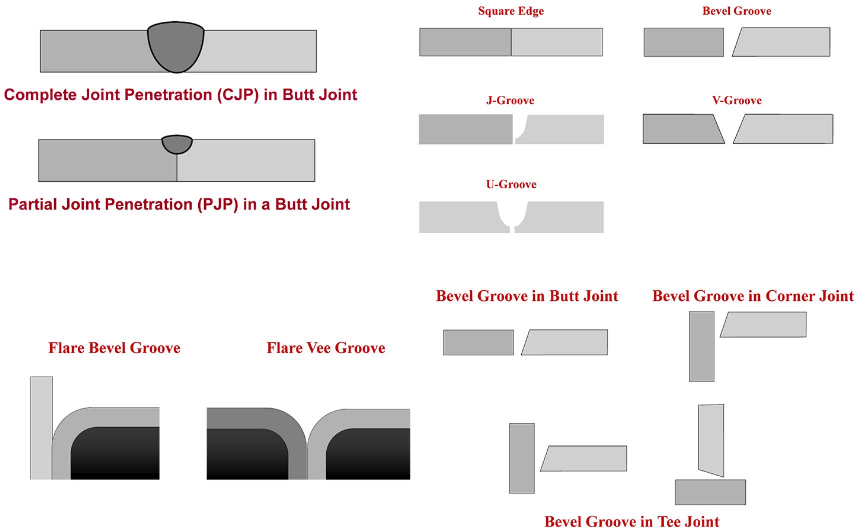


Figure 8: Types of groove welds.

Terminology for Groove Welds

Figure 9 shows commonly used terminology for groove welds.

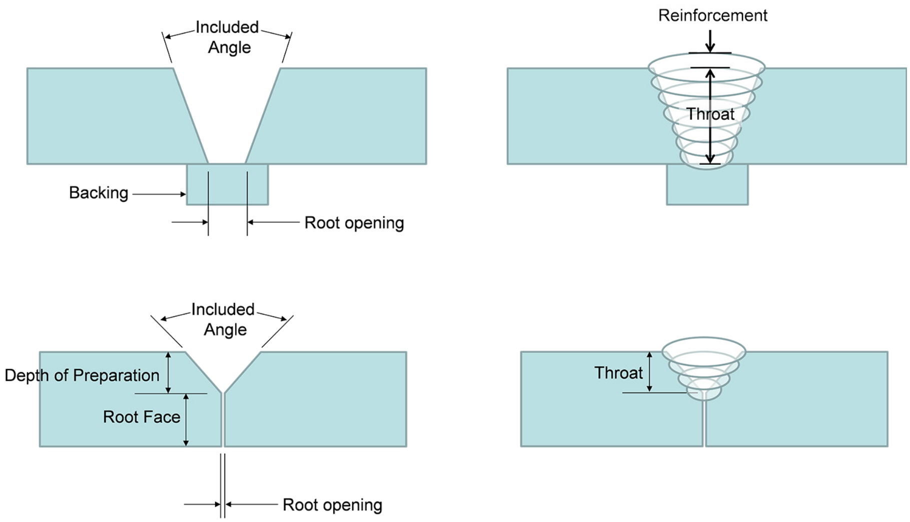


Figure 9: Terminology used for groove welds.

Complete Joint Penetration (CJP) Groove Weld

Single- versus Double-Sided

Single-sided CJP welds require backing. Without backing, WPS qualification is needed to ensure the full throat is developed.

Double-sided CJP welds require back gouging. Without back gouging, WPS qualification is needed to ensure the full throat is developed. Selection is based on:

- Access.
- Distortion control.
- Economy.

Back Gouging

Back gouging is the removal of weld and base metal by arc gouging or grinding from the other side of a partially welded joint to ensure complete fusion and penetration upon subsequent welding from that side (Figure 10).

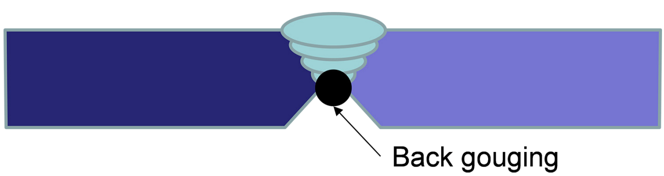


Figure 10: Back gouging.

Heat-Affected Zone

As shown in Figure 11, the heat-affected zone (HAZ) is the area of base material that has not melted and has had its microstructure and properties altered by welding.

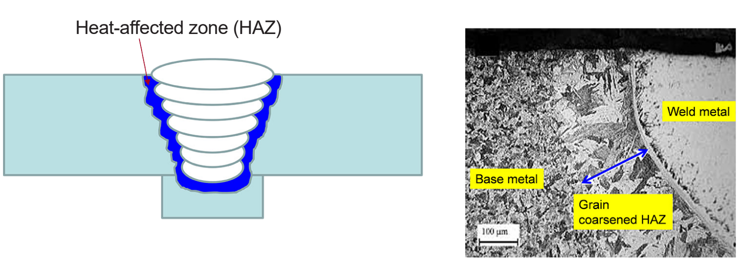


Figure 11: Heat-affected zone.

Backing

Backing is defined as material placed at the root of a weld joint for the purpose of supporting molten weld metal [Figure 12 (a)]. Its function is to facilitate complete joint penetration. Weld backing can be steel, copper, or ceramic.

Steel backing on welds transverse to the stress direction should be removed and the joint ground flat. Otherwise, the weld could be prone to cracking as shown in Figure 12 (b).

Backing has a recommended minimum thickness to prevent melt-through. For example, it is 3/16 inches for SMAW. Table 1 shows the minimum thicknesses for other processes.

The maximum gap between backing and base metal is 1/16 inch. If there is a gap, it will affect weld quality, ultrasonic testing (UT) inspection results, and could increase repair and testing costs.

Approval of the engineer is needed if non base metal backing is used.

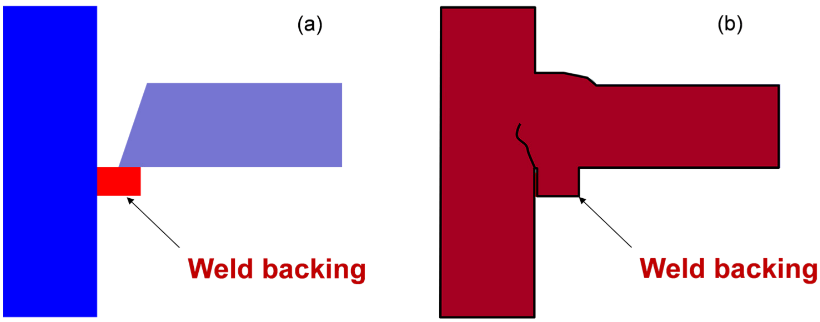


Figure 12: Weld backing.

Table 1: Minimum thickness for steel backing.

Steel Backing Minimum Thickness	
Process	**Minimum Nominal Thickness (inches)**
SMAW	3/16
GMAW	1/4
FCAW-S	1/4
FCAW-G	3/8
SAW	3/8

Partial Joint Penetration (PJP) Groove Welds

PJP groove welds may be used in butt, T- and corner joints. They also can be used for column splices (butt joint in compression) or corner joints of built-up box columns. The throat dimension is less than the thickness of the material and the weld may or may not develop the full capacity of attached material. AWS D1.5 provides prequalified details and prohibitions for this type of weld.

PJP Effective Weld Size

Figure 13 below shows the effective weld size for PJP groove welds.

$E = S + 1/8$ in.

- For groove angle > 45º and < 60º
  - SMAW
  - SAW
  - GMAW (vertical or overhead)
  - FCAW (vertical or overhead)

$E = S$

- For groove angle > 45º
  - GMAW (flat or horizontal)
  - FCAW (flat or horizontal)
- For groove angle > 60º
  - SMAW, SAW, GMAW, FCAW, EGW, ESW

Figure 13: Effective weld size for PJP groove weld.

Weld Size

The minimum effective weld size is a function of the thickness of the thicker connected member. It is based on weld related concerns (not strength), specifically fusion and cracking. A minimum amount of energy also needs to be introduced into the joint (i.e., the weld size correlates with heat input). Table 2 shows the PJP minimum weld size with respect to part thickness.

Table 2. PJP minimum weld size from Table 707-3 of the MDOT SSC.

Thickness of Thicker Part, T (inches)	Minimum Effective Weld Size, E (inches)
T ≤ 3/4	1/4
T > 3/4 – 1 1/2	5/16
T > 1 1/2 – 2 1/4	3/8
T > 2 1/4 – 6	1/2
T > 6	5/8

PJP Considerations

The cross-section of the joint is not fully fused, which can create stress risers.

Single-sided PJP: Check to ensure that no rotation occurs about the root of the joint. Diaphragms, stiffeners, and proper joint configurations can prevent rotation.

Double sided PJP: Requires less weld metal. Typically, more advantageous for controlling distortion. The sealed joint also prevents ingress of water and other corrosion causing substances in the gap between welded components.

Flare groove joints must not be used to join structural steel in bridges.

Fillet Welds

Figure 14 shows commonly used terminology for fillet welds.

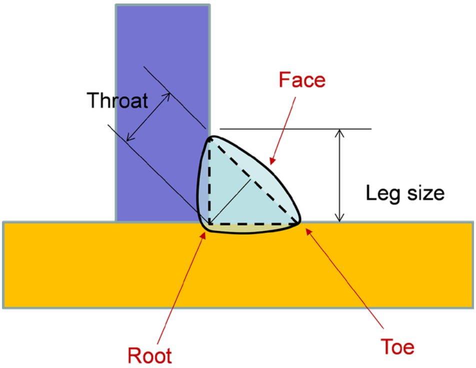


Figure 14: Fillet weld terminology.

Minimum Fillet Weld Size

The minimum size is a function of the thickness of the thicker connected part. The minimum fillet weld size need not exceed the thickness of the thinner connected part (Table 3).

Table 3. Minimum fillet weld size for single pass welds from Table 707-2 of the MDOT SSC.

Thickness of Thicker Part, T (inches)	Minimum Weld Size (inches)
T ≤ 3/4	1/4
T > 3/4 – 1 1/2	5/16
T > 1 1/2 – 2 1/4	3/8
T > 2 1/4 – 6	1/2
T > 6	5/8

Maximum Fillet Weld Size

A maximum size is imposed to avoid melting the top edge of the member (reduced weld throat). It only applies to welds made along edges (lap joints and some corner joints). Table 4 shows this limit.

Table 4. Maximum fillet weld size from AWS.

Thickness of Base Metal, T (inches)	Max Weld Size, E (inches)
T < 1/4	T
T > 3/4	T – 1/16

End Returns (Boxing)

Boxing is the continuation of a fillet weld around the corner of a member (Figure 15). It ensures quality terminations to welds, provides some prying resistance, and seals the weld.

It must be used when supporting a tensile force that is not parallel to the axis of the weld. The return length is indicated on design and detail drawings.

Figure 15: End returns in fillet welding.

Fillet Weld Termination

It is good practice to stop fillet welds short of the ends of the joint. It prevents undercut, improves weld quality, and creates no reduction in weld length for start or end crater. Welds on opposite sides of a common plane must be continuous and corners ground to eliminate notches greater than 0.01 inch. These welds provide smooth transition to weld metal after grinding.

Fillet Weld Considerations

Connected elements in a T joint should be brought in as close to contact as possible before joined with fillet welds. The increase in gap leads to a decrease in throat and is not apparent visually. If the gap is greater than 1/16 inch, increase the fillet weld size by the size of the gap and limit it to a 3/16 inches gap for connection elements less than 3 inches thick and a 5/16 inches gap for connection elements greater than 3 inches thick.

Plug and Slot Welds

Figure 16 shows plug and slot welds. They are applied to lap joints (center area of doubler plates). They transfer load by shear or prevent buckling of lapped parts. These types of welds require uniform fusion to the root of the joint. The depth of filling is the thickness of the plate if the plate is less than 5/8 inches and half the thickness of the plate if the plate is greater than 5/8 inches.

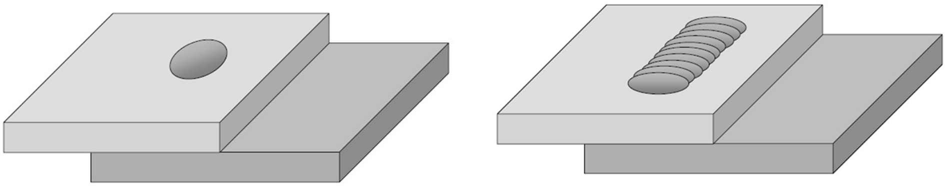


Figure 16: Plug and slot welds.

Plug and Slot Weld Considerations

Use SMAW, GMAW, or FCAW weld processes. The minimum hole diameter (or slot width) is at least 5/16 inches greater than the part thickness.

The maximum hole diameter (or slot width) is the greater of the minimum diameter plus 1/8 inch or 2.25 times the part thickness.

The slot length should not exceed 10 times the part thickness and the end of the slot must be semicircular.

Center-to-center spacing (plug welds):

- Minimum: Four times the diameter of hole.
- Maximum: Minimum spacing plus 1/2 inches.

Center-to-center spacing (slot welds):

- Transverse minimum: Four times the slot width.
- Longitudinal minimum: Two times the slot length.

General Weld Considerations and Terminology

Weld Tabs

Weld tabs (extension bars and run-off plates) ensure that welds are started and terminated in a sound manner (Figure 17). They are auxiliary pieces of material that extend beyond the end of the joint and are aligned as a continuation of the basic joint geometry (parallel to weld axis).

All approved base metal [including AASHTO M 270 (ASTM A 709) Grade 36 structural steel, AASHTO M 270 Grade 50 high-strength structural steel, or steel grades approved by the engineer] can be used for weld tabs, excluding 100 ksi steel with lower strength base metal.

They should be at least as long as the thickness (throat) of the groove weld and must be removed after completion of the weld. The end of the welds must be smooth and flush with the edge of the abutting part after the tabs are removed.

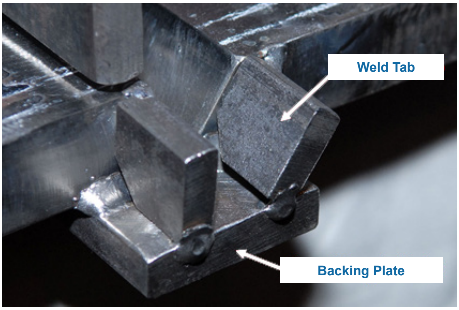


Figure 17: Weld tabs prior to welding.
(***http://awssection.org/syracuse/photo_large/january_19_2011***)

Weld Access Holes

Weld access holes permit access for welding or insertion of backing. They must be large enough to permit the welder to see the weld pool and allow the weld to be cleaned and visually inspected between weld passes.

Access holes must be properly sized with smooth surfaces (free of notches or gouges). Improper holes can lead to fatigue cracking.

Filler Metal Strength

The filler metal may be undermatched, matched or overmatched with the base metal.

The matching is determined as a function of tensile strength, not yield strength. Filler metal yield strength is typically larger than base metal and therefore encourages yielding in base metal (desirable).

When connecting different strength steels, consider lower strength base metal. Almost all filler metals have a specified tensile strength of 70 ksi.

Filler Metal Considerations

Never require overmatched filler metal.

For matched filler metal, select electrode or electrode/flux combination from AWS D1.5.

For undermatched filler metal, under match by up to 10 ksi.

Welds and Bolts in Same Connection

Welds in combination with bolts do not share load. Welds are stiffer and carry the load first. Therefore, design connection so welds can carry the entire load. Bolts used for assembly may be left in place (unless otherwise specified). The engineer will specify if holes are to be filled if assembly bolts are to be removed.

Filler Plates

Filler plates (also known as fillers, joint fillers, or fill plates) are permitted when splicing parts of different thicknesses and in connections that accommodate offsets to allow for simple framing.

They should be avoided when joining tension members and members subject to reversal of stress, specifically Fatigue Category E.

For filler plates less than 1/4-inch thick (Figure 18):

- Must not transfer stress.
- Keep flush with welded edges of stress carrying part.
- Increase required weld size along edge by the thickness of the filler plate.

For filler plates greater than or equal to 1/4-inch thick (Figure 18):

- Extend beyond edge of splice plate or connected material.
- Weld to part on which fitted.
- Joint has enough strength to transmit load as an eccentric load.
- Welds must be sufficient to transmit stresses.
- Weld must be long enough not to overstress filler plate at the toe of the weld.

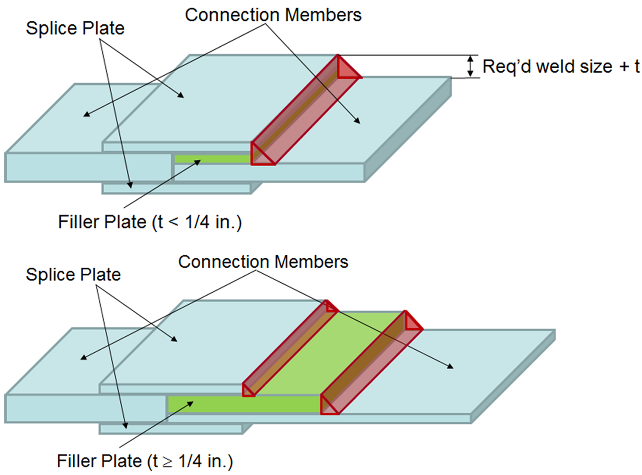


Figure 18: Filler plates.

Prohibited Joint Types and Welds

The following joint types are prohibited:

- PJP welds in butt joints, except connections or splices in compression that are bearing and full-milled.
- CJP welds made from one side without backing (or with unqualified backing) under tension and load reversal.
- Intermittent groove welds.
- Intermittent fillet welds not approved by the engineer.
- Flat position bevel- and J-groove welds in butt joints.
- Plug or slot welds in members subject to tension and load reversal.

Hydrogen Embrittlement

Hydrogen embrittlement is the process by which metals (such as steel) become brittle and fracture due to the introduction and subsequent diffusion of hydrogen into the metal. This is often a result of accidental introduction of hydrogen during forming and finishing operations. In arc welding, hydrogen is released from moisture, such as in the coating of welding electrodes. To minimize this, special low-hydrogen electrodes are used for welding.

MDOT Requirements for Electrodes

- Dry electrodes in an oven at a temperature of at least 500 F for at least two hours before use unless they come from a hermetically sealed container.
- Store the electrodes at a temperature of at least 250 F after drying. Use E70XX electrodes within two hours of exposure to the atmosphere, or re-dry.
- Do not re-dry electrodes more than once. Do not use electrodes that have been wet.

Why all these restrictions? Because welding can strip hydrogen from water, which causes hydrogen embrittlement.

Also note that **field welding is not permitted if the ambient air temperature falls below 40 F or during periods of precipitation**, unless heating and housing the weld area as approved by the engineer (MDOT SSC).

Discontinuities

All welds contain discontinuities and irregularities in the material due to a lack of homogeneity in mechanical, metallurgical, or physical characteristics. These discontinuities may or may not be acceptable, except for cracks, which are considered defects and are not acceptable. Figure 19 lists the types of discontinuities that can be present provided the acceptance criteria of AWS are met.

Planar (2-D)

- Cracks
(Not Acceptable – AWS D1.1.)
- Tears
- Incomplete Fusion
- Inadequate Joint Penetration
- Overlap
- Fins, Scabs, Seams and Laps
- Lamination and Delamination

Volumetric (3-D)

- Undercut
- Porosity
- Slag Inclusions
- Excessive Concavity
- Excessive Convexity
- Inadequate Weld Size
- Underfilled Weld Craters

Figure 19. Types of weld discontinuities.

Planar Discontinuities

Planar discontinuities are two dimensional imperfections that can provide initiation points for fracture. They result from the following (see Figure 20):

1. Incomplete fusion
   - A. Molten weld metal does not fuse with base metal or previous passes.
   - B. Can result from:
     - i. Excessive mill scale.
     - ii. Improper electrode position.
     - iii. Incorrect welding parameters.
2. Inadequate joint penetration:
   - A. Weld metal does not fully reach prescribed depth.
   - B. Can result from:
     - i. Improper back gouging.
     - ii. Incorrect electrode position or weld procedures.
     - iii. Poorly prepared joints.
3. Overlap:
   - A. Occurs on the surface of the base metal.
   - B. Excess weld metal that is not fused.
   - C. Can result from:
     - i. Thick mill scale.
     - ii. Slow travel speeds.
4. Fins, scabs, seams, and laps:
   - A. Discontinuities on surface of base metal.
   - B. Typically mill induced.
   - C. May open due to thermal cutting, preheating, or welding.
5. Lamination and delamination:
   - A. Base metal discontinuities parallel to surface.
   - B. Often occur mid-thickness.

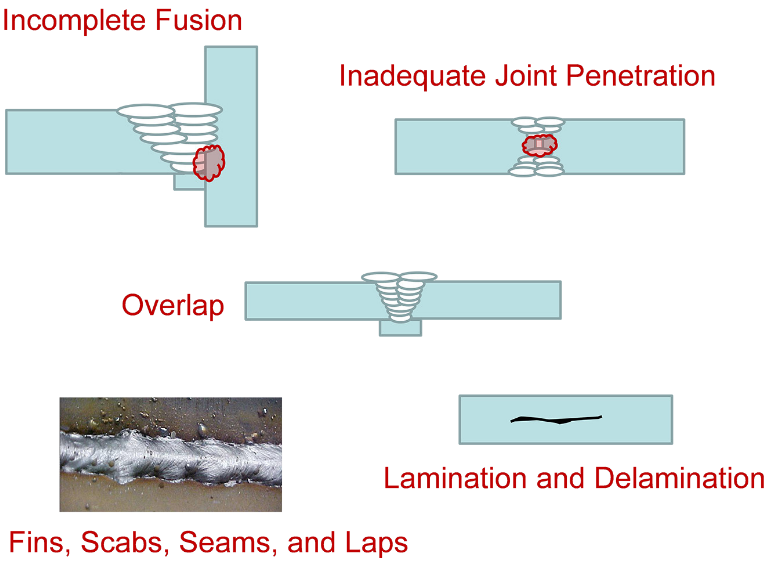


Figure 20: Types of planar discontinuities.

Volumetric Discontinuities

Volumetric discontinuities are three-dimensional imperfections in and around the weld. They result from the following (see Figure 21):

1. Undercut:
    - A. Small cavity melted into the base metal.
    - B. Can result from:
        - i. Improper electrode position.
        - ii. High arc voltage.
        - iii. Incorrect welding consumables.
2. Porosity:
    - A. Spherical or cylindrical cavities in the weld metal.
    - B. Due to gasses dissolved in the liquid weld metal.
    - C. Can result from:
        - i. Inadequate shielding.
        - ii. Excessive contamination of joint.

3. Slag inclusion:
    A. Non-metallic materials.
    B. Within weld metal or between base metal and weld metal.
    C. Can result from:
        i. Slag from previous weld pass not being removed completely.

4. Excessive concavity:
    A. Weld surface is concave.
    B. Reduced throat.
    C. Can result from:
        i. Low currents or voltages.
        ii. Improper weld procedures.

5. Excessive convexity:
    A. Weld surface exceeds acceptable limits.
    B. Typically associated with weld procedure problems.

6. Inadequate weld size:
    A. Weld too short or small.
    B. Also known as an undersized weld.
    C. Can result from:
        i. Procedural problems.
        ii. Too high travel speed.

7. Underfilled weld crater:
    A. Concave depressions at the end of weld.
    B. Localized reduction in weld throat.
    C. Typically associated with welder technique.

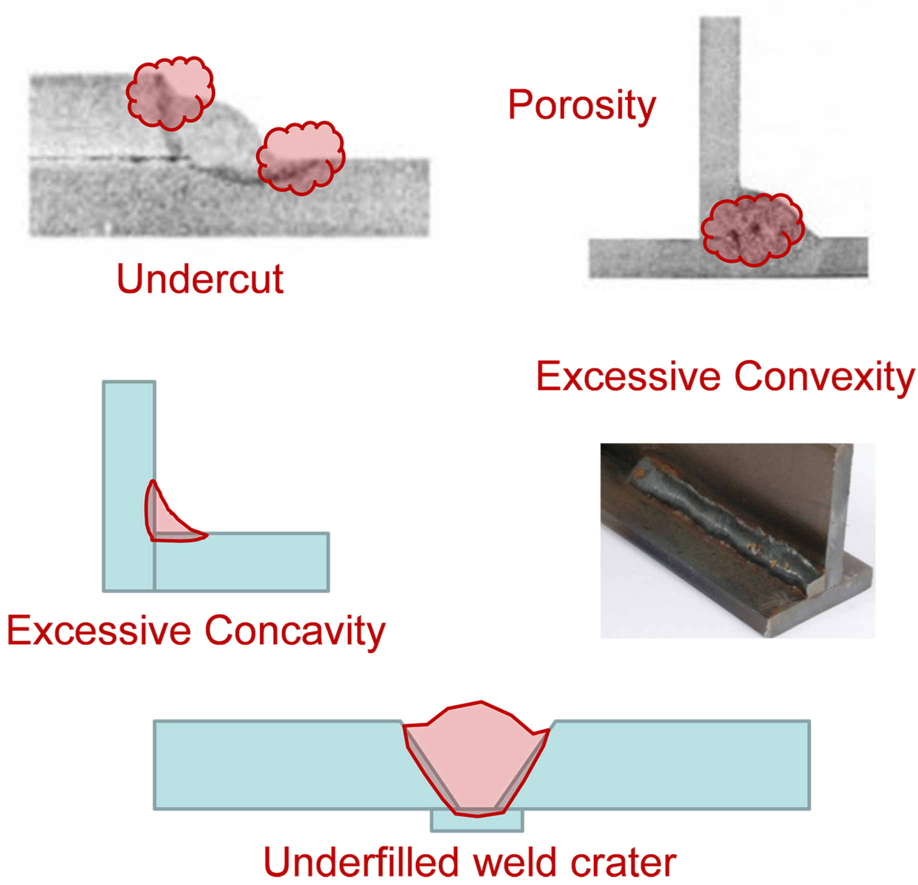


Figure 21: Types of volumetric discontinuities.

Special Considerations for Lap Joints

Avoid Fatigue Category E in members subject to tension and stress reversal.

Longitudinal fillet welds can only be used. The length must be at least the perpendicular distance between the welds, and transverse spacing must not exceed 16 times the thickness of the thinner connected part. The welds can be applied either at the edge of the members or in slots.

The minimum overlap of parts must be at least five times the thickness of the thinner connected part. At least two transverse lines or two or more longitudinal welds must be used to prevent unacceptable rotation.

Special Considerations for Butt Joints

Special requirements are needed for transition of different plate widths or thicknesses.

1. If subjected to tension or compression (unequal thickness):
    - A. Smooth transition between offset surfaces.
    - B. Slope of no more than one transverse to two-and-a-half longitudinal with the surface of either part:
    - i. Slope weld surfaces.
    - ii. Chamfer thicker part.
    - iii. Combination of both.
2. If subjected to shear (unequal thickness):
    - A. Same as tension or compression requirement when offset is greater than the thickness of the thinner part.
    - B. Offset less than or equal to the thickness of the thinner part:
        - i. Sloped no more than one transverse to two-and-a-half longitudinal from surface of thinner part.
        - ii. Or sloped to the surface of thicker part if less of a slope.
3. If subjected to tension (unequal width):
    - A. Smooth transition between offset surfaces.
    - B. Slope of no more than one transverse to two-and-a-half longitudinal with the surface of either part.
    - C. Or transitioned with 24 inches minimum radius tangent to the narrower part at the center of the butt joint.

Special Considerations for T-Joints

Special consideration needed for joints where T joint does not intersect at 90 degrees.

For the acute side of the joint (Figure 22) where there is a small dihedral angle, there is a possibility for incomplete fusion to the weld root (reduced throat).

For the obtuse side of the joint (Figure 22) where there is a large dihedral angle, the fillet weld throat is disproportionately small compared to the weld size.

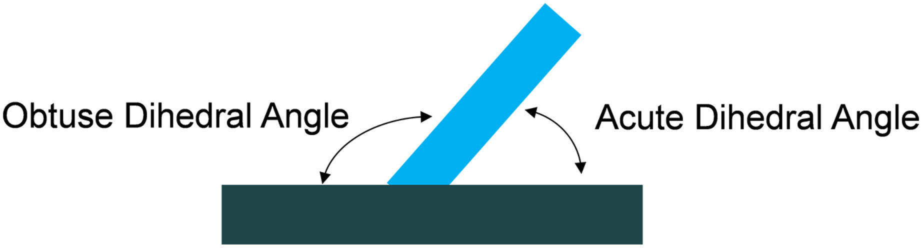


Figure 22: Special considerations for T-joint.

Special Considerations for Corner Joints

Access for welding corners of box sections must be considered. This may eliminate two sided welds. The environmental conditions for the welder must also be considered. Laminar tearing requirements must be considered when welds are large.

Weld Cracking

Types of Weld Cracking

Hot cracking occurs when the weld is hot. It is associated with solidification. It is usually manifested as centerline cracking (Figure 23).

Cold cracking occurs when the weld has cooled. It is typically hydrogen-related. Cold cracking usually occurs in the heat affected zone or is transverse (Figure 23).

All cracks are driven by shrinkage and restraint of this shrinkage.

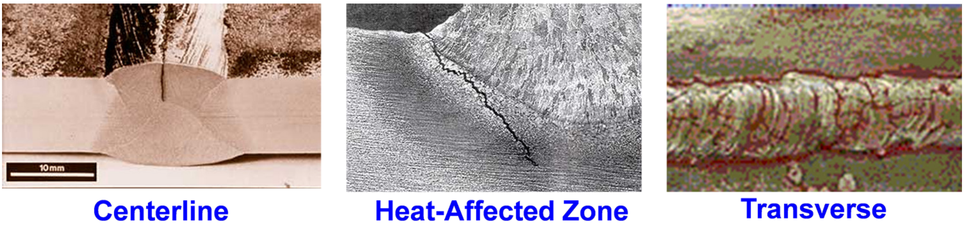


Figure 23: Types of weld cracking.

Shrinkage and Restraint

Weld metal and surrounding base metal expand during welding due to heating. These hot materials contract upon cooling. If materials are restrained from shrinking, then stresses will develop.

Colder base material resists contraction of the cooling hotter material. Resistance depends on the volume and strength of the colder material. Stiffness of the colder material is associated with its geometric configuration. Temperature also affects the elastic modulus of the material, which directly affects the stiffness.

Base metal thickness greater than 1.5 inches with yield strengths greater than 50 ksi lead to higher shrinkage stresses.

Members intersecting from all three geometric directions lead to higher constraint.

Practices to Reduce Shrinkage Stresses

1. Minimize weld material needed:
    - A. Specify smallest weld possible.
    - B. Use weld details that require least amount of weld metal.
    - C. Control fit-up and minimize gaps.
    - D. Do not over weld.
    - E. Limit weld reinforcement.
    - F. Limit back gouging to only what is necessary.
2. Weld in fewest number of passes (larger weld beads).
3. Use lowest strength filler metal possible.
4. Limit weld penetration.
5. Complete highly restrained weldments without interruption:
    - A. Around-the-clock welding.
    - B. Or maintain assembly at welding temperatures.
6. Only weld assembly once (requires proper planning).

Practices to Reduce Restraint

1. Fabricate small assemblies when possible.
2. Weld components with expected greatest shrinkage first.
3. Weld most rigid components first.
4. Sequence welding so shrinkage movement in parts is all toward a relatively fixed location.
5. Balance shrinkage on opposite sides.
6. Provide small gaps to help accommodate shrinkage.
7. Increase preheat and volume of preheated materials.
8. Preset members before welding and allow to move during welding.

Centerline Cracking

Segregation-Induced Cracking

Occurs when low-melting point constituents separate during weld solidification (Figure 24). The enriched liquid material at the middle of the weld solidifies last. This is of concern when steel has higher levels of sulfur, phosphorus, lead, or copper. To reduce the chance for this type of cracking, limit amount of contaminant pickup by:

- Controlling base metal composition.
- Limiting weld penetration (lower weld currents or change polarity).
- Providing buttering layer.

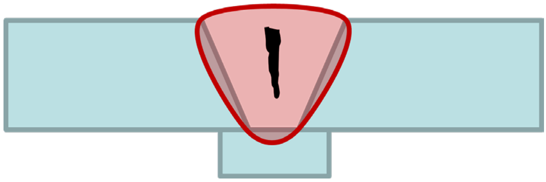


Figure 24: Centerline cracking.

Bead Shape-Induced Cracking

Bead shape-induced cracking is associated with deep penetrating weld processes such as SAW and Gas Shielded FCAW. It occurs when the depth of the weld bead is greater than the width. Therefore, it is recommended the width-to-depth ratio of the bead be between 1:1 and 1.4:1. Joint design is important to prevent this type of cracking and the following must be observed:

- AWS prequalified joints have proper root openings and included angles.
- For PJP welds made by SAW, 60 degree included angles are preferred.
- Fillet welds typically not a problem unless they have a skewed joint.

Surface Profile-Induced Cracking

Surface profile-induced cracking is associated with the surface profile of the weld bead (Figure 25). Convex profile induces compression internal shrinkage forces, while concave induces tension internal shrinkage forces. Concave weld surfaces occur with high arc voltages and vertical down welding. Avoid a concave surface profile with a slight decrease in arc voltage. Use vertical up welding instead of vertical down and change shielding gas for GMAW and FCAW-G.

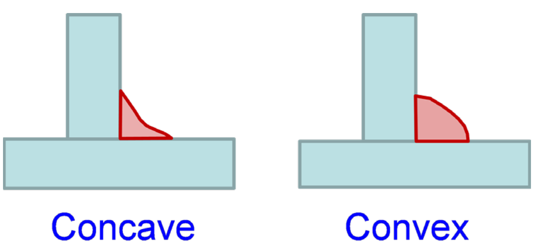


Figure 25: Weld surface profile.

Heat-Affected Zone (HAZ) Cracking

Heat-affected zone cracking is cracking in the base metal adjacent to the weld bead. It cannot form when the steel is hot (above 300 F). It typically occurs 16 to 72 hours after cooling. Hydrogen diffuses in the steel during this period and excessive quantities of hydrogen can accumulate leading to cracking. See Hydrogen Embrittlement section for additional details.

To reduce the chance for this type of cracking, do not introduce hydrogen-bearing compounds. Ensure the following:

- Dry electrodes in an oven at a temperature of at least 500 F for at least two hours before use.
- Store the electrodes at a temperature of at least 250 F after drying. Use electrodes within two hours (or less as required per the project specifications) of exposure to the atmosphere or redry.
- Do not redry electrodes more than once. Do not use electrodes that have been wet.
- Heat weld area to between 400 and 450 F for an hour for each inch of weld thickness (post-heat); must not have reached room temperature.
- Use approved base metal (AASHTO M 270 Gr. 36; AASHTO M 270 Gr. 50; other steels approved by the engineer).
- Follow proper preheat and interpass temperature guidelines.
- Reduce residual stresses.

Transverse Cracking

The controlling factors are the same as HAZ cracking:

- Excessive hydrogen, where multi-pass welds inhibit hydrogen release. In this case, thinner weld beads may help hydrogen diffuse faster.
- Susceptible microstructure. In overmatched welds, the weld metal becomes the susceptible material.
- Stress due to longitudinal shrinkage of the weld.

Limiting Transverse Cracking

1. Use undermatched welds:

    A. Ensure weld strength is adequate for anticipated loads.

    B. Alloy pick-up may cause higher weld metal strength even for lower-strength electrodes.

    C. Often used for PJP groove welds and fillet welds.

2. Increase preheat:

A. Assists in diffusing hydrogen.

B. Weld metal and joint also can contract simultaneously.

3. Post-heat treatment.

Lamellar Tearing

Lamellar tearing is caused by weld shrinkage strains perpendicular to the planes of the base metal outside the HAZ (Figure 26). It is associated with flattened discontinuities and inclusions in the base metal. It typically occurs well after the weld has solidified and cooled. Steels with lower sulfur levels and proper joint design can limit lamellar tearing. Figure 26 shows a weld detail that reduces the chance for this type of cracking.

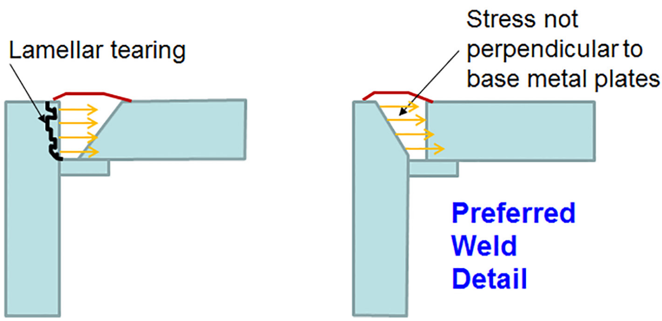


Figure 26. Lamellar tearing (orange arrows represent stress direction).

Distortion

Distortion is geometric deviation in the steel after welding (Figure 27). It causes problems for assembly, a reduction in buckling strength, and does not look good.

Distortion is caused by a number of factors:

1. Non-uniform heating:

A. Inherent in the arc welding process.

B. Localized heating of the steel.

2. Have same constrained expansion and contraction that causes cracking:

A. Rigid surrounding material leads to cracking.

B. Flexible surrounding material leads to distortion.

C. More flexible systems are susceptible to distortion.

3. Distortion can be controlled by using more rigid parts. However, control measures do increase the tendency for cracking:

A. Thicker members.

B. External restraints.

Figure 27: Distortion in welded components.

Angular Distortion

Angular distortion (Figure 28) occurs due to transverse shrinkage of the weld. It can be caused by any type of weld and can occur in any type of joint. Its effects can be offset with two sided welding (may require uneven welds).

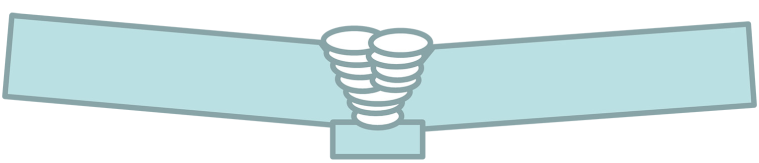


Figure 28: Angular distortion.

Transverse Shrinkage

Transverse shrinkage occurs due to transverse shrinkage of the weld (Figure 29). Its effects are directly related to volume of shrinking weld metal, and it occurs when the ends are free to move. This type of distortion is typically negligible.

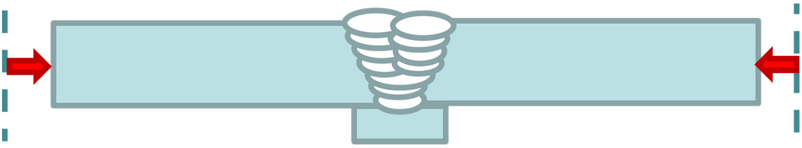


Figure 29: Transverse shrinkage.

Longitudinal Shortening

Longitudinal shortening occurs due to longitudinal shrinkage of the weld (Figure 30). The assembly generally shortens. It may also result in twisting, longitudinal sweep or camber, or buckling and warping. It is typically negligible, except with very long members such as long plate girders. In such cases, fabricate the girder longer than needed and cut to length.

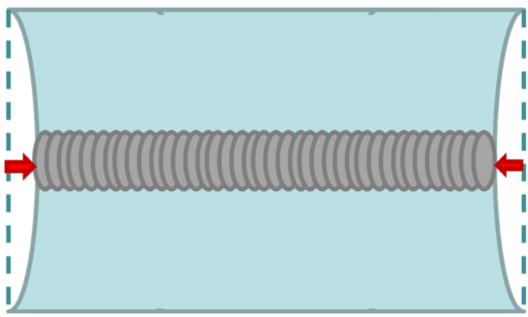


Figure 30: Longitudinal shrinkage.

Twisting

Twisting occurs due to longitudinal shrinkage of the weld. It results when the weld region shrinks but the outside steel does not. It is often seen with open sections with little torsional rigidity and may occur in deep plate girders with thin webs. It can be countered by increasing the torsional rigidity of the member (i.e., use closed sections).

Longitudinal Sweep or Camber

Longitudinal sweep or camber occur due to longitudinal shrinkage of the weld. Curvature occurs over the length of the part along the longitudinal axis. The center of gravity of the weld group in relationship with the neutral axis of the section dictates the direction of curvature.

Buckling and Warping

Buckling and warping occur due to longitudinal shrinkage of the weld when the base metal surrounding the weld is thin. Buckling can occur in the web of plate girders between stiffeners, while warping is common if there is a free edge.

These issues are often seen in open sections with little torsional rigidity. Their extent depends on the critical buckling stress of the section and can be countered by increasing the thickness and/or decreasing the length of the welded components.

Rotational Distortion

Rotational distortion occurs due to the transverse shrinkage of the weld (Figure 31). It is prominent in thin members (sheet metal) and members that are narrow compared to their length. The joint either opens or closes depending on the speed of welding and heat input. Its effects can be mitigated by clamping or back stepping.

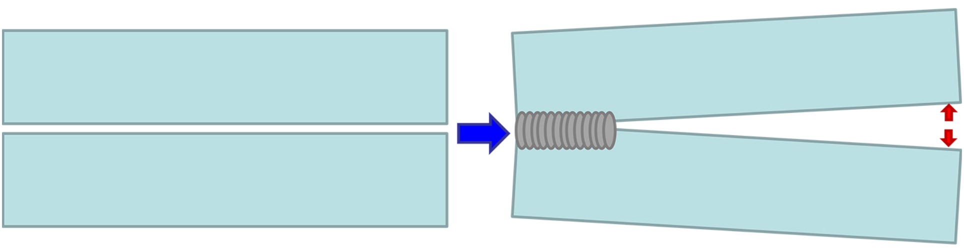


Figure 31: Rotational distortion.

General Distortion Control Measures

Many of the following measures also lead to economical joints and maximize productivity.

1. Minimize the volume of localized metal that expands during welding:
    - A. Minimize volume of weld metal.
    - B. Minimize volume of heated base metal around the weld.
    - C. Increase volume of base metal heated away from the weld.

2. Reduction measures:

   A. Specify smallest weld size possible.

   B. Use intermittent welds.

   C. Select details that minimize weld material.

   D. Make multi-pass welds with the fewest possible passes.

   E. Control fit-up.

   F. Limit weld reinforcement.

   G. Do not over weld.

   H. Limit back gouging to only required material.

   I. Limit weld penetration.

Specialized Distortion Control Measures

1. Add restraint:

   A. Keep part from moving when hot:

      i. Tack welds.

      ii. Welding fixtures.

   B. Will always have some elastic spring back.

2. Weld placement:

   A. Place welds on or near the neutral axis.

   B. Balance welds around the neutral axis.

3. Welding sequence:

   A. Minimize longitudinal weld sweep and camber with a properly planned weld pattern.

   B. Use subassemblies to weld closer to the neutral axis of each assembly.

AWS Distortion and Shrinkage Requirements

1. Balance applied heating as welding progresses.

2. Welding sequence and distortion control program must be submitted to the engineer prior to the start of welding.

3. Progress from points that are relatively fixed toward those that have greater freedom for movement.

4. Weld joints with greater expected shrinkage first with as little restraint as possible.

5. All shop splices in each component part of a cover plated beam or built up member must be made prior to the component part being welded to other component parts.

6. For cases of severe external shrinkage restraint, welding must be carried out continuously.

7. Distorted members must be straightened through:

    A. Mechanical means, or

    B. Through application of a limited amount of localized heat.

Allowable Dimensional Tolerances

Dimensions of welded structural members must comply with the tolerances set by the general specification governing the work.

AWS D1.5, Clause 5.5 provides special dimensional tolerances that must also be met in the presence of distortion.

Fatigue

Fatigue is cumulative damage caused by repeatedly applied cyclic loads. Fatigue is influenced by the following:

1. Stress range:

    A. Fatigue design is based on live load stress range.

    B. Difference between the minimum and maximum live load stress applied cyclically over time.

    C. Reduce loads or increase material available to resist loads.

2. Number of load cycles:

    A. Live load cycles between maximum and minimum stress.

    B. Typically, not addressed by the engineer.

3. Connection geometry:

A. Dictates the nature and extent of stress raisers.

B. Consider:

i. Type of weld.

ii. Weld orientation.

iii. Weld profile.

iv. Length of weld.

v. Weld reinforcement.

vi. Quality of weld.

C. All welded connections fall into a “Detail Category”:

i. Potential crack initiation point.

ii. Threshold fatigue stress range for infinite design life.

iii. From best to worst: A, B, B′, C, C′, D, E, E′.

Special Fabrication Requirements for Fatigue Resistance

Steel backing must be removed from the joint and the weld ground smooth.

Reinforcing or contouring fillet welds are required on top of PJP or CJP groove welds in T joint and corner joints:

- Minimum size greater than or equal to T1/4.
- T1 is the thickness of the member in which the groove weld is placed (need not exceed 3/8 inches).
- Minimum fillet weld size is 3/16 inches.

Weld tabs must be removed after completion of welding and cooling.

Tack welds and temporary welds:

- Subject to same quality requirements as final welds.
- If incorporated into final weld, then use electrode that meets final weld requirements.
- Tack welds not included in final weld must be removed in an appropriate manner.
- MDOT must approve tack welds that are not consumed by the root pass.

Miscellaneous attachments can cause unintended load paths.

Use notch tough weld metal (allows larger crack sizes prior to fracture).

Galvanized Steel

Galvanized steel pertains to electroplated sheet metal or hot dipped structural elements (Figure 32). Electroplated sheets typically do not pose a problem for welding, but proper ventilation is required.

Figure 32: Galvanized steel components.

Hot-Dipped Galvanized (HDG) Structural Elements

HDG structural elements have the potential for segregation cracking because zinc may enter the liquid metal. It may be difficult to detect these cracks. Factors affecting cracking of galvanized members include:

- Silicon content of weld metal.
- Degree of penetration of the weld beyond the root.
- Thickness of the base metal (affects restraint).
- Coating weight of zinc (coating thickness).
- Microstructure of zinc coating.

For fillet welds, the procedure qualification record (PQR) tests should be conducted considering the thickest zinc coating expected.

Groove welds are typically not a problem because of profiling of the joint (coating free).

All HDG must be removed since it is considered a contamination. Welding generally takes place prior to HDG. If not, it is recommended to remove the HDG coating at least 2 to 3 inches in all directions of the weld. Copper sulfate should be used to verify all zinc has been removed.

General Welding Requirements

MDOT requires welding to be conducted at an ambient temperature of 40 F and above. The size and length of welds must be no less than those specified. The location of welds and weld type must not be changed without approval of the engineer.

Base Metal Preparation

Base metal preparation ensures proper weld quality (no cracking or distortion) and minimizes objectionable fumes.

Surfaces and edges to be welded must be:

- Smooth.
- Uniform.
- Free from fins, tears, cracks, mill scale, pitting, irregularities, and other discontinuities.

Weld surfaces and adjacent surfaces must be free from loose or thick mill scale, slag, rust, moisture, grease, and other foreign materials. All edges must be conditioned by very shallow grinding to remove the hardened layer (martensite) left by re-solidification.

Edges of base metal must be inspected and repaired as early as feasible.

MDOT requires all weld repairs to be submitted in writing to the engineer and be approved prior to repairs taking place.

Re entrant corners of base metal cut edges must provide a smooth transition with a radius of not less than 1 inch unless the contract plans specify a larger radius due to fatigue.

Radii of beam copes and weld access holes also must provide a smooth transition between adjacent surfaces.

Joint and edge preparation can be done by:

- Machining.
- Thermal cutting.
- Air carbon arc cutting and gouging.
- Plasma arc gouging.
- Chipping and grinding.

Assembly

Fillet Welds

The assembly process is as follows:

1. Bring parts to be welded into as close contact as possible.

2. The maximum root opening is 3/16 inches (except for members 3 inches thick or greater).

3. If 3 inches thick or greater and cannot close root opening:

    A. The maximum root opening is 5/16 inches.

    B. Employ suitable backing.

4. Root openings greater than 1/16 inch require an increase in the leg of the fillet weld by the amount of the root opening (or demonstrate appropriate weld size).

Plug, Slot and Butt Joints

Faying surface separation must not exceed 1/16 inch.

Groove Welds

The assembly process is as follows:

1. Maintain zero (or as small as practical) root opening for PJP welds parallel to the member length (except for bearing joints). Otherwise, PJP welds have same requirements as fillet welds.

2. Carefully align parts joined by groove welds:

    A. Offset from theoretical alignment must not exceed 10 percent of the thickness of the thinner part joined.

    B. Maximum of 1/8 inch.

3. Correction of misalignment must not cause a slope greater than 1/2 inch over 12 inches measured at the part centerline.

The allowable groove weld root openings are shown in Table 5.

Table 5: Allowable groove weld root openings.

Location	Root Not Gouged (inches)	Root Gouged (inches)
Root Face of Joint	±1/16	No Limit
Root Opening of Joints Without Steel Backing	±1/16	+1/16 -1/8
Root Opening of Joints With Steel Backing	+1/4 -1/16	Not Applicable
Groove Angle of Joint	+10° -5°	+10° -5°

Peening

Peening improves the material properties of the metal's surface by inducing compressive stresses or relieving tensile stresses.

It must be approved by the engineer.

It is applied by mechanically striking the convex surface of intermediate weld beads using a specialized instrument, known as a ball peen hammer (see Figure 33).

The root and final passes should not be peened. However, the final passes can be peened with excess weld metal with approval by the engineer and peening marks must be removed by grinding.

Peening must be conducted when the weld is at 150 to 500 F. **MDOT does not permit peening.**

Figure 33: Ball-peen hammer.

Shop Welding

Highway structures are shop welded according to AWS D1.1, whereas bridges are shop welded according to AWS D1.5. Figure 34 shows a structure being prepared for shop welding. Shop welded main members include:

- Rolled beams.
- Cover plates.
- Flange and web plates.
- Link bars.
- End diaphragms.
- End diaphragm connection plates and stiffeners.
- Intermediate cross frames, connection plates and stiffeners (horizontally curved girders only).

For fabrication, design drawings are not to be used in lieu of shop drawings.

Figure 34: Structure being prepared for shop welding.

Requirements for Shop Welding

Qualification requirements:

- AWS welder, welding operator and tack welder qualification.
- MDOT Welder Qualification Program (WQP).
- Welding equipment.
- WPS.
- WPS qualification.

Welder must qualify for the welding process, welding position, material grade, and material thickness. Note that some positions, grades, and thicknesses qualify others.

MDOT WQP testing will be made under supervision of an MDOT representative.

Welding Procedure Specification (WPS)

A WPS is a document that describes weld procedures and is supported by a PQR. It provides direction to the welder or weld operator to ensure soundness and quality of the weld. It ensures repeatable and trusted welding techniques. It must be qualified unless using a prequalified weld detail (AWS D1.5, Clause 4). Essential variable changes or owner toughness requirements may result in a prequalified WPS requiring qualification testing.

A WPS shows that a weld prepared under the specified variables will have adequate properties and quality. It proves that standards regarding mechanical properties (strength, ductility, and toughness) can be met and ensures soundness.

The WPS qualification test uses a standard groove weld test (Figure 35) to determine mechanical properties and soundness of the weld through nondestructive and destructive testing.

MDOT requires all WPS to be qualified, except SMAW. MDOT recognizes prequalified WPS for AWS D1.1 welding. All WPS to be approved by MDOT's Structural Fabrication Unit.

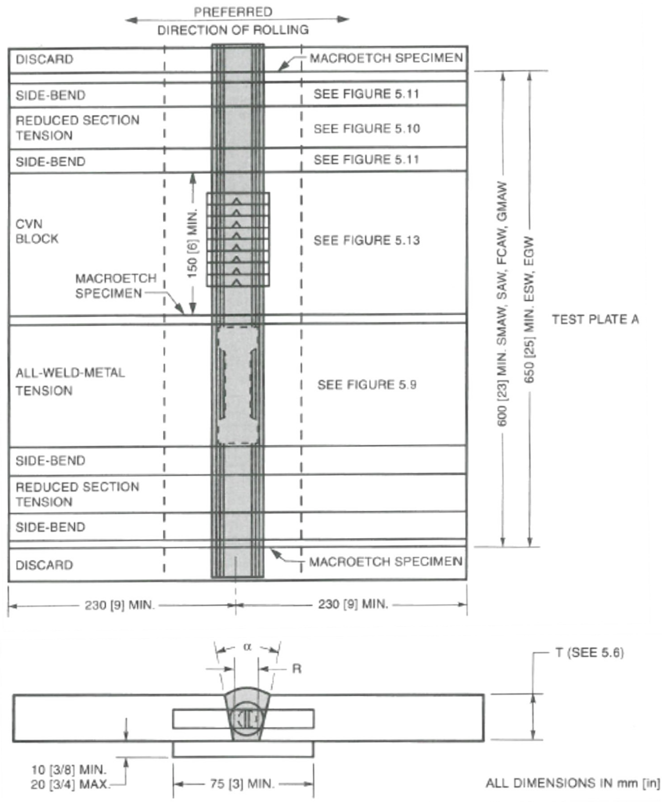


Figure 35: WPS qualification test plate.

Welding variables considered during WPS qualification are:

- Welding process.
- Base material.
- Welding consumables.
- Welding parameters and techniques:
    - Position.
    - Polarity.
    - Preheat.
    - Interpass temperature.
    - Back gouging.
    - Post-weld heat treatment.

Tests conducted during WPS qualification include:

- Mechanical:
  - Reduced section tension tests.
  - All weld metal tension tests.
  - Side bend tests.
- Soundness:
  - Radiographic testing (RT) for welds to fracture critical members (FCM).
  - Macroetch tests.
- Toughness:
  - Charpy V-notch tests.

MDOT does recognize AWS D1.1 and AWS D1.5 prequalified joints and procedures. Essential variable changes or owner toughness requirements may result in a prequalified WPS requiring qualification testing.

Procedure Qualification Test Record (PQR)

A production WPS's qualification is based on a PQR that is produced by the contractor in conformance with AWS D1.1 or AWS D1.5, based on the project specifications. MDOT reviews the PQR as supporting documentation during WPS approval but does not approve the PQR.

Shop Welded Plate Girders and Rolled Beams

MDOT requires SAW for:

- Flange to web groove welds using one of the following weld positions:
  - Flat (1F).
  - Flat (1G).
- Cover plate to beam flange welds using one of the following weld positions:
  - Flat (1F).
  - Horizontal (2F).
  - Stiffeners and connection plates to web.
  - Flange-to-web connection in box girders.

Use SMAW for stiffener and connection plates to rolled beams and girders when automatic or hand held SAW cannot be used. Employ E7018 electrodes unless a higher tensile strength is required to match the base metal (i.e., AASHTO M270 Gr HPS70W).

Note that MDOT does not allow electroslag or electrogas welding.

For fillet welds:

- Size by thicker of two joining parts (unless larger is required based on calculated stress).
- Not required to exceed thickness of thinner part.
- Preheat if smaller than minimum required.
- Minimum for beam flange is 5/16 inches.

Shop Splices

As shown in Figure 36, separate girder flange plate and web plate butt welds by at least 1 foot. Separate stiffener and connection plate attachment welds by at least 1 foot.

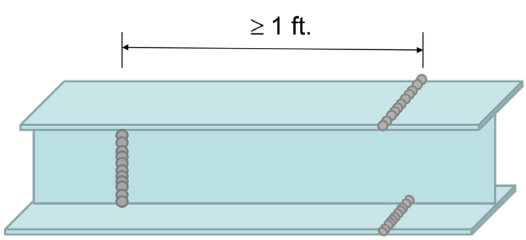


Figure 36: Restrictions on shop splices.

Weld Conditions

Remove paint, mill scale, grease, and other materials from welded edges and surfaces. For flange welds, grind flush on aligned side and merge smoothly on transition sides. Maintain areas (base metal) requiring automatic or semiautomatic welding at a temperature of at least 40 F for at least one hour prior to beginning work unless WPS requires a higher preheat temperature.

Shop Weld Nondestructive Testing for Bridges

Nondestructive testing (NDT) is required for all shop welds and is performed by the contractor. Identification marks should be made with paint on butt welds. Testing must be performed by an NDT technician qualified as American Society for Nondestructive Testing (ASNT) Level II on Recommended Practice No. SNT TC 1A.

Nondestructive Testing – Groove Welds

- Visual test 100 percent of groove welds.
- PT in accordance with ASTM E 165:
- Inspect both ends of groove welds for surface defects.
- Required because UT and RT are difficult at edges of a plate. Use RT in accordance with AWS D1.5, Clause 8 Part B:
    - Single-source X ray or gamma ray.
    - Use hole type or wire image quality indicators to judge sensitivity.
    - Double shoot film for quality control and quality assurance records.
    - For thickness transitions, place radiographic film on both sides of the joint, position the pack, and use tapered edge blocks.
    - Move film to planar side if substandard results when on transition side.
- For CJP groove welds at corner and T joints where RT is not possible:
    - Perform UT and agree on acceptance criteria.
    - Use glycerine as the coupling agent.
- UT all plug and slot welds.
- Test CJP groove welds of main members according to the following:
    - 100 percent of flexural member flange butt joint.
    - 100 percent of splices subject to tension or stress reversal.

- Web splices: 1/3 the length of all web splices beginning at the point of maximum tension, but not less than 12 inches. In addition, test 25 percent of the remainder of the web depth beginning at the point of maximum compression, but not less than 12 inches.

- 25 percent of each axial member subject to compression.

- 25 percent of each joint subjected to shear such as web to flange joints in flexural members.

- If unacceptable discontinuities are found in any of the above partial examinations, test the remainder of the weld and test 100 percent of similar welds.

Nondestructive Testing – Fillet Welds

Magnetic particle testing (MT) is required for fillet welds in accordance with AWS D1.5 except as modified herein. Perform MT in accordance with ASTM E709 with dry powder using the yoke method.

Test the entire length of the stiffener or connection plate to tension flange of main members. Test at least 12 inches in every 10 feet of each fillet weld for the joints specified in section 707 of the MDOT SCC and project special provision.

MDOT does not require the following members to be MT inspected:

- Diaphragm assemblies.
- Sway bracing.

If a defect is detected, then increase frequency to the least of either the full weld length or 5 feet on each side of the defect.

Defective Welds

Replace all welds that are rejected by any test method. Provide repair procedure for engineer's approval and repair weld in accordance with AWS D1.5, Clause 5.7.

Retest at least 3 inches to either side of the repair. If second repair attempt fails, then remove and replace entire weld.

Field Welding

Avoid field welding unless specified on plans or approved by the engineer. Perform it in accordance with AWS D1.1 or AWS D1.5 based on project specifications and use SMAW (E7018 Electrode). The engineer may approve SAW or FCAW. Do not use GMAW or other gas shielded processes.

Requirements for Field Welding

Qualification requirements (similar to shop welding requirements):

- AWS welder, welding operator, and tack welder qualification.
- MDOT WQP or MDOT Welder Certification Program (WCP) based on what is being welded.
- Welding equipment.
- WPS.

Welder must qualify for welding process, welding position, material grade, and material thickness. Note that some positions, grades, and thicknesses qualify others.

MDOT WQP testing will be made under supervision of an MDOT representative.

Field Welding Surface Requirements

- Blast clean or grind contact surfaces prior to welding:
  - Remove loose mill scale, paint, galvanizing, grease, oil, rust, moisture, or other materials.
  - Grind joints to remove pitting and irregularities.
- Bring parts into close contact:
  - Separation greater than 1/16 inch requires an increase in the fillet weld leg equal to the separation distance.
  - Do not exceed a separation distance of 3/16 inches.
- For heavy sections, 3 inches or greater:
  - Separation distance increases to 5/16 inches.
  - Unless “tight fit” or “mill to bear” are called out.

- Consider environmental conditions:
  - Temperature must be above 40 F.
  - No precipitation (rain, snow, or heavy fog).
- Electrodes:
  - Dry in oven for two hours before use at 500 F or greater.
  - Store at 250 F after drying.
  - Use within two hours of exposure to atmosphere or redry.
  - Do not redry more than once.
  - Discard if wet.
- Preheat (see Table 6):
  - 3 inches in every direction from weld.
  - Temperature based on base metal thickness.
- Weld Transitions:
  - Grind stop start areas.
  - Grind irregularities

Table 6. Base metal preheat temperatures.

Base Metal Thickness (inches)	Minimum Preheat Tempature (F)
T ≤ 1 1/2	250
1 1/2 < T ≤ 2 1/2	300
T > 2 1/2	400

Field Weld Nondestructive Testing

Field weld nondestructive testing is required by MDOT in addition to visual testing (VT). MDOT requires 100 percent NDT for fielding welding due to the difficult nature of field welding, whereas shop welding generally requires a reduced frequency. This is due to the shop being certified by the American Institute of Steel Construction (AISC), having a robust quality control program, favorable environmental conditions, and required to weld in favorable positions.

The required personnel are (certification must be provided):

- NDT Level II qualified per ASNT SNT TC 1A for penetrant testing (PT), magnetic particle testing (MT), ultrasonic testing (UT), and radiographic testing (RT).
- AWS Certified Weld Inspector (CWI) for VT.

Blast clean or grind all weld prior to NDT. The test must meet requirements of the project specifications. Below are typical NDT requirements for field welding:

- MT: fillet and PJP groove welds.
- UT: CJP groove welds, plug welds, and slot welds. Note base metal and weld repairs to make the section “whole again” are considered CJP groove welds.
- PT: ends of CJP and PJP groove welds.

Defective Field Welds

Replace all welds that are rejected by any test method and repair in accordance with AWS D1.1 or AWS D1.5, based on the project specifications. Inspect and retest welds prior to engineer’s acceptance.

Special Field Welding Cases

- Welding for supports and accessories:
  - May be approved by engineer if no other alternative.
  - Plans must be submitted to engineer.
  - Only weld to compression areas of beams.
- Welding shear studs:
  - Do not weld if temperature is below 32 F.
  - Remove rust, mill scale, paint, and galvanizing from base metal.
  - Clean stud end.
  - Do not preheat top flange.
  - Use automatically timed stud welding equipment.
  - Test stud welding in accordance with AWS D1.5, Clause 9.
  - Add a 5/16 inch fillet weld if stud does not have a full 360 degree fillet weld.

Weld Positions

Welders must be qualified for different welding positions and must follow the MDOT approved WPS. Weld positions are:

- 1G or 1F – Flat Groove or Fillet Weld.
- 2G or 2F – Horizontal Groove or Fillet Weld.
- 3G or 3F – Vertical Groove or Fillet Weld.
- 4G or 4F – Overhead Groove or Fillet Weld.

Figures 37 and 38 show the positions of the test plates for groove and fillet welding, respectively. Tabulation of weld positions can be found in AWS D1.5.

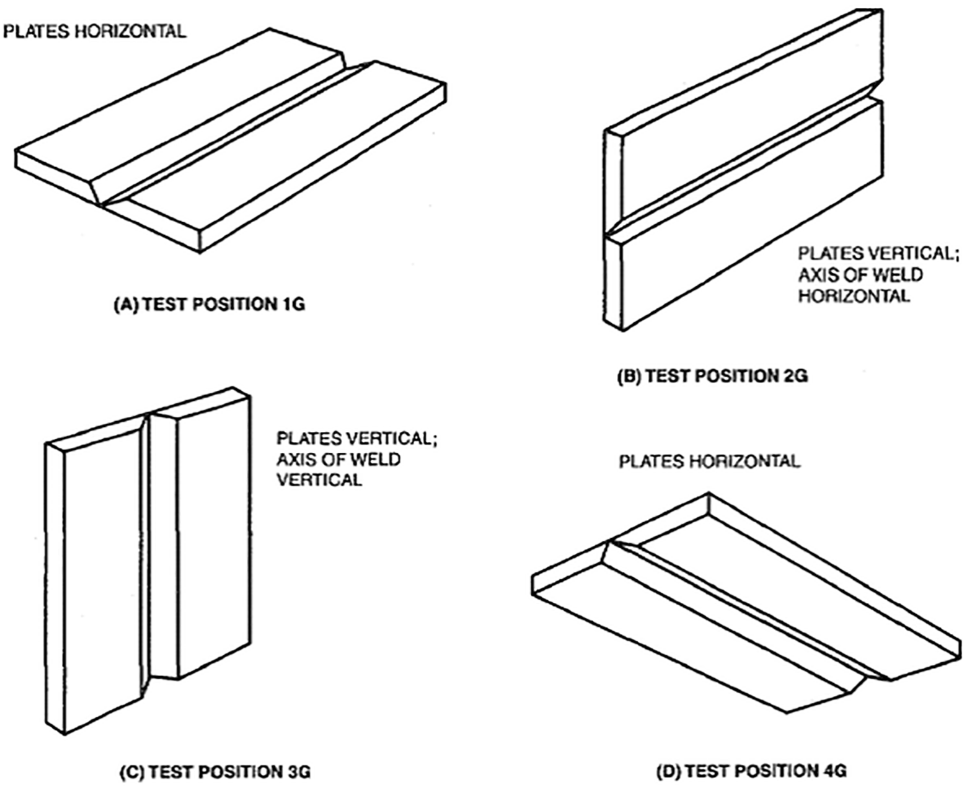


Figure 37. Positions of test plates for groove welds.

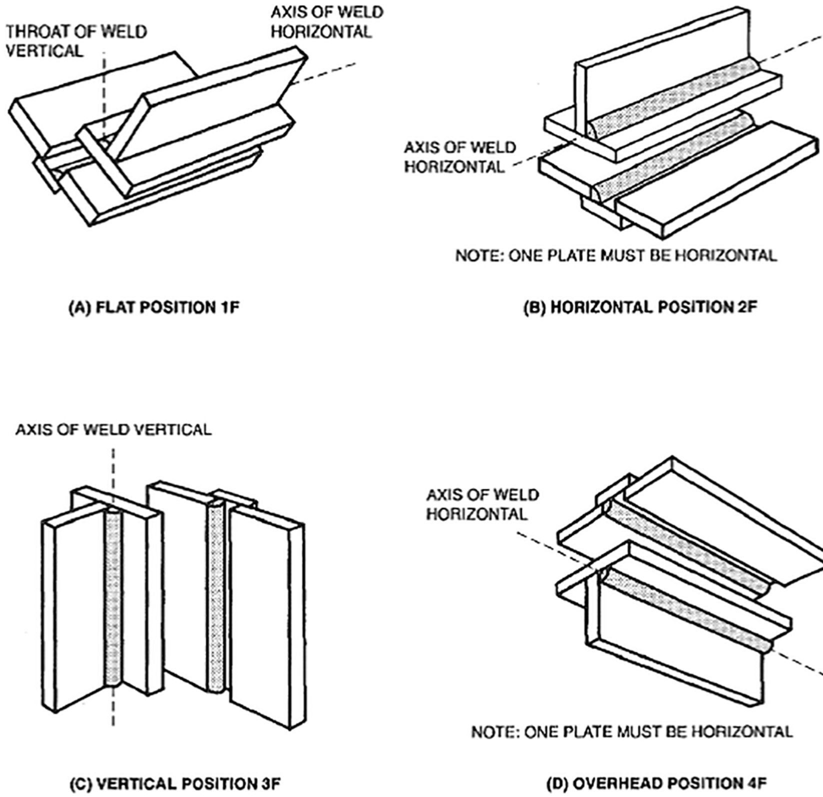


Figure 38. Positions of test plates for fillet welds.

Welder Certification and Endorsement

AWS Welder Endorsements

AWS Welder Certification (AWS QC7-93)

An accredited test facility must be used to test the welder in accordance with AWS for certification purposes. The applicant selects the performance tests needed for qualification. Note that:

- AWS QC7 93 Supplement G provides a list of performance requirements for each test.
- The applicant must provide an employer supplied WPS or use AWS standard procedure.
- The applicant's test assemblies must pass the exam.

If one or more weld fails, then rules for retesting must be followed. The period of effectiveness is considered indefinite, unless: 1) the welder was not involved in welding activities for six months or with that set procedure, or 2) there is a reason to question welder's ability.

AWS Performance Test

The test follows the WPS or the AWS standard procedure and is associated with a particular weld type and position. The test assemblies must be in accordance with the WPS. Acceptance standards include:

- VT inspection.
  - Fillet weld macroetch test (as applicable).
- Mechanical testing.
  - Bend test (as applicable, can be replaced with RT).
  - Fillet weld break test (as applicable).
- RT inspection.

MDOT Welder Endorsements

MDOT Welder Certification Program (WCP)

MDOT allows private testing agencies to perform MDOT welder certification testing. Contractors select from a list of authorized testing agencies located throughout the state and pay for the testing. The test plates may be welded under the authorized testing agency's observation.

Welder certification allows a welder to perform AWS D1.1 welding on non main members, except an MDOT certified welder may weld contractor add ons to main members in compression zones only. An MDOT certified welder is not permitted to weld on highway structures in accordance with AWS D1.1 nor perform AWS D1.5 welding. See MDOT's WCP for more information.

MDOT requirements are:

- Meet authorized testing agency responsibilities.
- Ensure certified welder guidelines are followed.
- Follow testing agency evaluation process.

MDOT WCP Guidelines

- Field welding allowed by welders endorsed through MDOT's WCP includes:
  - Pile welding (except main members).
  - Cofferdams and steel sheet piling.
  - Temporary supports (except main members).
  - False work.
- MDOT welding restrictions include:
  - Welders must always have certifications available when welding.
  - Certification good for specific rods and positions.
  - No welding below 0 F (heating and housing can be approved by the engineer).
  - No welding with precipitation or wet low hydrogen rods.
  - Preheat base metal 3 inches in each direction from weld when ambient temperature is between 0 and 32 F.
  - Welder is responsible for storage of electrodes.

MDOT Welder Qualification Program (WQP)

MDOT uses select third party laboratories to perform MDOT welder qualification testing and pays for the initial weld test. The contractor is responsible for the cost of additional testing if the welder fails the initial weld test or if the welder's qualification is revoked by MDOT prior to expiration of the original test.

A welder endorsed through MDOT's WQP can perform field or shop welding as follows:

- Bridge welding to AWS D1.5.
- Highway structure welding to AWS D1.1.
- Main member pile welding to AWS D1.5.
- Miscellaneous structures required by contract documents to use an MDOT qualified welder.

Welders that hold a MDOT WQP endorsement also have MDOT WCP privileges. Qualification testing must be done in accordance with AWS D1.5 and MDOT Special Provision 20SP-707 (A), Structural Steel and Aluminum Construction.

The qualification period is for two years for field welding and three years for shop welding unless:

- The welder was not engaged with welding for three months.
- There is reason to question welder's ability.

Program guidelines include:

- Similar to MDOT WCP guidelines.
- Qualify for field and shop welding separately.
- Must complete a field welding plan.
- Do not weld below 40 F (heating and housing can be approved by engineer).
- Preheat surface in accordance with section 707 of the MDOT SSC for AWS D1.5 and AWS D1.1 welding.

Economic Welding Practices

The majority of welding costs are associated with labor. A reduction in weld metal volume typically leads to more economic welds. Quality welds that are free of defects avoid the need for repairs that cost time and money (i.e., weld once).

Considerations Based on Weld Types

CJP Groove Welds

This is the most expensive type of weld, so reserve it for when it is the only viable option. It is generally advantageous with electroslag or electrogas welding; however, MDOT does not permit these welding processes.

PJP Versus Fillet Welds

Can be used in T joints and inside corner joints. You can generally assume that PJP welds require half the volume of material for a given strength. You can also estimate the time to bevel a PJP joint as equal to a single fillet weld pass. In general: 1) a fillet weld is more economical if it only requires a single pass, 2) PJP welds are ideal in a flat position, and 3) fillet welds are ideal in flat or horizontal positions. The general rule of thumb is:

- If leg size less than 1 inch, use fillet welds.
- If leg size more than 1 inch, use PJP groove weld.

Mixed PJP Fillet Welds

Figure 39 is an example of a mixed PJP fillet weld, also known as a fillet reinforced PJP weld. It might be more economical than an individual PJP or fillet weld. For T joints, fillet welds on top of a PJP weld provide a better contour at the intersection. This type of weld is preferable for welds in positions other than flat.

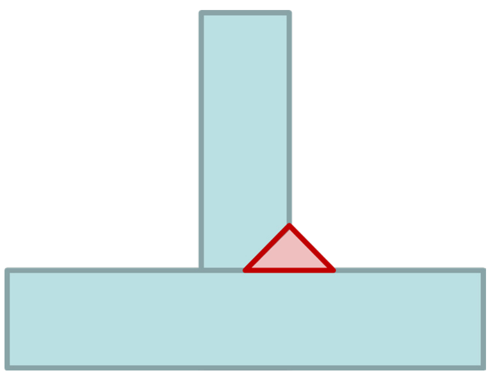


Figure 39. Mixed PJP fillet weld.

Other Welding Considerations

CJP Groove Welds

Single-sided welds are easier to fabricate unless distortion control is needed. The typical 2 to 1 savings assumed for double sided welds are not true for many prequalified joints.

The choice of root opening and included angle depends on throat dimension:

- If throat dimension is less than 1 inch, use the smallest permitted root opening with larger included angle.
- If throat dimension is greater than or equal to 1 inch, use the larger root opening and smaller included angle.

PJP Groove Welds

Single sided PJP groove welds typically require less than three weld passes and are more economical than double-sided. Double sided welds do prevent tearing of the unfused root region.

Flare Groove Welds

You do not always have to fill flush. You must specify the required throat to obtain required capacity.

Fillet Welds

Strength increases linearly with weld length and leg size. Note:

- 1 to 1 increase in weld volume with weld length.
- 4 to 1 increase in weld volume with weld leg size.
- Continuous welds are often chosen over intermittent.

Welding Inspection

Welds must be inspected to ensure that they meet specifications. There are two categories of inspection methods.

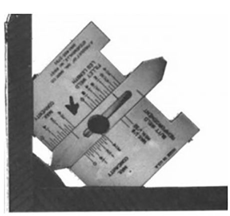
- Destructive:
  - Used for weld procedure qualification.
  - Suitable for tensile tests, Charpy impact tests, and bend tests.
- Nondestructive (NDT):
  - Inspect in situ weldment without damage.
  - MDOT specifies NDT requirements.
  - Methods include:
    - › Visual Testing (VT).
    - › Penetrant Testing (PT).
    - › Magnetic Particle Testing (MT).
    - › Radiographic Testing (RT).
    - › Ultrasonic Testing (UT).

Visual Testing (VT)

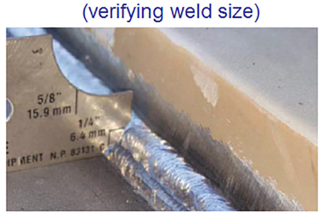
This method is a powerful tool before, during, and after welding. It requires good eyesight and lighting. The main tool is a flashlight and weld measuring gauges. MDOT requires that all welds are VT inspected. Figures 40 and 41 show the tools and process, respectively.

Flashlight

Fillet Weld Gage
(verifying weld size)



AWS Gage
(Fillet weld size, reinforcement, underfill)



Fillet Weld Gage
(verifying weld is not concave)

Figure 40: VT tools.

Pre-Welding	– Review specifications – Check in compliance with WPS – Check welder's AWS and MDOT endorsement – Review material certification – Inspect equipment – Check base metal for discontinuities and contaminates – Check fit-up and alignment – Check required preheat – Evaluate environmental condition – Record results
During Welding	– Ensure conformance with WPS procedures – Verify quality of weld root bead – Check joint root preparation prior to welding second side (two sided welds) – Check interpass temperature – Inspect after each weld pass (multi-pass welds)
Post-Welding	– Inspect for porosity, undercut, cracks and other discontinuities – Check final weld size – Inspect weld length – Ensure all welds are complete per drawings – Ensure no extra welds are present – Check for excessive distortion – Check for arc strikes

Figure 41: VT method

Penetrant Testing (PT)

This method uses capillary action to draw liquid into surface breaking discontinuities. The tester applies developer to make discontinuities visible and must provide adequate time for capillary action to draw in liquid (approximately 15 minutes). Figure 42 shows the process.

PT can only detect surface breaking discontinuities. It is effective at accentuating surface discontinuities that are hard to visually see. It is messy, slow, and not often used for magnetic materials such as steel.

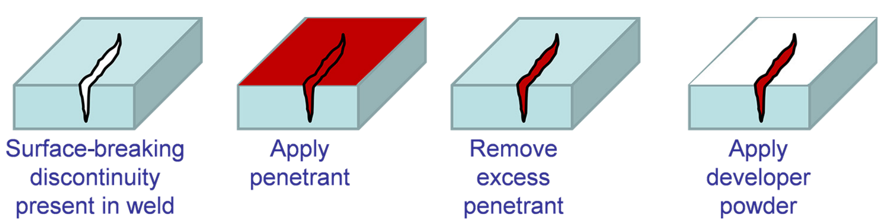


Figure 42: PT method.

Magnetic Particle Testing (MT)

MT detects discontinuities through a change in magnetic flux (visible through particles). It creates a different pattern and can detect surface and slightly subsurface discontinuities (Figure 43).

There are two methods to create an electromagnetic field:

- Pass current directly through the material:
    - Two prods placed in contact with the material.
    - Electrical current passed through them.
- Use a coil on a yoke to induce a magnetic field:
    - Current is passed through the coil.
    - End of yoke is placed in contact with material to test.

Cracks perpendicular to field are most easily detected by MT.

MT is used to ensure quality of repaired welds, especially PJP groove welds and fillet welds. It is also used for inspection of weld access holes.

MT is preferred over PT because it is quicker, simpler, and less messy.

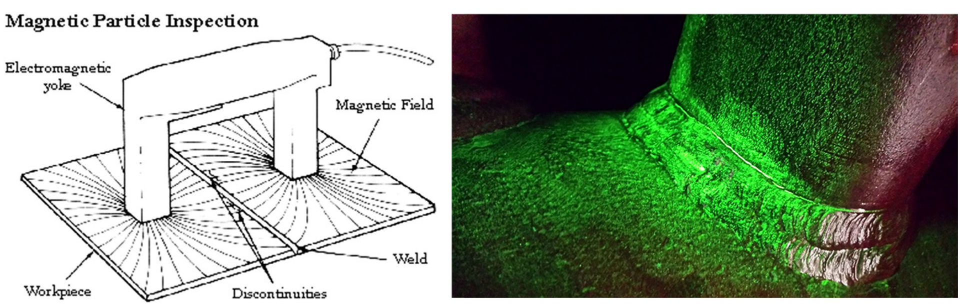


Figure 43: MT method.

Radiographic Testing (RT)

In RT, you pass gamma rays or X rays through the material. A radiographic film is placed on the opposite side of the joint to provide a picture of the inside of the weld. Thin parts (discontinuities) show darker (most exposed), and weld reinforcement shows as a lighter region (Figure 44). RT requires a skilled technician to read.

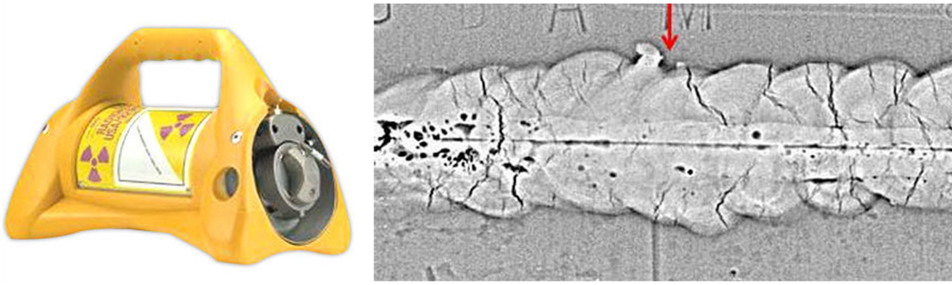


Figure 44: RT method.

RT requires access to both sides of the joint. Cracks oriented perpendicular to the direction of the radiation source (i.e., parallel to the film) may go undetected. This method provides a permanent record and is ideally suited for CJP groove welds in butt joints. However, it is not suitable for PJP groove welds or fillet welds and is difficult to interpret results from T joints and corner joints.

Ultrasonic Testing (UT)

In UT (Figure 45), high frequency sound waves are transmitted through the material. A receiver picks up sound waves reflected off the back surface of the material. Discontinuities cause an interruption of the sound waves and result in an intermediate signal. It is read on a display screen.

The magnitude of a signal from a discontinuity is proportional to the amount of reflected sound. It provides information on the size, type, and orientation of the discontinuity. It is sometimes too sensitive.

UT is most sensitive to planar discontinuities perpendicular to the sound path (such as cracks, laminations, and incomplete fusion). It is ideally suited for CJP groove welds (butt, corner, T joints). It can be used for inspection of PJP welds but cannot be used for fillet welds.

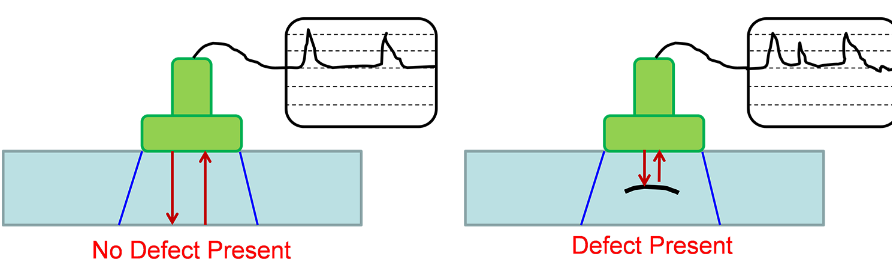


Figure 45: UT method.

Weld Repair

A welder has the option to repair or replace unacceptable welds. Unacceptable welds represent cost to the contractor. When a weld is unacceptable, the fabricator is allowed to perform the repair without a nonconformance report (NCR) unless the engineer's approval is required (i.e., fracture critical weld repairs or other weld repairs required by the contract). Although an NCR is not required to be submitted, MDOT does require the weld repair plan to be submitted prior to repair of the weld. The weld repair plan can be pre-approved for the project or blanket approved for the fabricator.

Material removal (weld metal or base metal) can be accomplished by machining, air carbon arc cutting and gouging, thermal cutting, chipping, or grinding. The remaining weld metal or base metal must not be nicked or undercut. Excess material beyond the unacceptable portion must not be removed and the surface must be cleaned prior to welding.

The repair procedures are as follows:

1. Remove excess weld metal for overlap or excessive convexity.
2. Add additional weld metal for excessive concavity, craters, undersized welds, and undercutting.
3. Remove unacceptable portions and reweld for excessive porosity, slag inclusions, and incomplete fusion.
4. For crack repair, remove full length of the crack plus 2 inches beyond each end, then reweld.

Weld Symbols

Weld symbols are a systematic means of communicating weld related information. Figure 46, which is adapted from AWS A2.4, shows how weld symbols are designated. Each symbol contains the following:

- Reference line (required).
- Arrow (required).
- Tail (optional).

The symbol is always read right to left no matter what side of the reference line the arrow is on.

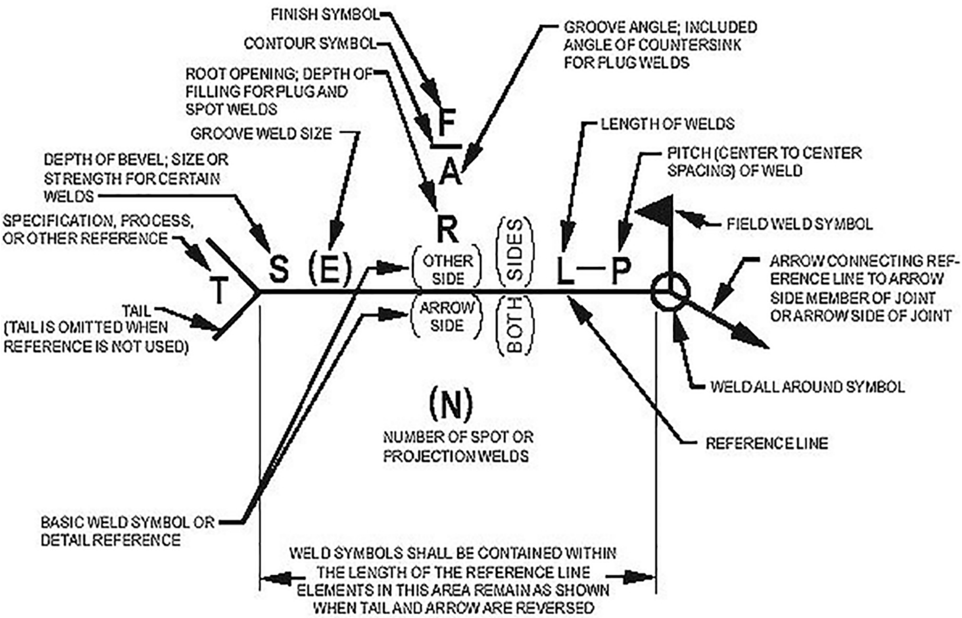


Figure 46: Weld symbols.

Notes:

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Notes:

MDOT Structural Fabrication Unit's E-mail Resource:

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Michigan Department of Transportation

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