PythonX®
A Lincoln Electric Company

THE PYTHONX® GUIDE TO PLASMA CUTTING IN CODES AND STANDARDS

LINCOLN® ELECTRIC

Table of Contents

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The Purpose and Use of This Guide

This Guide will address technical issues surrounding three features associated with parts processed by PythonX systems, as follows:

- Thermally cut holes that will be part of bolted connections
- Thermally cut surfaces other than bolt holes, such as member edges, web penetrations, beam copes, weld access holes, and reduced beam section flanges
- Markings for assembly locations, welding symbols, and permanent piece marks

Table 1 is intended to be used as a quick reference guide to determine the allowance or prohibition of plasma cutting for a particular application, and to direct the user of this Guide to the applicable sections of the Guide containing the appropriate information. The table and this Guide should not be used alone without consulting the codes and standards for the codified requirements.

TABLE 1. ALLOWANCE OF PLASMA CUT BOLT HOLES AND FREE EDGES, AND MEMBER MARKING

Application	Loading	US	Canada	Europe	Japan	Australia	New Zealand
Bolt Holes	Static	Yes	Yes	Yes	Application Dependent[1]	Yes	Yes
	Cyclic	Application Dependent[2]	Yes	Yes	No	Yes	Yes
	Seismic	Application Dependent[3]	No	Codes Do Not Address[4]	No	Codes Do Not Address[4]	Codes Do Not Address[4]
	See pages 19-26						
Free Edges	Static	Yes	Yes	Yes	Application Dependent[1]	Yes	Yes
	Cyclic	Yes	Yes	Application Dependent[1]	Application Dependent[1]	Yes	Yes
	Seismic	Yes	Yes	Codes Do Not Address[4]	Application Dependent[1]	Codes Do Not Address[4]	Codes Do Not Address[4]
	See pages 26-53						
Plasma Markings	Codes Do Not Address See pages 53-58						

Notes 1. See applicable text.

2. *RCSC 2014* and *AISC 360-16* differ slightly on the requirements, and *AISC 360-16* Appendix 3 contains some hole restrictions based on the type of bolted connection.

3. *AISC 358-16* contains requirements for several moment connection types; the acceptability of plasma cut holes is connection dependent. See pages 22-23 of this Guide.

4. The European, Australian, and New Zealand standards do not specifically address this application. The user of this Guide is encouraged to consult with the engineer of record or other technical authority on the project for guidance.

The PythonX system is popular for fabrication of steel members for building construction, which is typically regulated by Building Codes. Thus, for many PythonX applications, regulatory requirements will apply. In some cases, the use of plasma cutting for bolt holes, free edges, or marking has been restricted by applicable regulatory requirements. There may be many reasons for such restrictions. Codes and standards may intentionally preclude the use of the process for some known connection performance issue. In other situations, the requirements may not be up to date. An often-encountered situation is where the codes allow for the use of plasma cutting, but there is a misunderstanding of the standards and the process is inappropriately disallowed. This Guide provides information on when plasma arc cutting and marking is allowed, disallowed, and when codes and standards are silent on the topic.

In some cases, regulatory standards use the term "oxyfuel cutting" in lieu of the more inclusive term "thermal cutting". While "thermal cutting" would include plasma cutting, "oxyfuel cutting" would not. In many, and perhaps most cases, the use of the more restrictive term "oxyfuel cutting" was not selected to exclude plasma cutting but rather identified only the older technology that was in use before plasma cutting existed or became popular.

When the requirements surrounding the use of plasma cutting are not understood, when older standards are specified for a project, or the standards fail to directly address the use of plasma cutting, the engineer of record or other technical authority overseeing a project must decide to allow or disallow the process. When the governing standards are silent on the use of plasma cutting, the approach used by other standards (as discussed in this Guide) may assist the authority making the decision regarding the suitability of the process. Therefore, the user of this Guide is encouraged to present the information provided in this Guide to the appropriate governing body or bodies for consideration and acceptance of plasma cutting where appropriate.

For some applications where the PythonX system could be used, the work is not governed by regulatory codes or standards. For those applications, the information contained in this Guide will assist the technical authority in evaluating the suitability of thermally cut holes and edges, and thermal markings for non-regulated applications.

PythonX System

The PythonX system is a practical and economical machine for plasma cutting bolt holes, web penetrations, beam copes, weld access holes and other thermally cut modification to rolled shapes and built-up members. Additionally, the PythonX can be used to scribe identification and fitting marks or letters on the surface of the steel. The system is used to produce components used in building structures, as well as other structural members used for miscellaneous steel fabrications.

Plasma arc cutting can be used to sever most structural materials, including carbon and low alloy steels plates up to 2 in. [50 mm] in thickness, with high quality cuts. Plasma arc cutting provides a good balance in terms of capital costs, and provides excellent cut quality, high cutting speeds, higher productivity, and low operating cost when compared to other cutting methods.

The members produced by a PythonX are typically welded or bolted to other members; in some cases, both welds and bolts are used. Many of the thermal cuts made by the PythonX become part of a structural connection. The integrity of such cuts can affect the performance of the connection in service.

One of the many advantages of the PythonX system is the consistency by which thermal cuts can be made when compared to the common alternative: manual torch cutting. Specific required or preferred sizes and dimensions of certain geometric configurations such as weld access holes can be programmed and automatically and consistently cut. Fabrication costs can be reduced and quality improved when a PythonX cutting system is employed.

The PythonX system is capable of cutting round and slotted bolt holes. Slotted holes allow for greater alignment flexibility when bolted joints are assembled, but the use of slotted slots is prohibited in some situations.

The PythonX system relies on plasma cutting to make holes and cut surfaces. As is the case for all thermal cutting processes, plasma cutting creates a heat-affected zone (HAZ) adjacent to the cut, and induces some residual stresses (which also occurs with most thermal cutting and welding processes). Further, there is a surface roughness associated with thermally cut surfaces. Under most loading conditions, and when incorporated into most bolted and welded connections, these characteristics are not detrimental.

However, in some combinations of loading and some bolted connection types, these features may result in performance problems. Similarly, restrictions are placed on mechanically-produced holes in some bolted connection types and loading conditions. Punched holes are sometimes prohibited by construction codes; when this is the case, drilled holes, or punched and reamed holes may be required. Thus, restrictions on the means of manufacture of holes for some bolted connections and loading types is not isolated to thermally cut surfaces.

Plasma Arc Cutting

Plasma arc cutting is a thermal arc cutting process that provides an efficient method of severing material. Plasma cutting offers major advantages over oxyfuel cutting in terms of productivity, speed and cost, as well as providing higher cut surface quality, better mechanical properties, and tighter adherence to required tolerances. The process is defined as "An arc cutting process employing a constricted arc and removing molten metal with a high-velocity jet of ionized gas issuing from the constricting orifice" (AWS A3.0, 2010).

The plasma arc formation begins when a gas such as oxygen, nitrogen, argon, or even shop compressed air is forced through a small nozzle orifice inside the torch. An electric arc generated from the external power supply is then introduced to this high-pressured gas flow, resulting in what is commonly referred to as a "plasma jet". The plasma jet immediately reaches temperatures up to 40,000 °F [22 000 °C], quickly piercing through the work piece and blowing away the molten material.

With reduced levels of thermal energy from the plasma torch, it is possible to mark or etch the surface of the steel; such markings are called plasma markings.

Codes and Standards

Codes and standards govern the fabrication and construction of buildings, bridges and other steel structures throughout the world. These documents, developed by different committees, are based upon global and local practices and experience. Codes or standards may be specific to a certain loading condition, e.g. seismic loads, or they may govern general fabrication practices.

Every major steel construction standard permits the use of plasma cutting for some, if not all, cutting tasks in the fabrication of structural steel. These tasks include:

- making bolt holes for bolted connections
- making holes for anchor rods and other anchorages
- cutting of member and component edges, including trimming of sheared and rolled edges
- cutting for groove preparation of welded joints
- cutting of specific details, such as weld access holes and beam copes
- cutting of member penetrations

- cutting of flanges for Reduced Beam Section connections (a type of seismic moment connection)

Applications and limitations, as well as quality requirements, vary by construction standard. The user of this Guide is encouraged to review the applicable standards and identify the specific requirements as this Guide provides only summaries of the standards. Likewise, newer versions of the cited standards may modify the requirements discussed in this Guide. Generally, the latest versions of the standards will reflect the latest technological developments and research.

When older standards are specified for a project, or when the applicable standards fail to directly address the use of plasma cutting, the user of this Guide is encouraged to present the information provided to the appropriate responsible or governing body or bodies for consideration for acceptance of plasma cutting for the particular application or project, and for future revision of the applicable standard(s).

What follows are brief explanations of select code(s) and standard(s) that apply to plasma cutting and marking for a given country.

United States of America

The American Institute of Steel Construction (AISC) publishes several standards addressing specific categories of steel construction. The primary standard for steel-framed buildings and other structures is the *Specification for Structural Steel Buildings*, identified as *AISC 360*. At the time of the publication of this Guide, the most recent edition of *AISC 360* is the 2016 edition, and is identified as *AISC 360-16*.

For structural steel and composite structural steel/reinforced concrete building systems specifically detailed for seismic resistance, the requirements of the *Seismic Provisions for Structural Steel Buildings*, published in 2016 and identified as *AISC 341-16*, applies in addition to *AISC 360-16*. *AISC 341* adds to and modifies the requirements of *AISC 360*; if no deviations to *AISC 360* are listed in *AISC 341*, the requirements of *AISC 360* are applicable.

An additional standard, *Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications*, published in 2016 and identified as *AISC 358-16*, specifies design, detailing, fabrication and quality criteria for moment connections that are prequalified in accordance with *AISC 341-16*.

A fourth AISC standard is the *Specification for Safety-Related Steel Structures for Nuclear Facilities*, which addresses the design, fabrication and erection of safety-related steel structures for nuclear facilities, and supplements *AISC 360*. The current version was published in 2012 as *AISC N690-12*, with a supplement added in 2015, identified as *AISC N690s1-15*.

The aforementioned AISC standards can be downloaded at no cost from the AISC website: www.aisc.org.

AISC standards reference American Welding Society (AWS) standards for most welding and cutting requirements. For building construction, *AISC 360-16* references *AWS D1.1/D1.1M Structural Welding Code – Steel*, published in 2015, and identified as *AWS D1.1/D1.1M:2015*.

For structures detailed for seismic resistance, *AISC 341-16* references *AWS D1.8/D1.8M Structural Welding Code – Seismic Supplement*, which adds to and modifies the requirements of *AWS D1.1/D1.1M:2015*. The most recent version is *AWS D1.8/D1.8M:2016*.

AISC standards reference the Research Council on Structural Connections (RCSC) standard for installation and inspection requirements for most structural bolting. This standard is the *Specification for Structural Joints Using High-Strength Bolts*. *AISC 360-16* references the 2014 edition, and is commonly referred to the as the *RCSC Specification 2014*. An erratum to this standard was issued April 2015, but the erratum made no changes to bolt hole criteria.

Highway bridges are typically designed and constructed in accordance with American Association of State Highway and Transportation Officials (AASHTO) standards that reference *AASHTO/AWS D1.5/D1.5M Bridge Welding Code* for welding and cutting requirements. Railway bridges are typically governed by American Railway Engineering and Maintenance-of-Way Association (AREMA) specifications that reference *AASHTO/AWS D1.5/D1.5M,* modifying certain clauses. In addition to these national standards, individual states or railways may impose additional requirements on bridges.

Canada

The Canadian Institute of Steel Construction (CISC) does not directly publish a standard equivalent to *AISC 360*. Rather, the standard *Design of Steel Structures* is published as a Canadian Standards Association (CSA) standard, identified as *CSA S16*, with strong participation from the CISC. At the time this Guide was developed, the latest version was published in 2014, and is known as *CSA S16-14*. The CISC publishes the *CISC Commentary on CSA S16-14*, with is included in the 11th Edition of the *Handbook of Steel Construction*, published in 2016.

CSA 16 references *Welded steel construction (metal arc welding)*, published in 2013 and identified as *CSA W59-13*, for most welding- and cutting-related requirements. However, a new version of *CSA W59* was published in 2018, *CSA W59-18 Welded steel construction*, and is used for the purposes of this Guide. The next version of *CSA S16*, to be published in 2019, will reference *CSA W59-18*.

Unlike *AISC 360-16*, *CSA S16* does not reference the *RCSC Specification* for bolting requirements.

Europe

The design of structures in Europe is governed by a series of European Norms (EN), termed Eurocodes, developed by CEN (European Committee for Standardization). Related to steel structures are:

- EN 1990, *Basis of structural design*
- EN 1991, *Eurocode 1: Actions on structures*
- EN 1993, *Eurocode 3: Design of steel structures*
- EN 1994, *Eurocode 4: Design of composite steel and concrete structures*
- EN 1998, *Eurocode 8: Design of structures for earthquake resistance*

Within *Eurocode 3*, part 1.8, identified as *EN 1993-1-8 Design of joints,* addresses design of bolted and welded joints between structural members.

A National Annex (NA) to a European Norm may be adopted by a given European nation, when permission is given for an NA within the body of the Eurocode. These are often to specify or modify design values or an equation, or require a specific design method, or to address the use of an informative or normative annex.

None of the previously listed documents directly address fabrication issues such as cutting and holing (the making of holes for bolts), but rather reference *EN 1090-2 Execution of steel structures and aluminium structures —Part 2: Technical requirements for steel structures*, a separate standard developed by *CEN/TC 135 Execution of Steel Structures and Aluminium Structures*. This standard addresses the specific requirements for execution of steel structures for building and civil engineering works, including rules for quality management, materials, fabrication, erection and inspection, and specific requirements for cutting, welding and bolting. This standard was updated and published in 2018 (*EN 1090-2:2018*).

Australia and New Zealand

Australia and New Zealand share several joint standards, but New Zealand uses its own standards to address seismic design and construction. Standards are managed and published by Standards Australia (AS) and Standards New Zealand (NZS), as applicable. The Australian Steel Institute (ASI), Weld Australia (WA), formerly known as the Welding Technology Institute of Australia (WTIA), Steel Construction New Zealand (SCNZ) and New Zealand's Heavy Engineering Research Association (HERA) are instrumental in the development of AS/NZS standards related to steel construction, welding and cutting.

For design of steel structures, Australia uses *AS 4100-1998 (R2016) Steel structures*. It was originally adopted in 1998, received a Supplement in 1999, and was reaffirmed in 2016. In New Zealand, *NZS 3404.1: Steel Structures Standard (2007)* is used. The current version of this standard is the 2007 version, with two subsequent amendments.

Both Australia and New Zealand use *AS/NZS 5131:2016, Structural Steel Work—Fabrication and Erection*. This standard is based upon many of the principal topics of *EN 1090-2 Execution of Steel Structures and Aluminium Structures, Part 2: Technical Requirements for Steel Structures*, with modifications based upon work done for the development of ISO 17067.

For cutting and welding, both the Australian and New Zealand standards reference the *AS/NZS 1554 Structural steel welding* series. The current versions of these standards are:

AS/NZS 1554.1:2014 Structural steel welding, Part 1: Welding of Steel Structures, Ninth edition 2014

AS/NZS 1554.4:2014 Structural steel welding, Part 4: Welding of High Strength Quenched and Tempered Steels, Fourth edition 2014

AS/NZS 1554.5:2014 Structural steel welding, Part 5: Welding of Steel Structures Subject to High Levels of Fatigue Loading, Fifth edition 2014

Japan

The Architecture Institute of Japan (AIJ) writes design standards and execution specifications for steel construction. Another organization relevant to steel fabrication is the Japan Society of Steel Construction (JSSC). The Japan Welding Engineering Society (JWES) addresses welding and cutting standards.

Japanese Architectural Standard Specification 6 (JASS 6) Structural Steelwork Specification for Building Construction is available in English. An updated version of *JASS 6* was published in 2018, as the 11th Edition. No date has been set for an English translation of the newest version.

All other standards are available in Japanese only, and therefore the requirements in those standards are not included in the scope of this Guide.

Loading Types

Different types of structures are loaded in different ways. The four primary types of loading are static, cyclic, seismic, and impactive. There are other types of loading, but for the purposes of this Guide will not be addressed here. The design requirements for each loading type must be treated differently. Furthermore, the requirements for how to treat bolt holes, cut edges and plasma marked members may be different for each loading type. For example, a building is typically a statically loaded structure whereas a bridge is a cyclically loaded structure and therefore different design requirements exist.

Static Loading

Static loading includes the dead load of the structure, but also includes live loads and environmental loads such as wind or snow loads. Most buildings are subjected only to static loading, with the exception of seismic loading which will be discussed later. Because wind and snow loads are applied slowly and the structure deforms slowly, the strain rate is low, such loadings are considered static loads.

In general, when cyclic or seismic loading is involved, the standards add to or modify the requirements for static loading applications, typically making the requirements more rigorous. Accordingly, the requirements for static applications form a base specification that becomes applicable for all types of loading conditions. Thus, for situations where there are no unique additional requirements for cyclic applications, the static requirements will still apply; a similar situation exists for seismic applications.

Cyclic Loading

Cyclic loading involves a repeated live load applied to the structure; it may also be called fatigue loading. *AISC 360-16* Appendix 3 defines fatigue as the "Limit state of crack initiation and growth resulting from repeated application of live loads." AISC also states in section B3.11 that "Fatigue need not be considered for seismic effects or for the effects of wind loading on typical building lateral force-resisting systems and building enclosure components." (*AISC 360, 2016*). Structures subject to cyclic loading with bolt holes, thermally cut edges and marking may be required to meet more demanding requirements than a statically loaded structure.

Seismic Loading

Seismic loading occurs during earthquake events. This loading type may be referred to as inelastic loading since localized portions of the structure are anticipated to be strained to the extent that permanent deformation occurs during major seismic events. Seismic loading may also be termed "low-cycle fatigue", as the number of cycles from the seismic event is small. The requirements for bolt holes, thermally cut edges and plasma marking may be more demanding when a structure is designed for a seismic event, as compared to a structure designed for static loading. This includes ensuring that surface roughness is within limits and notches are minimized on thermally cut bolt holes or edges. These more demanding requirements may be applied to members and connections that resist the seismic loading, but are not applicable to members and connections that resist only gravity loading.

Impactive Loading

Impactive loading, sometimes called dynamic loading, involves the rapid introduction of load and the corresponding effect of higher strain rates. Such loading is often caused by large inertia forces, resisted by significant mass and stiffness, to cause rapid deceleration. Also included in this category is blast loading. Since blast resistance is a specialized construction application, this Guide does not discuss that topic nor other forms of impactive loading.

Bolted Joints

The design strength, installation and inspection requirements for a structural bolted joint depend upon the bolted joint type selected by the Engineer. The Engineer provides the bolted joint type in the design documents, and the bolted joint type is also shown on the shop drawings and erection plans.

Bolted joint designations provide the information needed for installation and inspection of the bolting assemblies, rather than defining the load transfer mechanism. There are three types of bolted joints: Snug-Tightened (ST), Pretensioned (PT), and Slip-Critical (SC), as described in Table 2.

TABLE 2. TYPES OF BOLTED JOINTS

Type of Joint[1]	Connection Function
Snug-Tightened (ST)	Resistance to shear loading by shear/bearing.
Pretensioned (PT)	Resistance to shear loading by shear/bearing. Bolt pretension is required, but for reasons other than slip resistance.
Slip-Critical (SC)	Resistance to shear loading by friction on faying surfaces is required.

[1] These terms are used by American Institute of Steel Construction (AISC) and Research Council on Structural Connections (RCSC). The terms in other standards may be different.

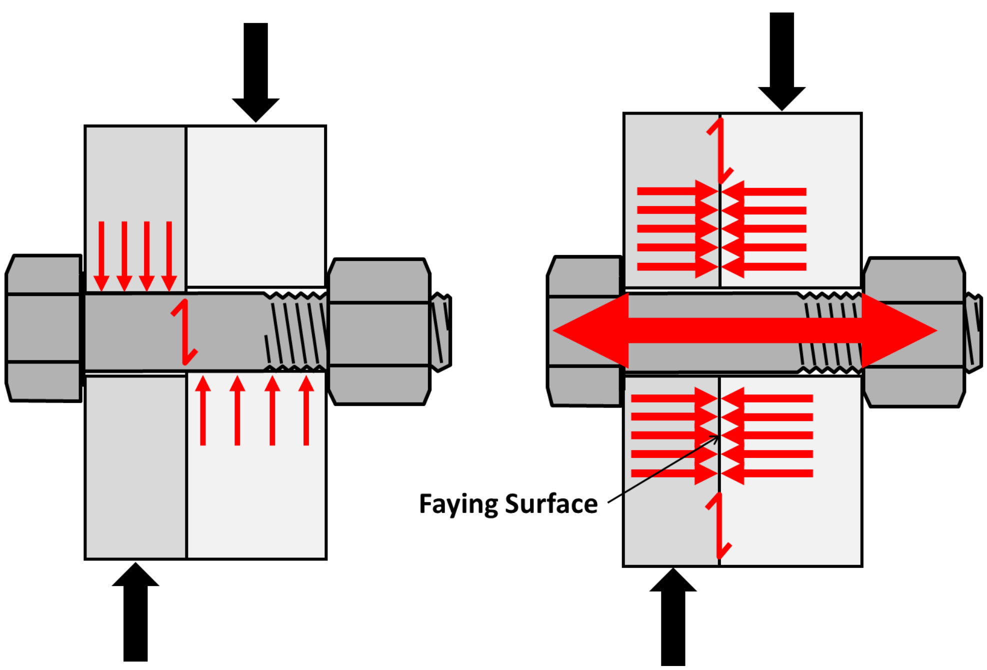


Figure 1. Example of snug tight (left) vs. slip critical (right) bolted connection

Snug-Tightened Joints

Snug-tightened joints are the most common bolted joints in building structures. Because the load is transferred by shear through the bolt that bears against the side of the bolt holes, there is no need to provide a high level of tension in the bolt. Rather, the steel plies of the joint are simply drawn together by the bolts themselves, using whatever effort is necessary to create the bolt tension needed to bring the plies into firm contact (Figure 1).

The *RCSC Specification 2014* defines a snug-tightened joint as "a joint in which the bolts have been installed in accordance with Section 8.1. The snug-tightened condition is the tightness that is attained with a few impacts of an impact wrench or the full effort of an ironworker using an ordinary spud wrench to bring the plies into firm contact." (*RCSC, 2014*).

When snug-tightened joints are used, only standard holes and slotted holes loaded transverse to the length of the slot are permitted by RCSC. Oversized holes, as well as slotted holes loaded in any direction other than approximately normal (between 80 and 100 degrees) are prohibited because they would allow too much movement in the joint, either during construction or after occupancy under the application of service loads.

Snug-tightened joints are not permitted for fatigue applications by RCSC. If the repeated live loads would cause the joint plies to slip repeatedly against one another, fretting fatigue on the surface of the steel plies themselves could eventually occur. If the bolt is loaded in cyclic tension, the bolt could fail in tensile fatigue.

In other parts of the world, steel construction standards use terms that convey the same concept, such as "non-preloaded" joints.

Pretensioned Joints

Pretensioned joints differ from snug-tightened joints in that the bolts are tightened so that they achieve a prescribed amount of pretension. The term pretension is used because the tension in the bolt comes from installation, rather than the applied load. The load transfer is the same as that for snug-tightened joints: shear through the bolt shank, and bearing against the sides of the bolt holes.

The *RCSC Specification 2014* defines a pretensioned joint as "a joint that transmits shear and/or tensile loads in which the bolts have been installed in accordance with Section 8.2 to provide a pretension in the installed bolt." There are currently four installation methods provided in the RCSC Specification.

When pretensioned joints are used, only standard holes and slotted holes loaded transverse to the length of the slot are permitted. Oversized holes, as well as slotted holes loaded in any direction other than approximately normal (between 80 and 100 degrees) are prohibited because they would allow too much movement in the joint, either during construction or after occupancy under the application of service loads.

Although the bolts are pretensioned to a very high level in a pretensioned joint, and the steel is tightly clamped together, there is little control of the nature of the faying surfaces, the contact surfaces of the plies of steel within the joint. Hence, a tight joint could still slip should the steel surface be coated with a material with a low coefficient of friction, or if the steel is not properly prepared to provide a specific level of slip resistance.

Joints where the bolts are loaded in tension and subjected to fatigue loading are designed and pretensioned so that the bolt itself does not directly experience the tensile stress range. Rather, the connected parts that are clamped together by the bolts will be subject to a change in clamping force under load, but the bolt tension will remain essentially unchanged.

In other parts of the world, steel construction standards use terms that convey the same concept, such as “preloaded” joints.

Slip-Critical Joints

The slip-critical joint also uses pretensioned bolts, but it has additional controls on the faying surfaces, the contact surfaces of the plies of steel within the joint. Criteria are applied to ensure that the faying surfaces provide the required slip resistance, whether the steel is bare or coated (Figure 1).

In slip-critical joints, the load is transferred from one element to the next through friction, rather than shear-bearing load transfer of snug-tightened and pretensioned joints. There is only a slight chance of joint movement, and should that occur, the load would then be transferred by shear-bearing. Because of the slip resistance provided by the clamping force of the bolts and the controlled faying surfaces, oversized holes and slotted holes in a direction other than approximately normal are permitted, in addition to standard holes and transversely loaded slotted holes.

The *RCSC Specification 2014* defines a slip-critical joint as “a joint that transmits shear loads or shear loads in combination with tensile loads in which the bolts have been installed in accordance with Section 8.2 to provide a pretension in the installed bolt (clamping force on the faying surfaces), and with faying surfaces that have been prepared to provide a calculable resistance against slip."

Slip-critical joints were termed "friction-type joints" in older North American standards. In other parts of the world, steel construction standards use terms that convey the same concept, such as "friction-grip" joints.

Bolt Holes

Standard Bolt Holes (STD)

Standard bolt holes are permitted in any and all plies of snug-tightened, pretensioned and slip-critical joints. The diameter of the permitted bolt hole varies according to the bolt diameter, applicable standard, and whether US Customary units or SI units are used for the bolts, holes, or both.

Oversized Bolt Holes (OVS)

Oversized holes allow additional clearance for installation of bolts, and for making minor adjustments at connections to bring parts into alignment. Oversized holes are particularly useful with thick plies of steel in the connection as reaming holes to permit bolt insertion would be difficult and time-consuming. However, it is more difficult to maintain building level, alignment and plumbness when oversized bolt holes are used. Where applicable specifications show oversized hole dimensions, the values in the tables should be considered maximum values.

Short- and Long-Slotted Bolt Holes

Slotted holes allow some additional clearance for installation of bolts, and for making adjustments at connections to bring parts into alignment or the building into plumbness tolerance (Figure 2). However, it is more difficult to maintain building alignment and plumbness when slotted holes are used. The Short Slot (SSL) and Long Slot (LSL) lengths shown in the tables of applicable specifications are maximum lengths, and shorter lengths can be used when desired.

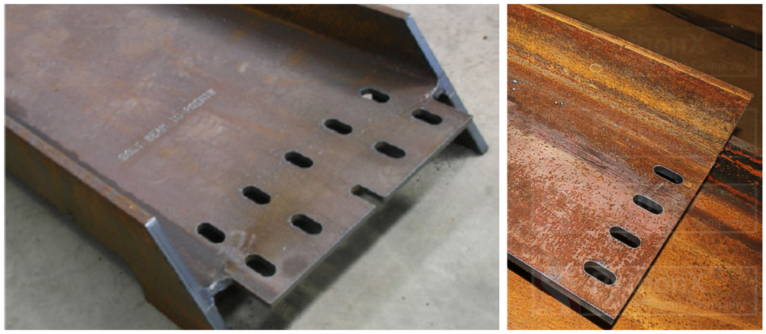


Figure 2. Examples of long slotted holes

Plasma Cut Bolt Holes

All of the previously mentioned steel construction standards for buildings permits the use of plasma cut bolt holes to some degree, with the exception Japan's standard *JASS 6* (2007). Some specify quality criteria for the cut surface of the hole, including surface roughness and gouges. Only the European standard includes criteria for slope within the hole.

With the exception of *JASS 6*, standards permit the use of thermal cutting to make slots between drilled or punched holes used for the slot ends. Where thermal cut holes are permitted, making the entire slotted hole using plasma cutting reduces time and effort. It also increases quality and accuracy, as it avoids the difficulty of alignment of the thermal cut surface with the point of tangency of the punched or drilled hole, and the subsequent grinding that may be required.

Only three standards address the accuracy of the location of bolt holes: the European standard *EN 1090-2*, the Australia-New/Zealand standard *AS/NZS 5131*, and the Japanese standard *JASS 6*. For North American standards, the hole location is deemed accurate enough if the connected members are located within their specified tolerance.

Restrictions are placed on thermal cutting of bolt holes in specific locations on structural steel members, depending upon application and location in the structure. These locations may include bolt holes in regions intended to experience high levels of inelastic strain (also called plastic hinging regions) that are expected to be created in major seismic events. This restriction does not include all seismic resistant structures, or even all seismic connections. In some connections, plasma cut holes may be permitted in part of the connection, but not another. The applicable code should be consulted for further information.

Studies in Europe (Bannister, et al, 2016, Section 8.6 Plastic tensile strain capacity of laser and plasma cut edges) on 15 mm [19/32 in.] thick steel plates indicate that plasma cut holes where the hole is initiated in the center and finished at a location in the hole parallel to the strain direction provided adequate strain capacity in 355 MPa and 460 MPa [50 and 65 ksi] yield strength steel at temperatures of -50 °C [-60 °F] and adequate strain capacity in higher strength steel at -20 °C [0 °F]. However, it must be noted that these were single tensile tests to failure, and do not consider the strains and repeated cycles that may be experienced in seismic loading.

In some standards, restrictions may be placed on thermal cut holes subjected to high-cycle fatigue. Plasma cut holes are often used in bolted connections for such applications, with appropriate fatigue design categories for the bolted connection. The applicable standard should be consulted for limitations for the specific case.

American Standards

Statically Loaded Applications

AISC 360-16 Chapter M titled *Fabrication and Erection,* section M2.5, states that

> "Bolt holes shall comply with the provisions of the *RCSC Specification for Structural Joints Using High-Strength Bolts* Section 3.3, hereafter referred to as the *RCSC Specification*, except that thermally cut holes are permitted with a surface roughness profile not exceeding 1,000 μin. (25 μm), as defined in *ASME B46.1*."

While *AISC 360-16* identifies the allowance of thermally cut holes as an exception, the *RCSC Specification* contains similar language that permits thermally cut holes. As long as the surface roughness requirements are met, thermal cut holes, which includes plasma cutting, may be used provided there are no gouges that exceed 1/16 in. [2 mm].

The PythonX system is capable of meeting 1,000 μin. (25 μm) requirements, with a typical surface roughness value is 75 μin. (2 μm), many times better than the requirements.

AISC 360-16 section M2.2 addresses thermal cutting in general. It states that the requirements of *AWS D1.1/D1.1M:2015* clauses 5.14.5.2, 5.14.8.3, and 5.14.8.4 must be met. Clause 5.14.5.2 covers repair procedures. Clause 5.14.8.3 covers roughness requirements for thermal cut holes, stating that the surface roughness must be no more than that represented by Sample 3 of *AWS C4.1-77*, *Criteria for Describing Oxygen-Cut Surfaces and Oxygen Cutting Surface Roughness Gauge*. Clause 5.14.8.4 covers notch and gouge limitations requiring that surface roughness greater than that represented by Sample 3 and gouges greater than 3/16 in. [5 mm] must be repaired by machining or grinding. *AISC 360-16* Section M2.2 also states that free edges not subject to fatigue must not have gouges greater than 3/16 in. [5 mm] in depth and any notches greater than 3/16 in [5 mm] in depth must be removed by grinding or repair welding.

Gouges requiring repair should not be an ongoing occurrence with a PythonX system in good operating condition.

The *RCSC Specification 2014* Section 3.3 allows thermally cut holes in statically loaded joints provided they are produced by mechanically guided means, with the restriction that surface roughness is not to exceed 1,000 microinches [25 µm]. RCSC also restricts "occasional gouges" to not more than 1/16 in. [2 mm] in depth. Free hand thermally cut holes and thermally cut holes for cyclic applications are allowed "if approved by the Engineer of Record." For holes cut free hand, the RCSC commentary states that the hole will usually need to be ground in order to achieve the maximum surface roughness of 1,000 microinches [25 µm].

Since the PythonX system is a mechanized system, these provisions involving hand cutting are not applicable.

Cyclically Loaded Applications

The *AISC 360* criteria for cyclically loaded connections is primarily contained in Appendix 3 of that standard. The content of the rest of *AISC 360* applies to cyclically loaded connections, except as modified in the appendix. Appendix 3 provides no restrictions are the method of production of bolt holes beyond those contained in the *AISC 360*. It is important to recognize, as discussed in the previously mentioned RCSC commentary, that the type of bolted connection (i.e., whether slip occurs or not) will determine the point of potential fatigue crack initiation. The bolted connections discussed in Appendix 3 are required to be made with high-strength bolts that are installed to slip-critical requirements.

A PythonX system should be acceptable for the production of holes for cyclically loaded structures, when the proper type of bolted connection is specified.

The RCSC commentary to section 3.2.2 states that

> "For cyclically loaded joints, test results have indicated that when no major slip occurs in the joint, fretting fatigue failure usually occurs in the gross section prior to fatigue failure in the net section (Kulak et al., 1987, p. 116, 117). Conversely, when slip occurs in the joints of cyclically loaded connections, failure usually occurs in the net section and the edge of a bolt hole becomes the point of crack initiation (Kulak

> et al., 1987, p. 118). Therefore, for cyclically loaded joints designed as slip critical, the method used to produce bolt holes (either thermal cutting or drilling) should not influence the ultimate failure load, as failure usually occurs in the gross section when no major slip occurs."

Thermal cutting of bolt holes with a PythonX system is allowed by RCSC Specifications with the Engineer's approval, and the commentary provides the justification for the use of thermally cut holes when slip critical connections are used.

Seismically Loaded Applications

AISC 358-16 lists nine moment frame connections that may be used in a building without additional testing, and are therefore identified as prequalified. The general requirements for the prequalified connections are listed in chapters 1 through 4. The specific requirements for individual prequalified connections are listed in the subsequent chapters. General bolting requirements for the prequalified moment connections are contained in Chapter 4 of that specification; no restrictions on plasma cut holes are listed in that chapter.

Plasma cut holes can be used for the following prequalified moment connections listed in *AISC 358-16:*

- Reduced Beam Section (RBS) Moment Connection
- Bolted Unstiffened And Stiffened Extended End-Plate Moment Connections
- Welded Unreinforced Flange-Welded Web (WUF-W) Moment Connection
- Sideplate Moment Connection
- Simpson Strong-Tie Strong Frame Moment Connection

In the case of the prequalified Double-Tee Moment Connection, the bolt holes in the T-stubs and beam flanges are required to be drilled or sub-punched and reamed, precluding thermal cutting. However, the bolt holes in the shear tab and the beam web may be thermally cut. No restriction on thermally cutting of holes in the column are listed in *AISC 358-16*.

The Reduced Beam Section (RBS) Moment Connection contains no restrictions on plasma cut holes, and the PythonX can be used to cut the web bolt holes, the weld access holes and the reduced beam sections associated with this connection detail.

The Welded Unreinforced Flange-Welded Web (WUF-W) Moment Connection has no restrictions on plasma cut holes, and the PythonX can be used to cut the web bolt holes as well as the special weld access holes that are required as part of the prequalified status of the connection.

In addition to the seismic connections where thermally cut holes are permitted, *AISC 358-16* restricts the method of hole production to drilling, or sub-punching and reaming, for these connections:

- Bolted Flange Plate (BFP) Moment Connection
- Kaiser Bolted Bracket (KBB) Moment Connection
- CONXTECH CONXL Moment Connection

Due to the nature of these connections, it is unlikely that components for either the Kaiser Bolted Bracket Moment Connection or the CONXTECH CONXL Moment Connection would be fabricated with a PythonX system. While it would be desirable to thermally cut the holes for Bolted Flange Plate Moment Connections, testing has not been performed to determine the suitability of holes produced in this manner.

For seismic moment connections that are not listed in *AISC 341*, tests may be performed in accordance with *AISC 358-16* Section K. When this is done, the method of hole production is a "prequalified variable (see *AISC 358-16*, section K1.4f(e)). If holes are thermally cut for the test specimen, then thermally cut holes can be used in production; if drilled holes are used for the test specimen, then thermally cut holes cannot be used in production.

Canadian Standards

Statically Loaded Applications

CSA S16:2014 discusses thermally cut holes in the section 28.4.3 Thermally cut holes, as follows:

> "Thermally cut holes produced by guided machine may be used in statically loaded structures if the actual hole size does not exceed the nominal hole size by more than 1 mm. Gouges not exceeding 1.5 mm deep may be permitted along edges of thermally cut slots. Manually cut fastener holes may be permitted only with the approval of the designer."

The PythonX is acceptable for producing holes for statically loaded applications as governed by *CSA S16:2014*.

Cyclically Loaded Applications

No additional requirements are listed.

Seismically Loaded Applications

CSA S16:2014 clause 28.4.2 Holes at plastic hinges, requires holes that are located in a plastic hinge region to be "…either sub-punched and reamed or drilled full size." To ensure that the holes are sub-punched and reamed or drilled, clause 28.4.2 additionally requires that "This requirement shall be noted on design drawings and shop details."

European Standards

Statically Loaded Applications

The European standards refer to cutting bolt holes as "holing". *EN 1090-2:2018* section 6.6.3 permits holing and "…may be formed by any process (e.g. drilling, punching, laser, plasma or other thermal cutting)…." Section 6.6.3 lists two primary requirements for a technique to be used, the hardness and quality requirements of section 6.4 must be met, and the holes allow fasteners to freely fit through the holes of the assembled members.

EN1090-2 lists a number of dimensional tolerances related to hole size, location, and cut angle. These tolerances should be reviewed in *EN1090-2* prior to commencing holing.

The PythonX system may be used to produce bolt holes under the *EN 1090-2*, provided the cutting procedure is qualified (see *EN 1090-2* Annex D), and the test results meet the required hardness (if applicable), surface roughness and taper requirements.

Cyclically Loaded Applications

No additional requirements are listed.

Seismically Loaded Applications

No additional requirements are listed.

Australian and New Zealand Standards

Statically Loaded Applications

The combined Australian and New Zealand Standards, similar to the European standards, refer to cutting holes as "holing". *AS/NZS 5131:2016* section 6.7.1 Holing methods, allows "…either machine cut…" or a number of other punching, drilling and reaming options to manufacture bolt holes. Machine cutting includes thermal cutting methods as described in Section 6.5.1 which states:

> "Steel material may be cut either by a sawing, shearing, cropping, machining, thermal cutting (including laser cutting and plasma cutting) or water cutting process, unless certain processes are otherwise excluded as identified in the construction specification or elsewhere in this Standard."

The PythonX system may be used to make holes when building to the Australian and New Zealand Standards.

Cyclically Loaded Applications

No additional requirements are listed.

Seismically Loaded Applications

For New Zealand only, *AS/NZS 5131:2016* clause 6.13.2 requires that bolt holes in yielding regions of Category 1, 2 or 3 have a maximum roughness (CLA) of 12 μm. Bolt holes in yielding regions of railway bridges must not be "machine flame cut" full size.

Japanese Standards

Statically Loaded Applications

Given Japan's high seismicity zone, buildings are built to resist seismic loads. There are no provisions that are specific to static applications.

Seismically Loaded Applications

As was previously stated, given Japan's high seismicity zone, buildings are built to resist seismic loads. *JASS* 6 (2007) section 4.9 requires all bolt holes to be drilled, with some exception for punched holes. Typical steel buildings in Japan use a bolted connection configuration that puts many of their bolt holes into plastic hinging regions, and thermal cut holes are generally not permitted.

An exception is explained in section 4.9 *Drilling*:

> "Gas cutting may be used for holes 30 mm or larger in diameter, for anchor bolts, form separators and equipment piping, and for holes for metal attachments, interior and exterior finish work, concrete placement, etc. The roughness of holes made by gas cutting shall not exceed 100 μmRz, and the accuracy of the hole diameter shall be within ±2 mm."

It is not clear if this exception to drilled holes, granted for “gas cutting” would extend to plasma cutting. The user of this Guide should consult the engineer of record or other technical authority as to the applicability of this exception when applied to cutting with a PythonX.

Cyclically Loaded Applications

English translations for Japanese requirements for cyclically loaded applications are not currently available, and therefore are not addressed in this Guide.

PythonX users should contact the engineer of record or other technical authority regarding the acceptability of plasma cut holes for cyclically loaded applications.

Plasma Cut Edges

Cut edges must be considered separately from holes for several reasons. Edges are never associated with bolted connections. As evidenced by the preceding discussion, there are many applicable rules for plasma cut holes, in part because bolted connections were first evaluated with drilled or punched holes; plasma cutting of holes for bolted connections is a more recent development. When considering the topic of plasma cut edges, the older technology was not mechanical cutting but oxy-fuel cutting, another thermal cutting process. The acceptance of plasma cutting as an alternative to oxy-fuel cutting is less complex and, in general, is permitted by most standards. Quality standards are imposed by various standards and geometric configurations may be specified (such as minimum radii dimensions).

Plasma cut edges fall into a number of different categories. For the purposes of this Guide, they will be separated into four categories: free edges, web penetrations, weld access holes, and beam copes. There will also be a separate section on thermal cutting of Reduced Beam Sections, a detail typically associated with seismic applications.

Free Edges

The term “free edge” is used to identify those locations that form an edge to the member, whether web or flange, rather than a location that makes up part of a welded joint. Member edges, thermally cut to width or shape, or simply trimmed to remove sheared and rolled edges when required, must meet the quality requirements of the applicable standard.

American Standards

AISC 360-16 section M2.2 Thermal Cutting mandates that the requirements of *AWS D1.1/ D1.1M:2015* clauses 5.14.5.2, 5.14.8.3, and 5.14.8.4 are met with the following exceptions: thermally cut free edges not subject to fatigue must be free of round-bottom gouges greater than 3/16 in. [5 mm] deep and free of sharp V-shaped notches. Gouges that are greater than permitted must be corrected by grinding or repair welding.

AWS D1.1/D1.1M:2015 clause 5.14.8 recognizes "electric arc cutting and gouging processes (including plasma arc cutting and gouging)..." The cuts must be smooth and free from cracks and notches. For cyclically loaded structures, free hand cutting is only permitted when the Engineer approves.

AWS D1.1/D1.1M:2015 clause 5.14.8.3 provides surface roughness limits as given in Table 3.

TABLE 3. AWS D1.1/D1.1M:2015 MAXIMUM SURFACE ROUGHNESS FOR THERMALLY CUT EDGES

Material Thickness		Maximum Surface Roughness AWS C4.1-77 Sample
inch	mm	
up to 4	up to100	3
4 to 8	100 to 200	2
ends of members (not subject to calculated stress at the ends)		2

The user of this Guide is referred to *AWS D1.1/D1.1M:2015* clause 5.14.8.4 for additional requirements for allowance on notches.

A PythonX system in good working condition is capable of meeting the AWS D1.1 criteria. No approval of the Engineer is needed for cyclically loaded structures since the PythonX does not use "free hand cutting."

Canadian Standards

In *CSA S16-14* clause 28.2 Thermal cutting, machine guided thermal cutting is permitted and the cut edges must meet the requirements of *CSA W59*. *CSA S16-14* clause 28.3.1 continues by saying post-cut planing or finishing (i.e., machining or grinding) is not required of thermally cut edges unless it is noted on the drawings or stipulated for edge preparation for welding.

CSA W59-18 clause 5.3.3 provides surface roughness limits as given in Table 4.

TABLE 4. CSA W59-18 MAXIMUM SURFACE ROUGHNESS FOR THERMALLY CUT EDGES			
Material Thickness		Maximum Surface Roughness	
mm	inch	µm	µin
up to 100	up to 4	25	1000
100 to 200	4 to 8 in	50	2000
ends of members (not subject to calculated stress at the ends)		50	2000

The user of this Guide is referred to *CSA W59-18* clause 5.3.4 for additional requirements for allowance on notches.

A PythonX system in good working condition is capable of meeting the *CSA S16* and *CSA W59* criteria.

European Standards

EN 1090-2:2018 section 6.4.1 requires that cutting of free edges meet the surface roughness, geometric and maximum hardness requirements. It states that "Known and recognized cutting methods are sawing, shearing, disc cutting, water jet techniques, and thermal cutting." Hand thermal cutting is limited to situations where machine thermal cutting is not practical.

EN 1090-2:2018 Table 9 provides surface roughness requirements, to be assessed using *ISO 9013:2017*, clause 7.2.3, as shown in Table 5.

TABLE 5. EN 1090-2:2018 SURFACE ROUGHNESS REQUIREMENTS FOR FREE EDGES	
Execution Class	Criteria
EXC1	Cut edges to be free from significant irregularities and dross shall be removed
EXC2, EXC3 and EXC4	Mean Height of the Profile, Rz5 = Range 4 110 + (1,8 a), where a = workpiece thickness in mm

EN 1090-2:2018 Table 9 also contains acceptance criteria for squareness, or perpendicularity, of a thermal cut edge, referencing *ISO 9013:2017* subclause 7.2.2. Table 7 provides the required perpendicularity or angularity tolerance, u. See Table 6 for the given execution class.

TABLE 6. EN 1090-2:2018 PERPENDICULARITY OR ANGULARITY TOLERANCE	
Execution Class	Criteria
EXC1	Cut edges to be free from significant irregularities and dross shall be removed
EXC2	Range 5
EXC3 and EXC4	Range 4

TABLE 7. ISO 9013:2017, TABLE 4 PERPENDICULARITY OR ANGULARITY TOLERANCE, U	
Range	Table 4 - Perpendicularity or angularity tolerance, u (mm)
1	0.05 + 0.003 a
2	0.15 + 0.007 a
3	0.4 + 0.01 a
4	0.8 + 0.02 a
5	1.2 + 0.035 a

a = work piece thickness

Oxyfuel gas cutting will generally produce very close to a 90° square edge. Conventional plasma cutting can be expected to give a square edge ± 2°. This ± 2° can be improved through use of enhanced plasma cutting and precision control of the torch angle. The small deviation from square rarely creates fit-up issues.

The PythonX system is capable of holding the taper under 1°, with a mean value of 0.5°. Because plasma cutting typically creates a slight bevel on one cut face and a relatively square edge on the other cut face, PythonX makes all of its cuts clockwise or from left to right and, using a patented process, adjusts the torch angle to improve the perpendicularity of the holes. A global setting on the PythonX allows for reversal of cutting direction.

EN 1090-2:2018 also limits surface hardness for carbon steels with a yield stress of 460 MPa or higher (65 ksi or higher) to a maximum of 450 (HV10). When the hardness of such free edge surfaces exceeds this limit, then preheating the steel in advance of the cutting is recommended. See ISO 6507 for the testing method.

For cyclic loading, *EN 1090-2:2018* cautions that some cutting methods can be unsuitable for components subject to fatigue. If there is concern regarding the applicability of thermal cut edges in a situation for fatigue, other codes and standards should be referenced for guidance and the engineer of record or other technical authority should be consulted.

Australia and New Zealand Standards

Methods of cutting that are permissible under *AS/NZS 5131:2016* clause 6.5.1 are "a sawing, shearing, cropping, machining, thermal cutting (including laser cutting and plasma cutting) or water cutting process, unless certain processes are otherwise excluded as identified in the construction specification or elsewhere in this Standard."

AS/NZS 1554.1:2014 Welding of Structural Steels, in clause 5.1.2, reference is made back to *AS 3990 Mechanical equipment - Steelwork*, *AS 4100 Steel Structures* for the requirements for edges not incorporated into a welded joint. Table 8. shows the surface roughness requirements given in *AS/NZS 4100*. *AS/NZS 1554.4:2014 Welding of High Strength Quenched and Tempered Steels and Welding of Steel Structures Subject to High Levels of Fatigue Loading* contain the same language as *AS/NZS 1554.1:2014* regarding surfaces of thermally cut edges not incorporated into a weld joint.

TABLE 8. AS 4100 TABLE 14.3.3 MAXIMUM CUT SURFACE ROUGHNESS

Application	Maximum roughness (CLA) (µm)
Normal applications, i.e., where the face and edges remain as-cut or with minor dressing	25
Fatigue applications (Detail categories) — detail category ≥ 80 MPa — detail category < 80 MPa	 12 25

Notes

1 Roughness values may be estimated by comparison with surface replicas, such as the WTIA Flame Cut Surface replicas.

2 Suitable techniques of flame-cutting are given in WTIA Technical Note 5.

3 CLA = Centre-line average method (see AS 2382).

Japanese Standards

JASS 6 (2007) section 4.6 Cutting and Machining, item (1), allows cutting to be made by "… the most appropriate method such as machine cutting, gas cutting or plasma cutting,…" Section 4.6 items (3) and (4) call for a surface roughness not be greater than 100 μmRz and notch depth not more than 1 mm [1/32 in.] and, if the surface roughness or notch depth does not meet these requirements, the edges may be dressed by grinding.

Web Penetrations and Reentrant Corners

Web penetrations are often required to accommodate the heating, ventilation and air conditioning (HVAC) ductwork in a building, but also to provide access for other mechanical, plumbing and electrical systems. In some structures, web penetrations are used for architectural purposes, for weight reduction, and for construction using customized beam or floor framing systems.

Penetrations must be cut accurately to the required dimensions, without removing more material than necessary; excessive removal will weaken the member. Corners must be smooth and rounded to reduce stress concentrations, and free of notches.

Many of the requirements applicable to web penetrations and reentrant corners have already been stated in the requirements for free edges with a few exceptions that will be explained here.

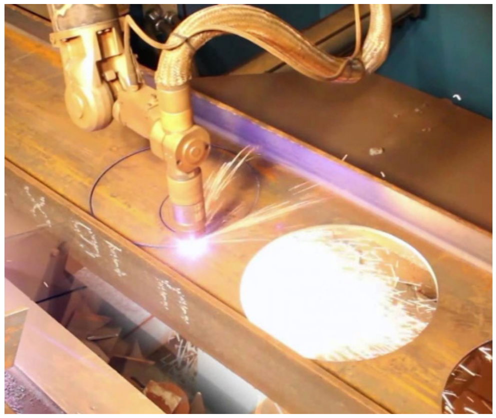


Figure 3. Examples of web penetrations

American Standards

The requirements of *AISC 360-16* M2.2, discussed previously, apply to web penetrations and reentrant corners. Reentrant corners must have a curved transition, but there are no minimum radius requirements. It is suggested that a radius of 1/2 to 3/8 in. (13 to 10 mm) is acceptable for reentrant corners in acceptable for statically loaded conditions.

AWS D1.1/D1.1M:2015 clause 5.15 deals specifically with reentrant corners. Thermal cutting is allowed and the radius of the reentrant corner must be 1 in. [25 mm] or greater, except for corners in connection material and beam copes. The larger radius provides a smooth transition for the flow of stresses in the member. The thermally cut surface is not required to be ground, although grinding is allowed is needed to comply with surface roughness requirements. It must be noted, however, that *AISC 360-16* takes exception to *AWS D1.1/D1.1M:2015* clauses 5.14 and 5.15.

For cyclically loaded members, AISC 360-16 Appendix 3 provides two radii dimensions, each with a different fatigue category (see AISC 360-16, Table A-3.1, example 1.3). Reentrant corners with a radius equal to or greater than 1 in. [25 mm], ground to bright metal, is assigned a fatigue Category C, whereas a radius equal to or greater than 3/8 in. [10 mm] is a Category E' detail. In the case of the Category E' detail, the surface need not be ground, and the maximum surface roughness is 1,000 µin. (25 µm), AWS C4.1 Sample 3.

Canadian Standards

Like the American standards, *CSA S16:2014* clause 28.2 also allows thermal cutting for reentrant corners. The radius of these reentrant corners must be as large as possible with a minimum radius of 14 mm [9/16 in.] and is required to be free from notches. This is also required by *CSA W59-18*, clause 5.3.6.

European Standards

For *EN1090-2:2018* the previous discussion of this Guide on Free Edges applies to reentrant corners and web penetrations. There are additional radius requirements in section 6.7 Cut outs. Any two faces that intersect at angles less than 180° is considered a reentrant corner. The minimum radius of the corners is 5 mm [3/16 in.]. The corner must be rounded, and over-cutting is not permitted.

Australia and New Zealand Standards

AS/NZS 5131:2016 clause 6.5.3 sets a minimum radius of 10 mm [3/8 in.] and states that the reentrant corners must be notch free. Any notches that do occur during cutting must be repaired. AS 4100 clause 14.3.3 requires the same 10 mm minimum radius.

Japanese Standards

JASS 6 (2007) contains no additional provisions for the cutting of web penetrations beyond those for thermal cut edges.

Beam Copes

A beam cope permits a beam to be fit into a supporting girder. A cope is created by cutting away the beam flange and a portion of the beam web.

The AISC *Steel Construction Manual*, 15th Edition, Figure 9-10 (see Figure 4) recommends cutting the web first, then cutting the flange on a bevel to reduce the risk of leaving such a notch at the intersection of the two cuts. A radius should be left in the corner, although no minimum radius is stated.

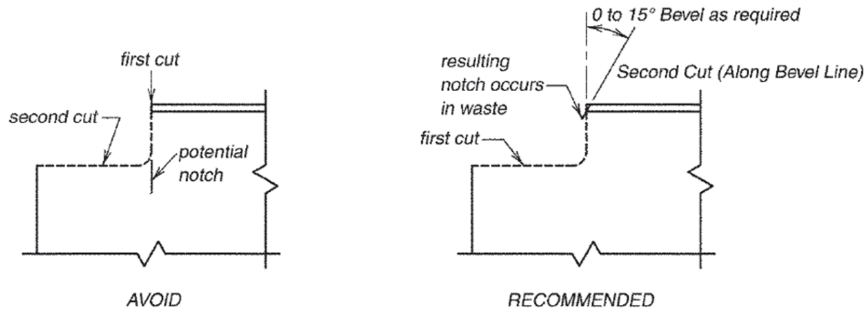
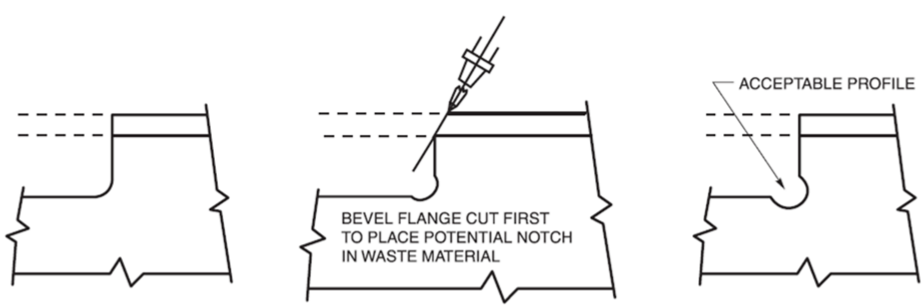


Fig. 9-9. Recommended coping practices.

Courtesy of American Institute of Steel Construction, Steel Construction Manual Figure 9-10

Figure 4. *AISC Steel Construction Manual* Figure 9-10

On the other hand, *AWS D1.1/D1.1M:2015*, Figure C-5.2 Examples of Good Practice for Cutting Copes, illustrates cutting the flange first on a sharper bevel to reduce the risk of leaving a notch, as more web material must be cut to reach the location of the horizontal beam web cut. This figure also shows the use of a large-radius intersection between flange cut and web cut, of particular benefit if repairing a notch left by cutting (see Figure 5).



Courtesy of American Welding Society AWS D1.1/D1.1M:2015 Figure C-5.2

Figure 5. *AWS D1.1/D1.1M:2015*, Figure C-5.2

The results of poor practice and technique when cutting a beam cope with oxyfuel gas cutting are shown in Figure 6.

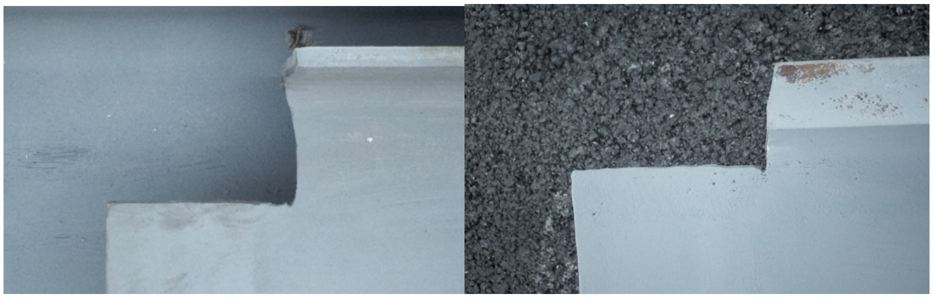


Figure 6. Poor beam cope cutting practices

The poor quality cuts in Figure 6 can be compared to the controlled beam cut in Figure 7, made using numerically controlled enhanced plasma cutting. An additional advantage of such controlled cutting is that the depth of the beam cope can be minimized, maintaining maximum beam web material depth for strength, reducing the need for reinforced webs, and maintaining desired bolt hole edge distances.

Figure 7. Controlled beam cope cut

American Standards

For beam copes, *AISC 360-16* prescribes the general requirements for thermal cut free edges and reentrant corners as described in the preceding sections, with two additions:

1) For rolled shapes with a flange thickness not exceeding 2 in. (50 mm), the maximum surface roughness is not to exceed 2,000 μin. (50 μm) (AWS C4.1 Sample 2).
2) For rolled shapes with a flange thickness exceeding 2 in. (50 mm), and welded built-up shapes with material thickness greater than 2 in. (50 mm), a preheat temperature of not less than 150°F (66°C) is required prior to thermal cutting.

The application of preheat just prior to cutting is to reduce the hardness of the surface layer.

AWS D1.1/D1.1M:2015 clause 5.15 Reentrant Corners exempts beam copes from the 1 in. [25 mm] minimum radius requirement applicable to other reentrant corners. *AISC 360-16* section M2.2 takes exception to this provision.

AWS D1.1/D1.1M:2015 clause 5.16.3 Heavy Shapes, for beam copes used at welded member splices, the cut surface of the beam cope must be ground to bright metal and inspected by either magnetic particle testing (MT) or penetrant testing (PT) methods prior to deposition of the splice welds. This requirement is not stated for beam copes in *AISC 360-16*. In shapes other than heavy shapes, and for locations other than at member splices, copes need not be ground and need not be inspected by PT or MT methods.

For cyclically loaded members, *AISC 360-16* Appendix 3 provides two radii dimensions, each with a different fatigue category (see *AISC 360-16*, Table A-3.1, example 1.3). Copes with a radius equal to or greater than 1 in. [25 mm], ground to bright metal, is assigned a fatigue Category C, whereas a radius equal to or greater than 3/8 in. [10 mm] is a Category E' detail. In the case of the Category E' detail, the cut surface need not be ground, and the maximum surface roughness is 1,000 μin. (25 μm), *AWS C4.1* Sample 3.

Canadian Standards

CSA S16-14 contains no specific criteria for beam copes, other than for cyclically loaded (fatigue) applications. *CSA W59-18* clause 5.3.7, Beam copes and weld access holes, requires that the radii of beam copes provide a smooth transition, free of notches or cuts past the points of tangency. The surface roughness must meet the same criteria as that for free edges.

For cyclically loaded members, CSA S16-14 Table 9 prescribes a Detail Category E1 for re-entrant corners of copes with a radius 35 mm [1-3/8 in.] or greater that are ground smooth.

European Standards

EN 1090-2:2018 does not contain any additional specific requirements for beam copes. The term "cope" is used in the standard, but it applies to a detail between the rib and crossbeams used for orthotropic deck plates.

Australia and New Zealand Standards

AS.NZS 5131:2016, Table F2.2, Elements of Fabrication of Components and Members, contains tolerance for the accuracy of beam copes in members, including both depth and length of the cope. There are no limits for "essential tolerances," beyond those necessary to satisfy the design assumptions for the structure in terms of design capacity and stability. For "functional tolerances," as may be needed for fit-up and appearance, for Class 1, the default condition (typical for Construction Categories 1 and 2), the tolerance on depth and length of cope is +0, -3 mm. For Class 2, recommended but not required for Construction Categories 3 and 4, the tolerance on depth and length of cope is +0, -2 mm.

Japanese Standards

JASS 6 (2007) does not contain requirements for thermally cut copes beyond the previously discussed general thermal cutting requirements.

Weld Access Holes

Weld access holes are to provide adequate access to make quality welds across the entire flange of a beam or column section, minimizing interference from the web. Small or missing weld access holes are known to contribute to significant weld defects near the flange/web intersection.

American Standards

AISC 360-16 section J1.6 Weld Access Holes, lists ten requirements including that

- the access hole be free of notches and sharp reentrant corners (item e),
- holes have a radius of 3/8 in. [10 mm] or greater (item f), and
- for heavy shapes, the cut surface must be ground to bright metal (item i).

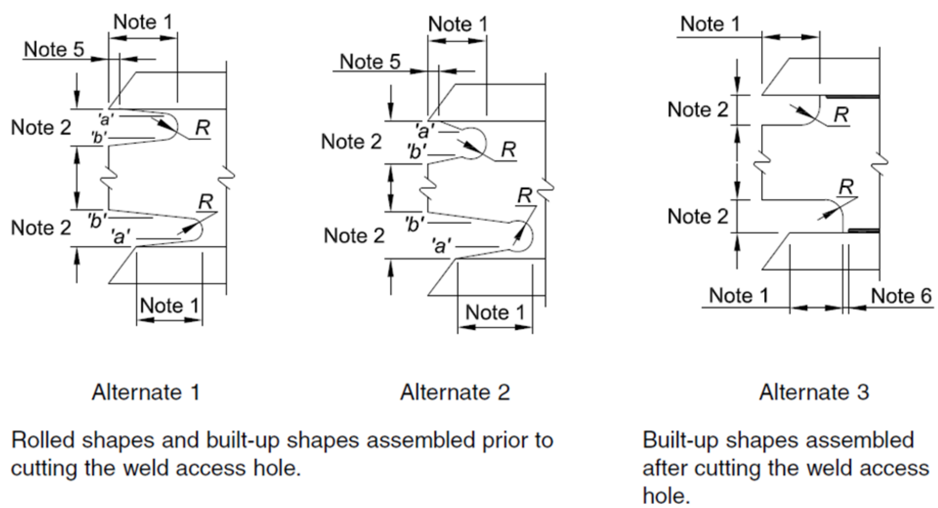
For weld access holes in shapes with flange thickness 2 in. [50 mm] and less, the surface roughness of the thermally cut edge is limited to a maximum of 2,000 μin. [50 μm].

AISC 360-16 Section A3.1(c) and (d) define heavy shapes as hot-rolled shapes with flange thicknesses exceeding 2 in. [50 mm] and built-up shapes with plates exceeding 2 in. [50 mm]. For these heavy plates and shapes, Section M2.2 requires a minimum preheat temperature of 150 °F [66 °C] be used prior to thermal cutting. After heavy shapes have the access holes or copes cut, the surface must be ground to bright metal.

To comply with these requirements when using a PythonX, the steel can be manually preheated before cutting; after cutting, the access holes can be manually ground to bright metal.

Additional consideration must be taken when thermal cuts are used on members that will be hot-dip galvanized. Steps may be taken to mitigate Liquid Metal Assisted Cracking (LMAC, also known as Liquid Metal Embrittlement (LME).

In the Commentary to *AISC 360-16*, Fig. C-J1.2. Weld access hole geometry, typical details for weld access holes for beam-column joints are provided, as shown in Figure 8.

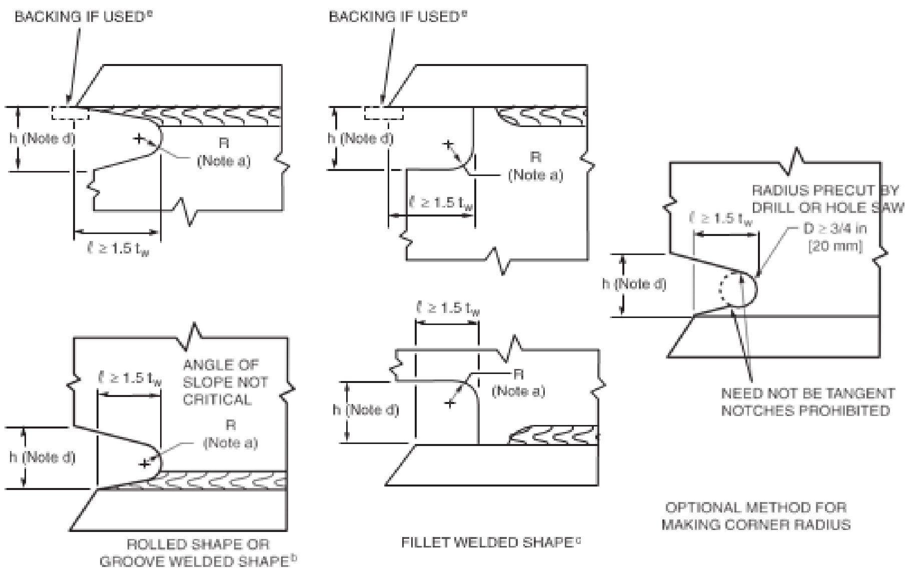


Notes: These are typical details for joints welded from one side against steel backing. Alternative details are discussed in the commentary text.
1. Length: Greater of $1.5t_w$ or 1-1/2 in. (38 mm)
2. Height: Greater of $1.0t_w$ or 3/4 in. (19 mm) but need not exceed 2 in. (50 mm)
3. R: 3/8 in. min. (10 mm). Grind the thermally cut surfaces of weld access holes in heavy shapes as defined in Sections A3.1(c) and (d).
4. Slope ‘a’ forms a transition from the web to the flange. Slope ‘b’ may be horizontal.
5. The bottom of the top flange is to be contoured to permit the tight fit of backing bars where they are to be used.
6. The web-to-flange weld of built-up members is to be held back a distance of at least the weld size from the edge of the access hole.

Courtesy of American Institute of Steel Construction AISC 360-16 Figure C-J1.2

Figure 8. *AISC 360-16* weld access hole geometry

AWS D1.1/D1.1M:2015 clause 5.14.8 allows plasma cutting of material “…for use in preparing, cutting, or trimming materials.” Clause 5.16 deals with the shape and dimensions of weld access holes. This clause, like other code clauses, prohibits notches. Weld access holes must provide a smooth transition. Figure 5.2 in *AWS D1.1/D1.1M:2015*, as shown in Figure 9, illustrates the various allowable geometries for weld access holes.



[a] Radius shall provide smooth notch-free transition; R ≥ 3/8 in [10 mm] (Typical 1/2 in [12 mm]).

[b] Access hole made after welding web to flange.

[c] Access hole made before welding web to flange. The web to flange weld shall not be returned through hole.

[d] h_{min} = 3/4 in [20 mm] or t_w (web thickness), whichever is greater, h_{min} need not exceed 2 in [50 mm].

[e] These are typical details for joints welded from one side against steel backing. Alternative joint designs should be considered.

Note: For rolled shapes with flange thickness greater than 2 in [50 mm] and built-up shapes with web material thickness greater than 1-1/2 in [40 mm], preheat to 150°F [65°C] prior to thermal cutting, grind and inspect thermally cut edges of access hole using MT or PT methods prior to making web and flange splice groove welds.

Figure 5.2—Weld Access Hole Geometry (see 5.16.1.2)

Reprint courtesy of American Welding Society AWS D1.1/D1.1M:2015 Figure 5.2

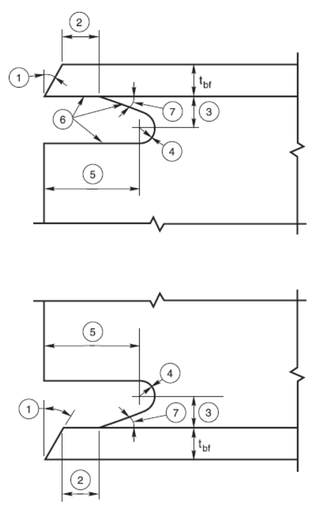
Figure 9. *AWS D1.1/D1.1M:2015* weld access hole geometries

In accordance with *AWS D1.1/D1.1M:2015* clause 5.16.3, a preheat temperature of 150 °F [65 °C] must be used where access holes are going to be cut in heavy shapes, defined as rolled shapes with flanges greater than 2 in. [50 mm] and welded sections with plates greater than 2 in. [50 mm]. The cut surface must also be ground to bright metal and inspected with either MT or PT. This requirement does not extend to other shapes, such as thinner material.

To comply with these requirements when using a PythonX, the steel can be manually preheated before cutting; after cutting, the access holes can be manually ground to bright metal.

For high seismic loading, *AISC 341-16* section A4.2(1) requires that design drawings and specifications for construction state the shape of the weld access hole if a shape other than what is prescribed in *AISC 360-16* is to be used. Commentary on section A4.2(l) explains that "Analysis and research regarding the use of weld access holes have shown that the shape of the weld access hole can have a significant effect on the behavior of moment connections." Ordinary Moment Frame (OMF) systems require that the shape and dimensions of the weld access hole comply with *AWS D1.8*. *AISC 341-16* section J6.2d also requires magnetic particle or penetrant testing of thermally cut copes and access holes when the flange thickness exceeds 1-1/2 in. [38 mm].

AWS D1.8:2016 does not directly address the process with which an access hole can be made, but because *AWS D1.8* is a supplement to *AWS D1.1*, then *AWS D1.1/D1.1M:2015* clause 5.14.8 applies and plasma cutting is therefore allowed. *AWS D1.8* clause 6.11.1 contains an additional weld access hole option that the contractor may use in lieu of the geometries contained in *AWS D1.1/D1.1M:2015* or *AISC 360*. A reprint of *AWS D1.8* Figure 6.2 illustrates that option (see Figure 10).



Notes:
1. Bevel as required for the WPS.
2. t_{bf} or 1/2 in [12 mm], whichever is larger (+1/2 t_{bf}, or –1/4 t_{bf}).
3. The minimum dimension shall be 3/4 t_{bf}, or 3/4 in [20 mm], whichever is greater. The maximum dimension shall be t_{bf} (+1/4 in [6 mm]).
4. 3/8 in [10 mm] minimum radius (–0, +unlimited).
5. 3 t_{bf} (±1/2 in [12 mm]).
6. See 6.11.2.1 for surface roughness requirements.
7. Tolerances shall not accumulate to the extent that the angle of the access hole cut to the flange surface exceeds 25°.

Figure 6.2—Alternate Geometry—Beam Flange Weld Access Hole Detail (see 6.11.1.2)

Reprint courtesy of American Welding Society AWS D1.8/D1.8M:2016 Figure 6.2

Figure 10. *AWS D1.8* alternate weld access hole geometry

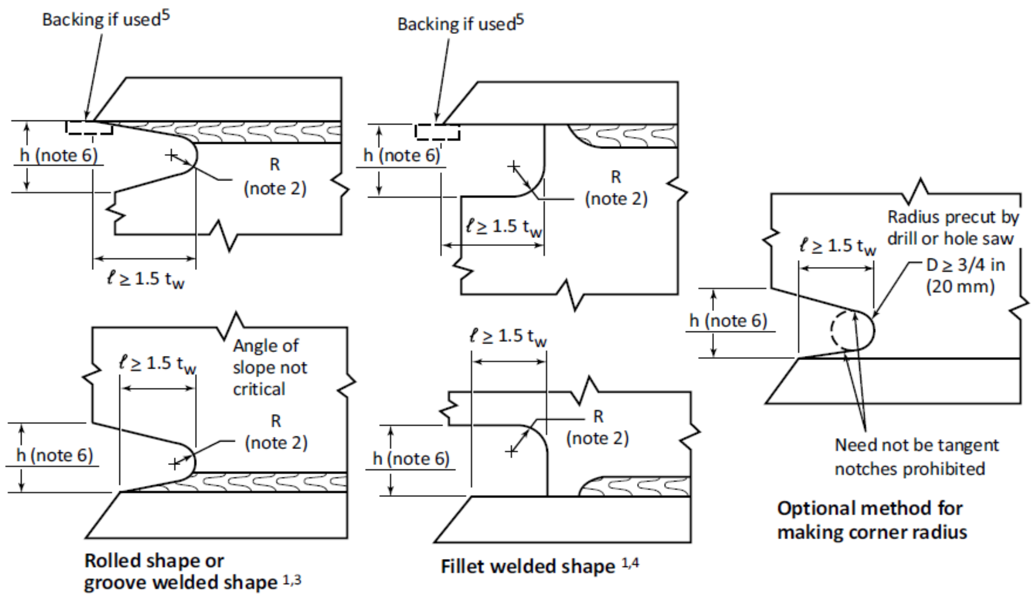
AWS D1.8 clause 6.11.2 Quality Requirements for Weld Access Holes requires a surface finish of not more than 500 µin. [13 µm] except for access holes that need only comply with *AWS D1.1* geometry. Sample 4 of *AWS C4.1* may be used as a guide for surface roughness of 500 µin. [13 µm]. Clauses 6.11.2.2 and 6.11.2.3 permit grinding to remove gouges, faired to a slope of not more than 1:5, or when in the curved portion of the weld access hole, to a radius not less than 3/8 in. [10 mm]. Large notches that cannot be repaired by grinding are allowed to be repaired by welding, provided proper preheat and a repair welding procedure are followed. After repair by welding, the entire area must be ground to a smooth finish.

Canadian Standards

CSA W59-18 clause 5.3.7 Beam Copes and Weld Access Holes requires that the cut surface of weld access holes be free from notches or gouges, the radius provides a smooth transition, and must meet the surface requirements of clause 5.3.3, the criteria used for free edges. Additionally, clause 5.3.8 Weld Access Hole Dimensions repeats the requirement for being free of notches, and adds a requirement that they be free of sharp re-entrant corners, except when fillet web-to-flange welds are used in built-up shapes, the access holes may terminate perpendicular to the flange. In this case, the fillet welds are not to be returned through the weld access hole.

The dimensions of weld access holes are shown in Figure 11.

Figure 5.1
Weld access hole dimensions
(See Clause 5.3.8.)



Notes:

1) *For ASTM A6/A6M and CSA G40.20 Group 4 and 5 shapes and welded built-up shapes with web thickness more than* 38 mm *(1-1/2 in), preheat to* 65 °C *(150 °F) prior to thermal cutting, and grind and inspect thermally cut edges of access hole using magnetic particle or dye penetration methods prior to making web and flange splice welds.*
2) *Radius shall provide smooth notch-free transition;* R ≥ 10 mm *(3/8 in) [typical* 12 mm *(1/2 in)].*
3) *Access opening made after welding web to flange.*
4) *Access opening made before welding web to flange. Weld not returned through opening.*
5) *These are typical details for joints welded from one side against steel backing. Alternative joint designs should be considered.*
6) h_{min} = 20 mm *(3/4 in) or tw (web thickness), whichever is greater.*

Courtesy of Canadian Standards Association CSA W59-18 Figure 5.1

Figure 11. CSA W59-18 weld access hole geometry

CSA W59-18 clause 5.3.9 addresses Group 4 and 5 shapes and states that *CSA G40.20* and *ASTM A6/A6M* Group 4 and 5 shapes and built-up members with web material with thicknesses greater than 38 mm [1-1/2 in.] must have the thermal cut edges ground smooth and inspected with magnetic particle or dye penetrant testing. This grinding and inspection requirement does not apply to weld access holes in other shapes.

European Standards

EN 1090-2:2018, does not contain any requirements for weld access holes beyond the previously discussed general thermal cutting requirements.

Australia and New Zealand Standards

AS/NZS 5131:2016, *AS 4100-1998 (R2016)*, and *NZS 3404.1 (2007)* do not contain any requirements for weld access holes beyond the previously discussed general thermal cutting requirements.

Japanese Standards

Japanese standards refer to weld access holes as “scallops.” Under *JASS 6* clause 4.5 on scallops, when Special Notes are not given, the scallop must comply with specific dimensional requirements. The overall radius of the access hole must be approximately 35 mm [1-3/8 in.] and the smaller radius of the access hole tip must be equal to or greater than 10 mm [3/8 in.]. Special Notes are contract documents that may provide alternate or additional requirements for the preparation or dimensions of the scallop.

Scallops can be cut with a milling machine or “manual gas flame cutter with attachment.” When manual gas flame cutting is used, the cut surface must be ground smooth. Elsewhere in *JASS 6*, plasma cutting is explicitly referenced. Because plasma cutting is not explicitly stated as an acceptable process for scalloping, the user of this Guide should consult the engineer of record or other technical authority responsible for a project and request that plasma cutting be allowed in lieu of gas flame cutting.

Cutting Reduced Beam Sections

Reduced Beam Sections, also known as RBSs and “dogbones,” are specially cut beam flanges used in specific seismic moment resisting frames. The RBS is one of the connections that has prequalified status as a moment connection in *AISC 358-16*. RBSs are also used in some applications to improve member and connection ductility for blast loads when seismic connections have been selected for this purpose.

Figure 12. Example of an RBS cut edge

The entire system is prescribed in Chapter 5 Reduced Beam Section (RBS) Moment Connection of *AISC 358-16*, and Figure 5.1 from the standard illustrates the detail as shown in Figure 13.

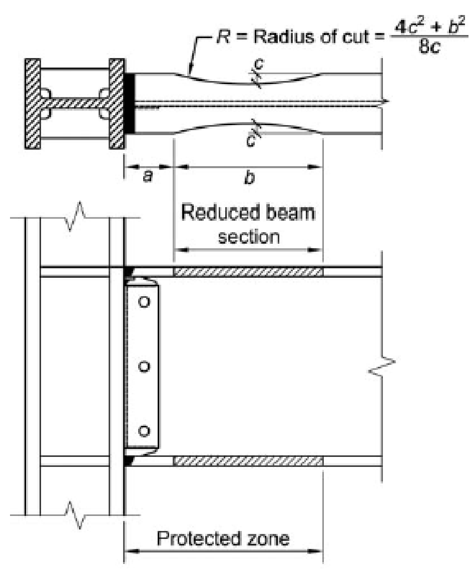


Fig. 5.1. Reduced beam section connection.

Courtesy of American Institute of Steel Construction AISC 358-16 Fig. 5.1

Figure 13. RBS connection detail

AISC 358-16 section 5.7 Fabrication of Flange Cuts, provides the detailed requirements, including a maximum surface roughness Ra profile of 500 µin. [13 µm], limitations on gouges, and tolerances on the accuracy of the cut dimensions.

Fatigue and Plasma Cutting

The design of members that have thermally cut edges has been addressed in the major steel construction standards. The specific terms used in these standards vary, but the considerations are similar whether cutting by oxyfuel, plasma, or another thermal cutting process, with distinction being made in some but not all standards.

American Institute of Steel Construction

Thermal Cut Edges

For fatigue in buildings and similar structures, *AISC 360-16*, Appendix 3 Fatigue, Section 3.5 Fabrication and Erection Requirements for Fatigue requires that "The surface roughness of thermally cut edges subject to cyclic stress ranges, that include tension, shall not exceed 1,000 µin. [25 µm]." ASME B46.1 Surface Texture, Surface Roughness, Waviness, and Lay is given as the reference standard for the measurement of surface roughness, but *AWS C4.1* Sample 3 is commonly used to evaluate surface roughness at the stated value.

Appendix 3, Table A-3.1 Fatigue Design Parameters uses the historic term "flame-cut edges" rather than thermally cut edges, but other text throughout the Specification and the Appendix would indicate that plasma cut edges would be included with "flame-cut edges". Section 1 Plain Material Away from any Welding, Item 1.1 assigns Stress Category A to base metal without reentrant corners, except non-coated weathering steel, with "flame-cut" edges with surface roughness value of 1,000 µin [25 µm] or less, the same stress category as as-rolled or cleaned surfaces. If the base metal is uncoated weathering steel, the stress category is B, per Item 1.2. See Figure 14.

For highway bridge structures, the *AASHTO LRFD Bridge Design Specification,* section 6 Steel Structures, should be used rather than AISC. For railway bridge structures, the *AREMA Manual for Railway Engineering*, Chapter 15 Steel Structures, should be used. Both AASHTO and AREMA use the term "flame cut" rather than thermal cut.

Table 9 contains recommendations from research conducted by Hobbacher (Hobbacher, 2016) and Garcia and Cicero (Garcia and Cicero, 2016) on fatigue design values for plasma cut edges for AASHTO Specifications. These recommendations suggest reducing the Stress Category A mentioned above to either Stress Category B or B'.

TABLE 9. RECOMMENDATIONS FROM HOBBACHER AND FROM GARCIA AND CICERO		
	Current Category	Proposed Category
Flame (oxyfuel) cut edges Surface roughness of 25.4µm (1000 µin.) or less	A	
Flame (oxyfuel) cut edges Surface roughness of 45µm (1780 µin.) or less		B'
Plasma cut edges Thickness 25 mm (1 in.) or less, Rz5 ≤ 10 µm		B

Reentrant Corners, Weld Access Holes and Beam Copes

For fatigue applications, Appendix 3 of *AISC 360-16* section 3.5 allows weld access holes to be thermally cut: "Reentrant corners at cuts, copes and weld access holes shall form a radius not less than the prescribed radius in Table A-3.1 by predrilling or sub-punching and reaming a hole, or by thermal cutting to form the radius of the cut." The commentary on Appendix 3.5 discusses the rationale for the 1,000 µin. [25 µm] requirement:

> "Experimental studies on welded built-up beams demonstrated that if the surface roughness of flame-cut edges was less than 1,000 µin. [25 µm], fatigue cracks would not develop from the flame-cut edge but from the longitudinal fillet welds connecting the beam flanges to the web (Fisher et al., 1970, 1974). This provides stress Category B fatigue resistance without the necessity for grinding flame-cut edges."

In addition, reentrant corners at cuts and copes, including block-outs and other geometrical discontinuities, whether made by thermal cutting or other means, must have a radius not less than the radius prescribed *AISC 360-16* Appendix 3, Table A-3.1. For Stress Category C, the radius must be at least 1 in. [25 mm], and the thermal cut surface must be ground to bright metal. Without grinding to bright metal, the stress category is E', with a minimum radius of 3/8 in. [10 mm] permitted for this case (see Item 1.3). For weld access holes complying with Section J1.6 in rolled shapes, the same provisions apply (see Item 1.4). However, if the weld access hole is used in built-up members rather than in rolled shapes, Stress Category D is used in place of Stress Category C (see Item 3.3).

It should be noted that Table A-3.1, section 6 Base Metal at Welded Transverse Member Connections, calls for grinding of the weld end, and that grinding of the thermal cut edge of the attachment is not required (see Items 6.1 through 6.4). Similarly, for Item 7.2 in section 7 Base Metal at Short Attachments, only the weld end need be ground.

Bolt Holes

The allowance of thermally cut bolt holes for cyclically loaded applications as governed by RCSC was previously discussed (see pages 21-22).

AISC 360-16, Appendix 3 Fatigue, Table A-3.1 Fatigue Design Parameters, addresses bolted connections in Section 2 Connected Material in Mechanically Fastened Joints. When high-strength bolts are used and pretensioned, with faying surfaces prepared to provide slip resistance as either Class A or B, then Stress Category B is used for the base metal around the bolt hole (see Items 2.1 and 2.2). This condition includes plasma cut bolt holes that comply with the AISC requirements for thermally cut holes (*AISC 360-16,* section M2.5).

If the bolt is pretensioned, but the faying surface is not prepared for slip resistance to either Class A or B, and the hole is drilled or reamed, then Stress Category C is used (see Item 1.5).

If the hole is drilled or reamed, and no bolt is placed in the hole, then Stress Category D is used (see Item 1.5).

If the bolt is installed only to the snug-tight condition, the Note to the figures for Item 2.3 would indicate that Stress Category C can be used, which was originally used for riveted joints. Only riveted joints are included in the written description of Item 2.3. The inclusion of snug-tightened joints, with no provisions as to hole-making method, as a Stress Category C, the same as for pretensioned bolts in drilled or reamed holes, appears non-conservative. Until this topic is resolved, it is suggested that a connection with a bolt tightened only to the snug-tight condition be considered as:

1) an open hole similar to eyebar holes in Item 2.4, and that Stress Category E be used, or
2) a geometric discontinuity with radius above 3/8 in. [10 mm] that has not been ground (reamed) to bright metal, as described in Item 1.3, and that Stress Category E’ be used.

The latter recommendation is in agreement with recommendations from research using 1/2 in. [12.7 mm] thick plate (unpublished as of the date of this publication) that Stress Category E’ be used for non-pretensioned bolts in shear-bearing joints made using high definition plasma cut bolt holes. As noted below, other research has recommended Stress Category E for this condition.

For highway bridge structures, the *AASHTO LRFD Bridge Design Specifications*, Section 6 Steel Structures, should be used rather than AISC. Research by Garcia and Cicero (Garcia and Cicero, 2016) have recommended the fatigue design values in Table 10 for thermal cut bolt holes for AASHTO specifications, but it must be noted that these values are for open holes without bolts, and would be applicable to open holes and connections with bolts that are not pretensioned.

TABLE 10. RECOMMENDED FATIGUE CATEGORIES FOR OPEN HOLES AND FOR HOLES WITH SNUG-TIGHT BOLTS

	Current Category	Proposed Category
Drilled, or punched and reamed holes	D	No change proposed
Flame (oxyfuel) cut holes Thickness 25 mm (1 in.) or less	Not addressed	C
Plasma cut holes Thickness 25 mm (1 in.) or less	Not addressed	E

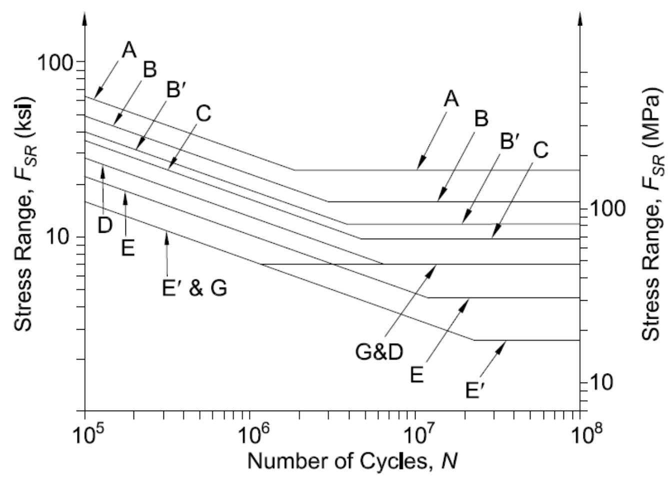


Fig. C-A-3.1. Fatigue resistance curves.

Courtesy of American Institute of Steel Construction AISC 358-16 Fig. C-A-3.1.

Figure 14. *AISC 360* fatigue curves

Canada

Thermal Cut Edges

CSA S16-14, clause 26 Fatigue, provides fatigue requirements. Table 9 in *CSA S16*, Detail Categories for load-induced fatigue, provides detail categories that are equivalent to the stress categories used in AISC. For thermal cut edges, the classifications are identical to those of AISC.

Bolt Holes

CSA S16-14 subclause 28.4.3 Thermally cut holes, limits thermally cut holes to statically loaded structures, and therefore plasma cut holes cannot be used for fatigue applications. In fatigue applications, holes may be punched (within limits), sub-punched, sub-drilled and reamed, or drilled, in accordance with subclause 28.4.1 Drilled and punched holes.

Europe

Thermal Cut Edges

Eurocode 3, *EN 1993 Design of steel structures*, Part 1-9: Fatigue, provides what are termed “Detail Categories”, often referred to as FAT Categories, short for Fatigue categories. The higher the value, which is based on the permitted stress range (in MPa) at 2,000,000 cycles, the greater the permitted stress range.

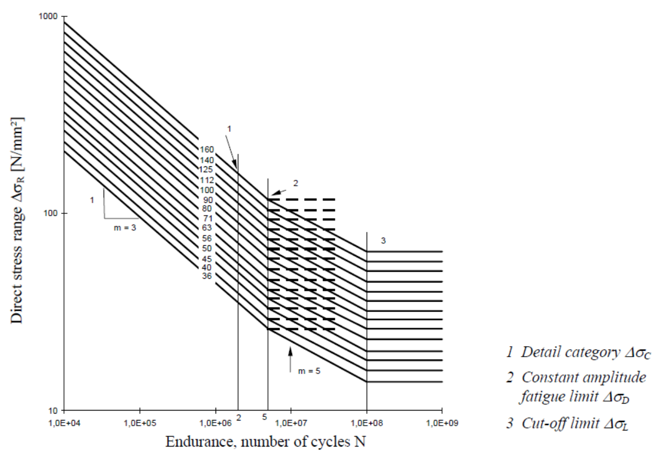


Figure 7.1: Fatigue strength curves for direct stress ranges

Courtesy of EN 1993-1-9:2005 Figure 7.1

Figure 15. *EN 1993-1-9:2005* fatigue curves

There are two FAT Categories for machine gas cut edges:

FAT140: Material with machine gas cut edges having shallow and regular draglines, with all visible signs of edge discontinuities removed. Cut areas are to be machined or ground and all burrs removed. Any machining scratches, for example from grinding operations, can only be parallel to the stresses. Re-entrant corners to be improved by grinding (slope ≤ 1/4) or evaluated. If weathering steel, downgrade to FAT125.

FAT125: Material with machine gas cut edges having shallow and regular drag lines or manual gas cut material, subsequently dressed to remove all edge discontinuities. Machine gas cut with cut quality according to *EN 1090*. Re-entrant corners to be improved by grinding (slope ≤ 1/4) or evaluated. If weathering steel, downgrade to FAT112.

As a matter of comparison, FAT160 includes rolled and extruded products comprising plates and flats, rolled sections, and seamless hollow sections, either rectangular or circular. Sharp edges, surface and rolling flaws must be improved by grinding until removed and a smooth transition is achieved.

Welded attachments where a radius is cut to transition stresses into the attachment, similar to *AISC 360-16* Table A-3.1 Section 6, are shown in *EN 1993:* Table 8.4 Weld attachments and stiffeners. Values range from FAT90 to FAT50, depending upon dimensional characteristics and weld type. For these details, the smooth transition radius may be made by machining or gas cutting the gusset plate before welding, followed by grinding the weld area so that the weld toe is removed at the end of the attachment.

Research was undertaken in Europe to update design standards to study new cutting methods, including plasma cutting, and to make recommendations for updating and incorporating these methods into the design standards. Testing included plasma cutting of structural steels ranging from 345 MPA [50 ksi] to 890 MPa [120 ksi], in thicknesses of 15 and 25 mm [0.59 and 1 in.] (Bannister et al, 2016).

For straight line plasma cuts, the study recommends the continued use of FAT125 as used in Eurocode 3. It does not address the use of FAT140 for plasma cut edges that have been finished, as the study focused on as-cut surfaces.

The study recommends the use of Class B in the British standard *BS 7608 Guide to Fatigue Design and Assessment of Steel Products*, for as-cut plasma cut surfaces, an improvement over what would have been considered Class C. Class B is defined as "Any flame cut edges subsequently machined or ground smooth. All visible signs of draglines should be removed from the flame cut-edge by grinding or machining." Class C is defined as "Any cutting of edges by planing or machine flame cutting with controlled procedure." There is no Class A in the standard.

The *BS 7608* standard uses a unique set of fatigue curves without a knee point. Class B has a similar S-N line as Stress Category B in *AISC 360-16*, except for beyond the AISC knee point (Figure 16).

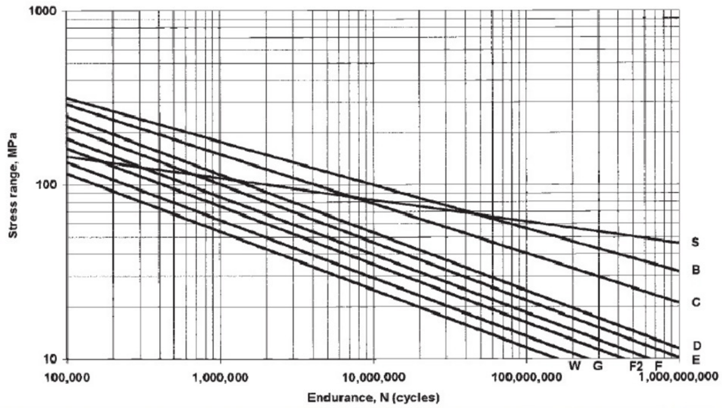


Figure 16. Fatigue curves from *BS 7608*

The IIW Fatigue Recommendations (Hobbacher, 2016) provide four FAT classes for thermal cut edges, two for machine cut and two for manually cut:

FAT140 Machine gas cut or sheared material with subsequent dressing, no cracks by inspection, no visible imperfections. All visible signs of edge imperfections are to be removed. The cut surfaces to be machined or ground, all burrs to be removed. No repair by welding refill. Notch effects due to shape of edges shall be considered.

FAT125 Machine thermally cut edges, corners removed, no cracks by inspection. Notch effects due to shape of edges shall be considered.

FAT100 Manually thermally cut edges, free from cracks and severe notches. Notch effects due to shape of edges shall be considered.

FAT80 Manually thermally cut edges, uncontrolled, no notch deeper than 0.5 mm. Notch effects due to shape of edges shall be considered.

The IIW Fatigue Recommendations also include FAT classes for welded attachments.

Within the finite fatigue life range, oxyfuel and plasma cutting edges have similar fatigue performance. Fatigue life decreases slightly with increasing material thickness, attributed to a higher statistical probability of crack initiation with thicker materials. Dross formation and edge conditions are more influential on fatigue performance than cut surface roughness. Because plasma cutting leaves minimal dross, crack initiation, should it occur, would be at either the top and bottom corner edge.

Bolt Holes

Bolt holes in fatigue applications are permitted to be made using plasma cutting, as stated in *EN 1090-2* clause 6.6.3 Execution of holing, which identifies acceptable holing methods as drilling, punching, laser, plasma or other thermal cutting, provided the hole meets the requirements for local hardness and quality of cut surface, according to clause 6.4 Cutting.

Fatigue design for members with bolt holes are addressed in *EN 1993-1-9* Table 8.1. *EN 1993-1-9* also considers the configuration of the bolted joint in determining the FAT class, in addition to bolt pretensioning (termed preloading). No reference is made to the condition of the faying surface for slip resistance.

FAT112 Double covered symmetrical joint with preloaded high strength bolts, checked on gross section

FAT90 Double covered joint with fitted bolts, checked on net section

One sided connection with preloaded high strength bolts, check on gross section

Structural element with holes subject to bending and axial forces, checked on net section

FAT80 One sided connection with fitted bolts, checked on net section

FAT50 One sided or double covered symmetrical connection with non-preloaded bolts in normal clearance holes, with no load reversals, checked on net section

The IIW Fatigue Recommendations do not include FAT classes for holes.

The Bannister, et al research performed extensive studies on thermally cut bolt holes, without consideration for influence of bolts (Bannister et al, 2016). For open holes, the following recommendations in Table 11 are made for plasma cut bolt holes:

TABLE 11. RECOMMENDED FATIGUE CATEGORIES FOR PLASMA CUT BOLT HOLES

	BS 7608	EN 1993-1-9
Flame (oxyfuel) cut bolt holes Thickness 25 mm [1 in.] or less	F	90
Plasma cut bolt holes Thickness 25 mm [1 in.] or less	G	63

Most fatigue crack initiation points are in the cut surface; therefore the piercing point and/or termination point is to be located at the end of the hole diameter parallel to the load direction. Fracture initiation from the plasma cut surface is unlike the crack initiation points for straight cut edges, which are at the top or bottom corner of the cut surface.

In the finite fatigue life range, oxyfuel cutting showed the best fatigue performance for holes. This is believed to be related with thermal heating during cutting. With oxyfuel cutting, the heat and time necessary to pierce the material, as well as to make the cut, are greater than that required for plasma cutting. The greater heat slows cooling, reducing the risk of a brittle heat-affected zone.

Australia / New Zealand

AS 4100-1998 (R2016), uses fatigue Detail Categories that parallel those of Europe's *EN 1993-1-9*. The term "thermal cutting" is used in clause 14.3.3. For highway and railroad bridges, the applicable standard is *AS 5100.6:2016* Bridge Design, Part 6: Steel, and Composite Construction.

Thermal Cut Edges

In *AS 4100-1998 (R016)*, there are two FAT Categories for thermal cut edges provided in Table 11.5.1(1) Detail Category Classification – Group 1 Non-Welded Details, as shown below. The term used is "gas-cut", although subclause 14.3.3 vCutting states that "Cutting may be by sawing, shearing, cropping, machining, thermal cutting (including laser cutting and plasma cutting) or water cutting processes, as appropriate."

FAT140 Material with gas-cut or sheared edges with no draglines. All hardened material and visible signs of edge discontinuities to be removed by machining or grinding in the direction of applied stress.

FAT125 Material with machine gas-cut edges with draglines or manual gas-cut material. Corners and visible signs of edge discontinuities to be removed by grinding in the direction of the applied stress.

No reduction is taken for weathering steel, as done in other standards, as subclause 11.1.1 states that "reduction of fatigue life due to corrosion or immersion" is not addressed.

In *AS 5100.6:2016*, there are two FAT Categories for thermal cut edges, similar to *EN 1993-1-9*:

FAT140 Machine gas cut or sheared material with subsequent dressing. All visible signs of edge discontinuities to be removed. The cut areas are to be machined or ground and all burrs to be removed. Any machinery scratches for example from grinding operations, can only be parallel to the stresses. Re-entrant corners to be improved by grinding (slope ≤ 1/4or evaluated using the appropriate stress concentration factor. No repair by weld refill. If weathering steel, downgrade to FAT125.

FAT125 Material with machine gas cut edges having shallow and regular drag lines or manual gas cut material, subsequently dressed to remove all edge discontinuities. Machine gas cut with cut quality according to Appendix F. Re-entrant corners to be improved by grinding (slope ≤ 1/4) or evaluated using the appropriate stress concentration factor. No repair by weld refill. If weathering steel, downgrade to FAT112.

In *AS 5100.6:2016*, subclause F3.3 Cutting permits cutting "by sawing, shearing, cropping, machining or thermal cutting, as appropriate." Table F3.3 Maximum Cut Surface Roughness, provides two criteria for maximum surface roughness in fatigue applications: for Detail Categories ≥ 80 MPa, 12 µm CLA; and for Detail Categories < 80 MPa, 25 µm CLA. For normal applications, i.e., where the face and edges remain as-cut or with minor dressing, the maximum surface roughness is 25 µm CLA. Cut surface roughnesses greater than the values given in Table F3.3 are to be improved by grinding, with grinding marks parallel to the direction of the cut.

Bolt Holes

In *AS 4100-1998 (R2016)* Table 11.5.1(1) Detail Category Classification – Group 1 Non-Welded Details, addresses bolted connections with 8.8/TF bolting category (high-strength pretensioned bolts in friction type joints with designated slip resistance) as FAT140, checked on the gross section. If not designated 8.8/TF, it remains Detail Category 140, but is checked on the net section. A warning is added that "Unsupported one-sided coverplate connections shall be avoided or the effect of the eccentricity taken into account in calculating stresses." There is no specific Detail Category provided for open holes. Subclause 14.3.5.1 on holing permits round holes for a bolt to be "machine flame cut, or drilled full size, or subpunched 3 mm [1/8 in.] undersize and reamed to size, or punched full size."

In *AS 5100.6:2016*, clause F3.5 Holing, subclause F3.5.1 General, states "A round hole for a bolt shall either be machine flame cut, or drilled full size, or subpunched 3 mm [1/8 in.] undersize and reamed to size, or punched full size. For railway bridges, holes that are machine flame cut full size or punched full size shall not be permitted."

AS *5100.6:2016* Table 13.10.1(B) Plain Members and Mechanically Fastened Joints, has adopted the requirements of *EN 1993-1-9* Table 8.1, as previously described for Europe, for Detail Categories for bolted joints.

Plasma Marking

Plasma cutting equipment can also be used to perform marking functions using the same cutting head but with reduced power (current density). This can include not only piece marks and labelling, but also accurately locating positions on the steel member where parts are to be attached, identifying the parts to be attached at that location, providing the weld symbol, marking locations for welded stud attachments, "center-punching" hole locations that may be made using other hole-making methods, and indicating other special work to be performed.

Such markings must be made using adequate power to provide visibility during fabrication, and provide for permanent visibility of piece marks and other assembly indicators, if used, after surface preparation and the application of coatings. In the case of architecturally exposed structural steel, it may be desirable to minimize the visibility of permanent marks exposed to view at close range.

Current standards neither explicitly permit nor prohibit the use of plasma markings on structural steel. Recent research has provided some information on the effects of plasma marking on the performance of structural steels in both static and cyclic applications.

NOTE: Issues that are not covered in a particular construction code or specification should be dispositioned by the engineer of record or other technical authority.

Wagner, et al, (Wagner, 2010) tested 345 MPa [50 ksi] structural steels marked with plasma using argon shielding gas at currents of 6, 10 and 14 amps. The line cut depths were 9, 130 and 240 μm [0.00035, 0.005, and 0.0094 in.], respectively, for locations other than the points of initiation, and cut depths of 130, 310 and 870 μm [0.005, 0.012, and 0.034 in.], respectively, at the points of initiation and at locations where the cutting passed over a previously marked location (Figure 17.).

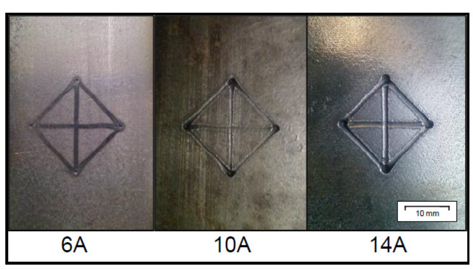


Figure 3. Plasma marking using the plasma gas argon at an intensity of the marking current of 6 A, 10 A, 14 A

Figure 17. Plasma markings at 6A, 10A and 14A

Under predominantly static loading, no reduction in tensile strength was noted from plasma marking.

Fatigue tests were performed using relatively thin tubular specimens of 3, 5 and 10 mm [1/8, 3/16, and 3/8 in.] thickness. High-cycle fatigue life was not significantly influenced by the material thickness, but was influenced by the depth of the plasma mark. Tests indicated a fairly flat slope to the S-N curve, with little difference between the 6 and 10 amp cuts, and a noticeable decrease with a 14 amp cut. Tests using a mechanical marking punch showed similar performance to that of the 14 amp cut, but with a slightly steeper slope to the S-N curve.

Using the S-N curves of the IIW Fatigue Recommendations, a 6 or 10 amp cut would be classified as 144 N/mm², and the 14 amp cut at 128 N/mm². The research suggested that a FAT class of 125 be used, which is the same FAT class for thermally cut edges (Figure 18).

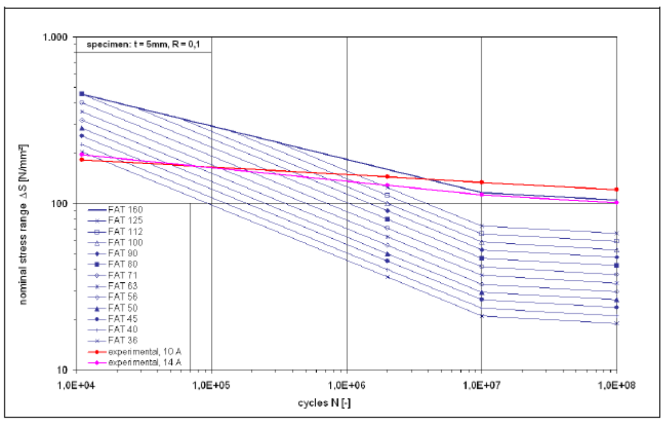


Figure 12. Results in the IIW net of S-N curves

Figure 18. Experimental Results for Fatigue Life with Plasma Marking (Wagner, 2010)

Stranghöner and Jungbluth (Stranghöner and Jungbluth, 2015) performed fatigue tests on 345 MPa [50 ksi] and 460 MPa [65 ksi] structural steel plates with thicknesses of 15 mm, 25 mm and 40 mm [0.59, 1, and 1.57 in.]. Marks were conventional letters and numbers, rather than the diamond pattern used by Wagner.

When marks were made with 6 amp current, there was no influence on fatigue life compared to that of the base metal. At 10 amp current, plasma marks were even with a rounded shape, with a maximum marking depth at initiation or crossing points between 400 µm to 500 µm [0.016 to 0.020 in.], somewhat more than reported by Wagner. The S-N curves, plotted against the curves of the IIW Fatigue Recommendations (similar to *EN 1993-1-9*), are shown in Figure 19. The results for the 15 mm and 25 mm [0.59 and 1 in.] plates were similar to those by Wagner that used the diamond pattern, and showed better fatigue life than those specimens using hard stamping. No influence of steel strength upon fatigue performance was noted. Fatigue tests on 40 mm [1.57 in.] plate were irregular for both grades of steel, so further testing was planned.

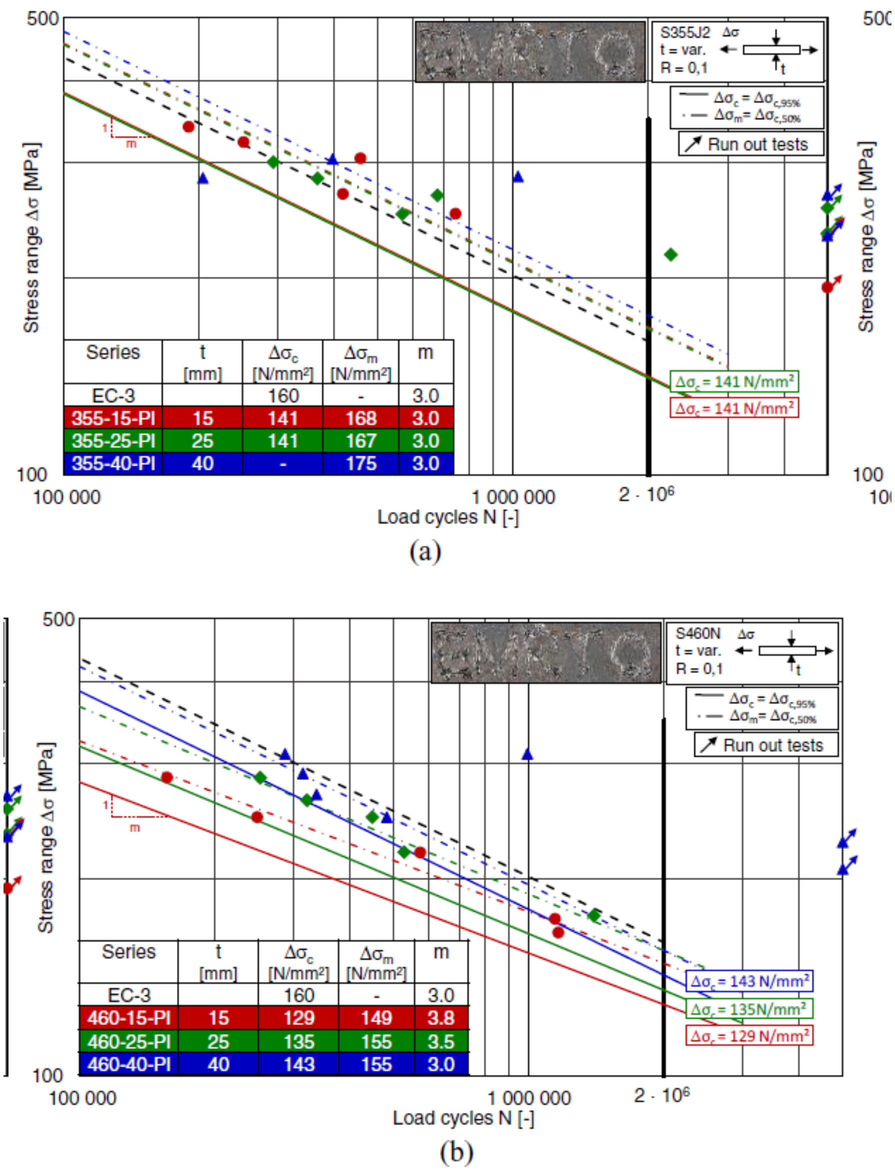


Figure 12 S-N curves of plasma marked specimens of (a) S355J2 and (b) S460N

Figure 19. S-N curves for plasma marked specimens

Manuel, et al, (Manuel, 2014) tested 50 ksi [345 MPa] weathering steel plate, ASTM A709 Grade 50W, of 1/4 in. [6 mm] thickness. Plasma markings with a depth of approximately 6 μin[150 μm] were made. A heat-affected zone (HAZ) of approximately 8 μin [200 μm] lied beneath the surface of the mark, and hardness testing and the resultant stress concentration factor was considered. Fourteen specimens were tested, where the results shown were plotted using standard AISC/AWS/AASHTO S-N curves (See Figure 20). The fatigue life of the specimens with plasma marks was not measurably different from the fatigue life of plain material. The authors, however, stated that more samples needed testing before firm conclusions could be made.

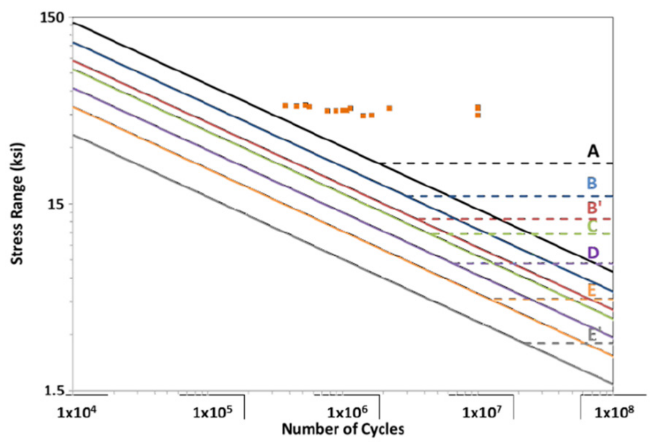


Figure 5-9. S-N curve for plasma-scribed 50W steel.

Figure 20. S-N curve for plasma marked 50W steel

Based upon the above studies, marks made using up to 10 amp, and perhaps to 15 amp, should be considered acceptable for static loading applications. For fatigue applications, marks made using up to 10 amp should be considered acceptable when design using fatigue values for thermal cut edges is used, and marks made using in the range of 5 amps to 6 amps may be considered acceptable with design values similar to base metal. These conditions, however, have not yet been codified, and research is still ongoing. Note that locations that are deemed fracture critical in bridge applications may warrant further limitations, and marks should not be made in locations of the member deemed fracture critical.

At the time of this publication, no known testing has been performed on steels subjected to high-strain, low-cycle fatigue applications, such as in the protected zones of seismic structures. Until such testing is done, markings should not be placed in areas inside the region subjected to plastic strain.

Quality Criteria for Plasma Cut Surfaces

The quality of a thermal cut surface is dependent on many variables, including:

(1) Material thickness

(2) Material surface condition

(3) Cutting procedure, including selection of gas

(4) Condition and design of cutting machine, including cutting heads

(5) Vibrations from nearby equipment, and

(6) Movement of the workpiece due to thermal expansion and contraction

There are several quality criteria applicable to the quality requirements for a thermal cut edge. These include surface roughness (the most common criteria for quality), but more specific criteria such as perpendicularity and surface hardness of the heat-affected zone (HAZ) may be required for certain applications and in certain standards.

Surface Roughness

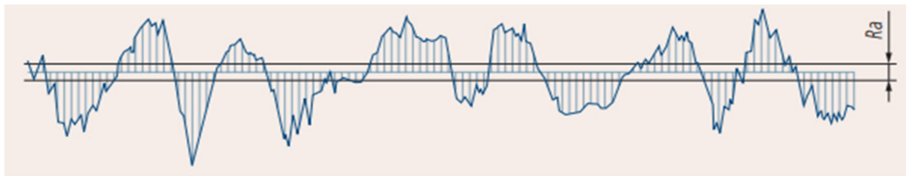
Surface roughness measurement, including general terminology, definitions of most measurement parameters, measurement procedures, data filtering and related information, is addressed in three major standards:

- *ISO 4287:1997 Geometrical Product Specifications (GPS) — Surface texture: Profile method — Terms, definitions and surface texture parameters*
- *ISO 4288:1996 Geometrical Product Specifications (GPS) — Surface texture: Profile method — Rules and procedures for the assessment of surface texture*
- *ASME B46.1:2009 Surface Texture (Surface Roughness, Waviness, and Lay)*

Two criteria, Ra and Rz, are the most commonly criteria used for surface roughness. The two criteria are not directly related, and cannot be mathematically converted from one criterion to the other. Ra and Rz measurements are stated in terms of µin in US Customary units, and µm in SI units.

µin —microinch, one millionth of an inch (0.000001 in.), 1 µin equals 0.0254 µm

µm — micrometer, one millionth of a meter (0.000001 m), 1 µm equals 39.37 µin



> **Figure 6**: Arithmetical mean roughness value Ra

Source: Mitutoyo Quick Guide to Surface Roughness Measurement

Figure 21. Arithmetical Mean Roughness Value Ra

Ra (Roughness average) is defined as “arithmetic average of the absolute values of the profile heights over the evaluation length” and is equal to the sum of the shaded areas of the profile divided by the evaluation length L, which generally includes several sampling lengths or cutoffs. For graphical determinations of roughness, the height deviations are measured normal to the chart centerline.

Ra is also known as centerline arithmetic average (AA) and centerline average (CLA).

The other common parameter, the average maximum height of the profile Rz, is defined in ASME B46.1 as the “the average of the successive values of Rt_i calculated over the evaluation length.” and is illustrated in Figure 22. Surface Profile Containing Two Sampling Lengths, l_1 and l_2, Also Showing the Rp_i and Rt_i Parameters. Rt_i is “the vertical distance between the highest and lowest points of the profile within a sampling length segment labeled *l*.” Rz5 indicates that five sampling lengths, or cutoffs, are used (see Figure 23).

Fig. 1-10 Surface Profile Containing Two Sampling Lengths, l_1 and l_2, Also Showing the Rp_i and Rt_i Parameters

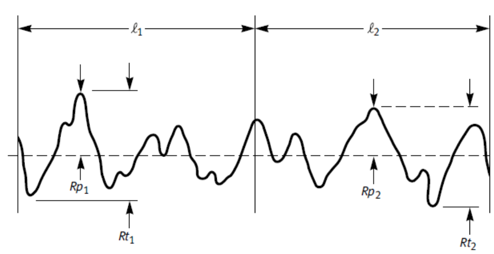


Figure 22. *ASME B46.1* Figure 1-10 on Surface Profile Measurement

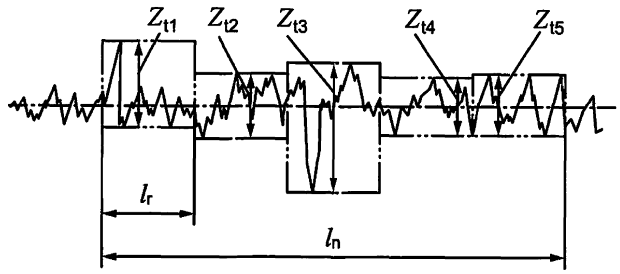


Figure 23. ***ISO 9013:2017*****, Figure 7 - Mean height of the profile Rz5**

Surface Roughness Measurement Tools

AWS C4.1-77 (R2010) *Criteria for Describing Oxygen-Cut Surfaces and Oxygen Cutting Surface Roughness Gauge* was originally published in 1977, and was reaffirmed in 2010. This standard uses text and a separate plastic replica Surface Roughness Guide for Oxygen Cutting, which shows four samples of oxygen cut surfaces with varying levels of quality. Although the title of the standard and plastic replica states "Oxygen Cutting", it is commonly used for plasma cutting as well (see Figure 24).

Use of the plastic replica is to serve as a visual comparator, rather than a tactile comparator, by holding it in close proximity to the thermal cut surfaced being examined, then selecting the most representative surface roughness value.

The standard and plastic replica does not state the specific surface roughness value, but it has been verified and it is commonly accepted to use the samples for the following surface roughness Ra values:

TABLE 12. RA SURFACE ROUGHNESS FOR EACH AWS SAMPLE NUMBER

Sample Number	Surface Roughness Ra	
	µin.	µm
1	4000	100
2	2000	50
3	1000	25
4	500	12.5

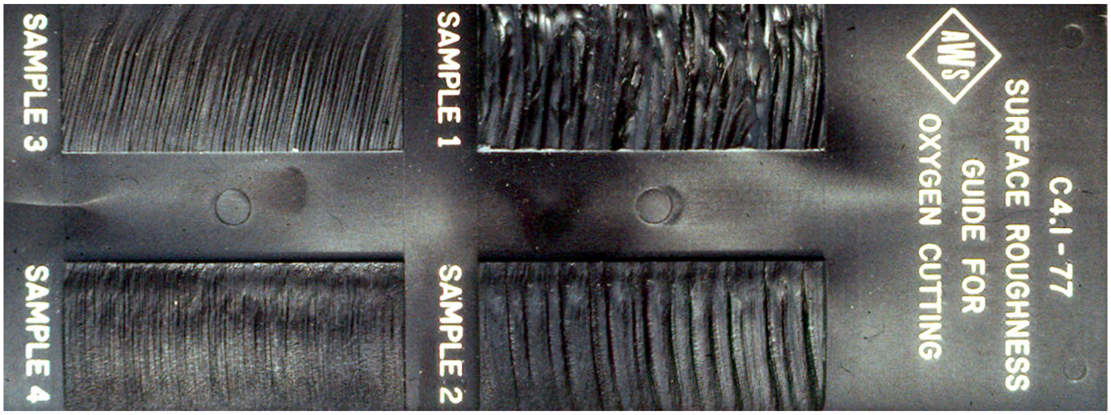


Figure 24. ***AWS C4.1-77*** **surface roughness guide**

Australia / New Zealand Cut Surface Roughness Measurement

Surface Roughness may be assessed by visual examination assisted by comparison with the surface of polyester resin replicas. These replicas represent 3 classes of surface roughness as described in Figure 25 which is from WTIA *Technical Note 5 – Flame Cutting of Steel*, published in April 1975 (WTIA, 1975).

The flame cut replica surfaces were prepared by the AWRA (Australian Welding Research Association, predecessor organization to the Welding Technology Institute of Australia, or WTIA), now called Weld Australia (WA). They were developed using machine flame cutting with standard equipment in a well-maintained condition.

Table 11 — AWRA Flame Cut Surface Roughness Classes

Class of Cut Note 1	Roughness (CLA) AS 1100 Part II — 1974 (Microns) Notes 2, 3, 4, 5	Roughness (CLA) AS B131 — 1962 (Micro-inches) Notes 2, 3, 4, 5
1	< 6.3	< 250
2	6.3 — 12.5	250 — 500
3	12.5 — <25	500 — < 1000

Notes

1 All three classes of flame cutting are readily obtainable with good quality equipment and correct techniques.

2 AS B131-1962 "Centre-line-average Height Method (M-System) for the Assessment of Surface Texture", and AS 1100, Part II-1974 "Drawing Practice Indication of Surface Texture".

3 These standards define surface roughness in terms of the centre-line-average value (CLA). For flame cutting the average trough to peak height of the surface is typically 4 times the CLA heights listed.

4 1 micron = 0.001 mm; and 1 micro-inch = 0.000001 in = 0.025 micron (μm)

5 The actual roughness of the AWRA replicas are 3, 6.3 and 19 micron for Class 1, 2 and 3 respectively.

Figure 25. Reprint of AWRA Flame Cut Surface Roughness Classes

Table 13 compares the plastic replica *AWS C4.1-77* (R2010) *Surface Roughness Guide for Oxygen Cutting* to the above WA/WTIA Classes:

TABLE 13. COMPARISON OF WTIA REPLICA VERSUS THE AWS REPLICA

WTIA Replica actual roughness µm	WTIA Class range roughness µm	WTIA Class	AWS C4.1 Sample	AWS Replica roughness	
				µm	µin
3	< 6.33	1	None	–	–
6.3	6.3 – 12.5	2	4	12.5	500
19	12.5 ≤ 25	3	3	25	1000
–	–	None	2	50	2000
–	–	None	1	100	4000

The AWS replica can be used to verify compliance with WTIA Class 2 using Sample 4 as a maximum surface roughness, and compliance with WTIA Class 3 using Sample 3 as a maximum surface roughness. To verify WTIA Class 1, another surface roughness gauge, such as those used for machining, must be used.

Contact-Type Surface Roughness/Profile Measuring Instruments

There are numerous manufacturers and styles of contact type surface roughness measuring instruments. These instruments use a stylus tip that makes direct contact with the surface of a sample. The stylus tip traces the surface of the sample and electrically detects the vertical motion of the stylus. The electrical signals are processed, including filtering, and digital records are generated.

Figure 26. Contact-type surface roughness instrument

Surface Hardness

EN 1090-2:2018 contains acceptance criteria for maximum hardness of a thermal cut edge, stated in 6.4.4 Hardness of free edge surfaces.

Thermal cut edges of carbon steel 460 MPa [65 ksi] yield strength cannot exceed a maximum hardness of 450, measured using the HV10 scale. Also, a note states that requirements can be necessary if the free edge is subject to fatigue or impact forces, is susceptible to hydrogen embrittlement, or for the purpose of ensuring the edge is suitable for surface preparation prior to application of paints and related products.

In addition, extra consideration should be made for free edges to be hot-dipped galvanized.

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AISC 341-16	Seismic Provisions for Structural Steel Buildings	2016
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	Steel Construction Manual, 15th Edition	2016

American Welding Society	www.aws.org	
AWS D1.1/D1.1M:2015	Structural Welding Code – Steel	2015
AWS D1.8/D1.8M:2016	Structural Welding Code – Seismic Supplement	2016
AASHTO/AWS D1.5M/ D1.5:2015	Bridge Welding Code	2015
AWS C4.1-77	Criteria for Describing Oxygen-Cut Surfaces and Oxygen Cutting Surface Roughness Gauge	1977

Research Council on Structural Connections	www.boltcouncil.org	
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Summary and Disclaimer

Plasma cutting and marking is an efficient and widely used process. Often times, the provisions of codes or standards are not understood and plasma cutting and marking are unnecessarily restricted for an application. This document sought to discuss and shed light on applicable code provisions that deal with plasma cutting in the structural industry.

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