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An American National Standard

Structural Welding Code— Titanium



American Welding Society®



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Structural Welding Code— Titanium

1st Edition

Prepared by the
American Welding Society (AWS) D1 Committee on Structural Welding

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

This code covers the requirements for design and welding of any type of titanium structure. Titanium pressure vessels and fluid-carrying pipe lines are specifically excluded. Clauses 1 through 5 and Annex A constitute a body of rules for the regulation of welding in titanium construction. A commentary on the code is also included with the document.



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Foreword

This foreword is not part of AWS D1.9/D1.9M:2007-ADD1, *Structural Welding Code—Titanium*, but is included for informational purposes only.

This first edition of the AWS D1.9/D1.9M, *Structural Welding Code—Titanium* (hereafter referred to as the code), represents the continuing AWS policy to provide standards for structural welding. This code is provided for the fabrication, erection, and manufacturing industries as a set of rules and regulations for the welding of structural titanium. This code does not concern itself with such design considerations as the arrangements of parts and the computation of stresses for proportioning the load-carrying members of a structure and their connection. Such considerations, it is assumed, are covered elsewhere in a general specification.

Users of the AWS D1.1/D1.1M, *Structural Welding Code—Steel*, will note similarities in the general format of this code and D1.1. This was done in order to benefit from the long established history of D1.1, adjusted for the specific requirements for titanium. In the early 2000s, interest was expressed in developing a similar consolidated code for the structural welding of titanium. Because of the interest of both the U.S. Department of Defense and the American Welding Society, it was decided to commence the task of developing a structural welding code for titanium.

A major difference between the AWS D1.1 and this code is that the former allows for prequalified welding procedures, this code does not. This is mainly because of the need to have a method of demonstrating evidence of a fabricator's competency to fabricate in one or more of the structural titanium alloys that may be welded under this code. Therefore, all the WPSs used for fabrication of work governed by this code are required to be qualified by test.

Clauses 1 through 5 constitute a body of rules for the regulation of welding on titanium structures. Procedures and standards are outlined for several methods of nondestructive testing. Methods included are visual, radiographic, ultrasonic, and dye penetrant.

Comments and suggestions for the improvement of this standard are welcome. They should be sent to the Secretary, AWS D1 Committee on Structural Welding, American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

Addenda

The following Addenda has been made and incorporated into the current edition of this document.

Page 81—Add a row above “Fine Scattered Porosity” to Table 5.2 for crack discontinuity types as follows:

Table 5.2
Radiographic Allowance for CJP and PJP Welds (see 3.8.2, 5.22, and A4.3.2)

Discontinuity Types	Base Material Thickness Range, in [mm]	Radiograph Category, in [mm]	Acceptance Level (Reference ASTM E 390 Radiographs)
Cracks	All	N/A	None allowed
Fine Scattered Porosity	$\geq 1/8$ [3] and $\leq 1/2$ [12]	Up to 3/8 [10], incl.	1
	$> 1/2$ [12] and $\leq 1-1/2$ [38]	Up to 3/4 [19], incl.	1
	$> 1-1/2$ [38] and ≤ 3 [76]	Up to 2 [50], incl.	2
Coarse Scattered Porosity	$\geq 1/8$ [3] and $\leq 1/2$ [12]	Up to 3/8 [10], incl.	1
	$> 1/2$ [12] and $\leq 1-1/2$ [12]	Up to 3/4 [19], incl.	1
	$> 1-1/2$ [38] and ≤ 3 [76]	Up to 2 [50], incl.	2
Linear Porosity or Rounded Indications	$\geq 1/8$ [3] and $\leq 1/2$ [12]	Up to 3/8 [10], incl.	1
	$> 1/2$ [12] and $\leq 1-1/2$ [38]	Up to 3/4 [19], incl.	1
	$> 1-1/2$ [38] and ≤ 3 [76]	Up to 2 [50], incl.	2
Nonmetallic Inclusions	$\geq 1/8$ [3] and $\leq 1/2$ [12]	Up to 3/8 [10], incl.	2
	$> 1/2$ [12] and $\leq 1-1/2$ [38]	Up to 3/4 [19], incl.	2
	$> 1-1/2$ [38] and ≤ 3 [76]	Up to 2 [50], incl.	3
Tungsten Inclusions	$\geq 1/8$ [3] and $\leq 1/2$ [12]	Up to 3/8 [10], incl.	2
	$> 1/2$ [12] and ≤ 3 [76]	Up to 3/4 [19], incl.	2
Incomplete Joint Penetration CJP only	$\geq 1/8$ [3] and $\leq 1/2$ [12]	Up to 3/8 [10], incl.	2
	$> 1/2$ [12] and $\leq 1-1/2$ [38]	Up to 3/4 [19], incl.	2
	$> 1-1/2$ [38] and ≤ 3 [76]	Up to 2 [50], incl.	3
Incomplete Fusion CJP only	$\geq 1/8$ [3] and $\leq 1/2$ [12]	Up to 3/8 [10], incl.	2
	$> 1/2$ [12] and $\leq 1-1/2$ [38]	Up to 3/4 [19], incl.	2
	$> 1-1/2$ [38] and ≤ 3 [76]	Up to 2 [50], incl.	3
Incomplete Joint Penetration—Partial joint penetration welds only	All	N/A	1/32 [0.8] width full weld length 1/16 [1.5] width 4T in 8T weld length
Incomplete Fusion—Partial joint penetration welds only	All	N/A	1/32 [0.8] width full weld length 1/16 [1.5] width 4T in 8T weld length

Notes:

- Porosity or inclusions allowed by this table shall be cause for rejection when closer than twice their maximum dimension to an edge or extremity of a weldment in a highly stressed or critical area, as determined by design engineering personnel.
- Linear is described as having a length greater than three times the width. Rounded is defined by the converse.

Table of Contents

	Page No.
<i>Personnel (Addenda)</i>	v
<i>Personnel (Original)</i>	vii
<i>Foreword</i>	ix
<i>List of Tables</i>	xiv
<i>List of Figures</i>	xv
1. General Requirements	1
1.1 Scope	1
1.2 Limitations	1
1.3 Terms and Definitions	1
1.4 Responsibilities	2
1.5 Approval	2
1.6 Welding Symbols	2
1.7 Safety Precautions	2
1.8 Standard Units of Measurement	3
1.9 Reference Documents	3
2. Design of Welded Connections	5
Part A—General Requirements	5
2.1 General	5
2.2 Drawings and Design Data/Model	5
2.3 Allowable Stresses	5
Part B—Weld Lengths and Areas	5
2.4 Groove Welds	5
2.5 Fillet Welds	6
2.6 Plug and Slot Welds	6
Part C—Structural Details	7
2.7 Filler Plates	7
2.8 Backing Removal	7
2.9 Lap Joints	7
2.10 Transitions of Butt Joints	7
2.11 Connections or Splices	7
2.12 Combinations of General Types of Welds	8
2.13 Skewed T-Joints	8
Part D—Cyclically Loaded Structures	8
2.14 General	8
2.15 Region of Applicability	8
2.16 Allowable Stresses	8
2.17 Combined Stresses	8
2.18 Cyclic Load Stress Range	8
3. Qualification	17
3.1 Scope	17

Part A—General Requirements	17
3.2 General	17
3.3 Qualification of WPSs.....	17
3.4 Qualification of Welding Personnel.	18
3.5 Common Requirements for WPS and Welding Personnel Performance Qualification	18
Part B—Types of Tests, Test Methods, and Acceptance Criteria.....	19
3.6 Types of Tests, Test Methods, and Acceptance Criteria Tests	19
3.7 Visual Examination	19
3.8 Radiographic Examination.....	20
3.9 Macroexamination and Microexamination	20
3.10 Tension Tests—Groove Welds	21
3.11 Bend Tests—Groove Welds—Plate and Pipe	21
3.12 Chemical Analysis	23
Part C—WPS Qualification.....	23
3.13 General WPS Qualification.....	23
3.14 Limits of Qualified Positions for WPSs.....	23
3.15 Limitation of Essential Variables—WPS Qualification	23
3.16 Tests—WPS Qualification	23
3.17 Retests	24
Part D—Performance Qualification	24
3.18 General Performance Qualification.....	24
3.19 Limits of Qualified Positions for Performance	24
3.20 Test Plate Weldment Types	24
3.21 Limitation of Essential Variables—Welder, Welding Operator, and Tack Welder Performance Qualification.....	25
3.22 Tests—Performance Qualification	25
3.23 Retests	26
4. Fabrication	57
4.1 Scope.....	57
4.2 Processes	57
4.3 Base Metals	57
4.4 Filler Metal.....	57
4.5 Tungsten Electrodes	57
4.6 Shielding Gases.....	57
4.7 Welding and Cutting Equipment.....	57
4.8 Backing	58
4.9 Preheat and Interpass Temperatures.....	58
4.10 Welding Environment	58
4.11 Compliance with Design.....	58
4.12 Preparation of Base Metal.....	58
4.13 Assembly.....	58
4.14 Tack Welds and Temporary Welds	59
4.15 Dimensional Tolerances	59
4.16 Arc Strikes.....	61
4.17 Cleaning After Completion of Welds.....	61
4.18 Weld Termination.....	61
4.19 Control of Distortion and Shrinkage	61
4.20 Weld Profiles	61
4.21 Repairs	61
4.22 Anti-Spatter Compound	62

Page No.

4.23 Peening.....	62
4.24 Stress-Relief Treatment.....	62
5. Inspection	71
Part A—General Requirements	71
5.1 General	71
5.2 Inspection of Materials.....	72
5.3 Inspection of Welding Procedure Specifications and Equipment	72
5.4 Verification of Welder, Welding Operator, and Tack Welder Qualifications	72
5.5 Inspection of Work and Records	72
5.6 Obligations of the Contractor.....	73
5.7 Nondestructive Testing.....	73
Part B—Visual Inspection	73
5.8 General	73
Part C—Penetrant Testing	74
5.9 General	74
Part D—Radiographic Inspection.....	74
5.10 General	74
5.11 Radiographic Procedures	74
5.12 Coverage and Acceptability of Welds	76
5.13 Examination, Report, and Disposition of Radiographs.....	76
Part E—Ultrasonic Testing of Groove Welds.....	76
5.14 General	76
5.15 Operator Requirements	77
5.16 Procedure	77
Part F—Other Examination Methods	77
5.17 General	77
5.18 Radiation Imaging Systems	77
Part G—Acceptance Criteria	77
5.19 General	77
5.20 Visual Examination	78
5.21 Penetrant Testing	78
5.22 Radiographic Testing	78
5.23 Ultrasonic Testing	78
Annex A (Normative)—Welding of Titanium Armor Structures	91
Annex B (Normative)—Reference Documents	103
Annex D (Informative)—Safe Practices.....	107
Annex E (Informative)—Sample Welding Forms	111
Annex F (Informative)—Guidelines for the Preparation of Technical Inquiries.....	121
Annex G (Informative)—Metallurgical Sample Preparation	123
Commentary	127
List of AWS Documents on Structural Welding.....	145

List of Tables

Table	Page No.
2.1 Allowable Stresses in Connections	9
2.2 Minimum Diameter of Hole for Plug Welds or Width of Slot for Slot Welds.....	9
2.3 Fatigue Stress Provisions	10
3.1 WPS Qualification—Type of Weld and Position Limitations.....	27
3.2 Welder, Welding Operator, and Tack Welder Performance Limitations	28
3.3 Limitations of Essential Variables: of a WPS	29
3.4 Limitations of Variables for Base Materials	33
3.5 Number and Type of Test Specimens and Range of Thickness Qualified—WPS Qualification.....	34
3.6 Number and Type of Test Specimens and Range of Thickness Qualified for Welder, Welding Operator, and Tack Welder Qualification.....	36
4.1 Strengths of Welded Titanium Alloys and Products Available for Structure Applications	63
4.2 Recommended Titanium Alloy Filler Metals for Structural Welding of Various Base Titanium Alloys	66
5.1 Visual and Penetrant Acceptance Criteria.....	79
5.2 Radiographic Allowance for CJP and PJP Welds	81
5.3 Coloration Acceptance Criteria.....	82
5.4 Hole-Type IQI Requirements.....	82
5.5 Wire IQI Requirements	83
5.6 IQI Selection and Placement.....	83
A.1 Thickness of Test Plates and Requirements for Ballistic Tests.....	95
A.2 Radiographic Sampling Requirements.....	95

List of Figures

Figure	Page No.
2.1 Maximum Fillet Weld Size Along Edges in Lap Joints	11
2.2 Fillets in Skewed T-Joints	11
2.3 Thin Filler Plates	12
2.4 Thick Filler Plates	13
2.5 Minimum Amount of Lap and Double Fillet Weld.....	13
2.6 Thickness	14
2.7 Plan Views of Width Transitions.....	15
2.8 Effective Throat.....	15
2.9 Cyclic Load Stress Range	16
3.1 Positions of Groove Welds	38
3.2 Positions of Fillet Welds	39
3.3 Position of Test Plates for Groove Welds.....	40
3.4 Positions of Groove Welds in Pipe or Tubing	41
3.5 Positions of Test Plates for Fillet Welds	42
3.6 Positions of Test Pipes for Fillet Welds	43
3.7 Weld Contact Angle Definition.....	44
3.8 Root Fusion Requirements for Complete Penetration T-Joints in Material Numbers M51, M52, M53, and M54.....	44
3.9 Reduced Section Tension Specimens—Plate and Pipe	45
3.10 Alternate Reduced Section Tension Specimen for Pipe (3 in [76 mm] Diameter or Less) or Tubing.....	46
3.11 Full Section Tension Specimens—Small Diameter, 1 in [25 mm] Outside Diameter or Less, Pipe or Tubing.....	46
3.12 Reduced All-Weld Tensile Specimens	47
3.13 Transverse Side Bend Specimens	48
3.14 Transverse Face and Root Bend Specimens.....	48
3.15 Longitudinal Face and Root Bend Specimens	50
3.16 Wraparound Guided Bend Jig.....	50
3.17 Plate—Relative Location of Test Specimens	51
3.18 Box Tubing—Relative Location of Test Specimens for WPS and Performance Qualifications	51
3.19 Relative Location of Test Specimens	52
3.20 Fillet Weld—Relative Location of Test Specimens	52
3.21 Fillet Weld Pipe—Relative Location of Test Specimens	53
3.22 Fillet Weld Plate to Pipe—Relative Location of Test Specimens	54
3.23 Plug Weld Macroetch Test Plate—Welder, Welding Operator, and Tack Welder Qualification.....	55
3.24 Requirements for Requalification Based on the Replacement of Permanent Backing with an Inert Gas Backing and Vice Versa for CJP Welds.....	56
4.1 Acceptable and Unacceptable Weld Profiles	67
4.2 Warpage of Flanges: Measurement of the Flange Toe Offset for an “I” or “H” Configuration Section.....	68
4.3 Depth Variation: Relative Location at Which the Beam Depth A-B is Measured for an “I” or “H” Configuration Section	69
4.4 Least Panel Dimension “d”	70
5.1 Hole Type IQI Design	84
5.2 Wire IQI Design.....	85
5.3 RT Identification and Hole-Type or Wire IQI Locations on Approximately Equal Thickness Joints 10 in [250 mm] and Greater in Length	86

Figure	Page No.
5.4 RT Identification and Hole-Type or Wire IQI Locations on Approximately Equal Thickness Joints Less than 10 in [250 mm] in Length.....	87
5.5 RT Identification and Hole-Type or Wire IQI Locations on Transitions Joints 10 in [250 mm] and Greater in Length	88
5.6 RT Identification and Hole-Type or Wire IQI Locations on Transition Joints Less than 10 in [250 mm] in Length	89
A.1 Specimen for Armor Welder Qualification	96
A.2 Ballistic Test Plate.....	96
A.3 Single Groove Welds.....	97
A.4 Double Groove Weld.....	97
A.5 Examples of Weld Cracks That Can Occur from Projectile Impact and Indication of Measurement of Total Weld Crack for Acceptance Purposes.....	98
A.6 Welded Armor Data	99
A.7 Armor Plate Data	100
A.8 Weld Radiographic Report.....	101
G.1 Well Prepared Grade 2 Titanium Metallographic Specimen	126
G.2 Poorly Prepared Grade 2 Titanium Metallographic Specimen	126

Structural Welding Code—Titanium

1. General Requirements

1.1 Scope

The code contains the requirements for fabricating titanium structures. When the code is stipulated in contract documents, conformance with all provisions of the code shall be required, except for those provisions that the Engineer (see 1.4.1) or contract documents specifically modify or exempt.

Annex A of the code contains requirements for the ballistic testing of structural titanium welds.

The following is a summary of the code clauses:

(1) **General Requirements.** This clause contains basic information on the scope and limitations of the code.

(2) **Design of Welded Connections.** This clause contains requirements for the design of welded connections.

(3) **Qualification.** This clause contains the qualification requirements for WPSs and welding personnel (welders, welding operators, and tack welders) necessary to perform code work.

(4) **Fabrication.** This clause contains the requirements for the preparation, assembly, and workmanship of welded titanium structures.

(5) **Inspection.** This clause contains criteria for the qualifications and responsibilities of inspectors, acceptance criteria for production welds, and procedures for performing visual inspection and NDE (nondestructive testing).

1.2 Limitations

The code is not intended to be used for the following:

- (1) Pressure vessels or pressure piping.
- (2) Base metals other than titanium.

(3) Aerospace structures.

(4) Titanium material less than 1/8 in [3 mm]. When base materials thinner than 1/8 in [3 mm] are to be welded the requirements of AWS B2.1, *Specification for Welding Procedure and Performance Qualification*, apply for qualification in conjunction with applicable provisions of this code.

1.3 Terms and Definitions

The welding terms used in the code shall be interpreted in conformance with the definitions given in AWS A3.0, *Standard Welding Terms and Definitions*, and the following definitions:

1.3.1 Owner. The “Owner” is the individual, company, or government agency that has legal title or right to the product produced under the code.

1.3.2 Engineer. “Engineer” shall be defined as a duly designated individual who acts for, and in behalf of, the Owner on all matters within the scope of the code.

1.3.3 Contractor. “Contractor” shall be defined as any company, or that individual representing a company, responsible for the fabrication, erection, manufacturing, or welding, in conformance with the provisions of the code.

1.3.4 Subcontractor. A person or business, which has a contract (as an “independent contractor” and not an employee) with a Contractor to provide some portion of the work or services on a project, which the Contractor has agreed to perform.

1.3.5 OEM (Original Equipment Manufacturer). “OEM” shall be defined as that single Contractor that assumes some or all of the responsibilities assigned by the code to the Engineer.

1.3.6 Inspectors

1.3.6.1 Contractor's Inspector. "Contractor's inspector" shall be defined as the duly designated person who acts for, and in behalf of, the Contractor on all inspection and quality matters within the scope of the code and of the contract documents.

1.3.6.2 Verification Inspector. "Verification Inspector" shall be defined as the duly designated person who acts for, and in behalf of, the Owner or Engineer on all inspection and quality matters specified by the Engineer.

1.3.6.3 Inspector(s) (unmodified). When the term "Inspector" is used without further qualification as the specific Inspector category described above, it applies equally to the Contractor's Inspector and the Verification Inspector within the limits of responsibility described in 5.1.1.

1.3.7 Code Terms. "Shall," "Should," and "May." "Shall," "should," and "may" have the following significance:

1.3.7.1 Shall. Code provisions that use "shall" are mandatory unless specifically modified in contract documents.

1.3.7.2 Should. The word "should" is used to recommend practices that are considered beneficial, but are not requirements.

1.3.7.3 May. The word "may" in a provision allows the use of optional procedures or practices that can be used as an alternative or a supplement to code requirements. Those optional procedures that require the Engineer's approval shall either be specified in the contract documents, or require the Engineer's written approval. The Contractor may use any option without the Engineer's approval when the code does not specify that the Engineer's approval shall be required.

1.4 Responsibilities

1.4.1 Engineer's Responsibilities. The Engineer shall be responsible for the development of the contract documents that govern products or structural assemblies produced under the code. The Engineer may add to, delete from, or otherwise modify, the requirements of the code to meet the particular requirements of a specific structure. All requirements that modify the code shall be incorporated into contract documents.

The Engineer shall specify in contract documents, as necessary, and as applicable, the following:

(1) Code requirements that are applicable only when specified by the Engineer.

(2) All additional NDE that is not specifically addressed in the code.

(3) Verification inspection.

(4) Weld acceptance criteria other than that specified in Clause 5.

(5) Level of inspection—Class A, B, or C and the applicability of Annex A.

(6) All additional requirements that are not specifically addressed in the code.

(7) For OEM applications, the responsibilities of the parties involved.

1.4.2 Contractor's Responsibilities. The Contractor shall be responsible for performing work in conformance with the requirements of the code and contract documents.

1.4.3 Inspector's Responsibilities

1.4.3.1 Contractor Inspection. Contractor inspection shall be supplied by the Contractor and shall be performed as necessary to ensure that materials and workmanship meet the requirements of the contract documents.

1.4.3.2 Verification Inspection. The Engineer shall determine if Verification Inspection shall be performed. Responsibilities for Verification Inspection shall be established between the Engineer and the Verification Inspector.

1.5 Approval

All references to the need for approval shall be interpreted to mean approval by the Engineer.

1.6 Welding Symbols

Welding symbols shall be those shown in AWS A2.4, *Symbols for Welding, Brazing, and Nondestructive Examination*. Special conditions shall be fully explained by added notes or details.

1.7 Safety Precautions

Safety and health issues and concerns are beyond the scope of this standard and therefore are not fully addressed herein. Annex D does address some safety

issues. Safety and health information is also available from other sources, including, but not limited to, ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*, and applicable federal, state, and local regulations.

are shown within brackets [] or in appropriate columns in tables and figures. The measurements may not be exact equivalents; therefore, each system must be used independently.

1.8 Standard Units of Measurement

This standard makes use of both U.S. Customary Units and the International System of Units (SI). The latter

1.9 Reference Documents

Annex B contains a list of all documents referenced in the code.

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2. Design of Welded Connections

Part A *General Requirements*

2.1 General

This clause covers the design of welded connections. The provisions are applicable to structures welded from wrought, tubular, and cast titanium alloys, and combinations of these product forms.

2.2 Drawings and Design Data/Model

2.2.1 General. The drawing and or design data/model shall clearly show full and complete information regarding the following:

- (1) Base metal specifications
- (2) Dimensions of the members being joined
- (3) The location, type, size, and extent of all welds

2.2.2 Special Details. When special groove details are required, they shall be detailed in the contract documents.

2.2.3 Joint Preparation. The detail drawings shall clearly indicate, by means of welding symbols, sketches, or both, the preparation and tolerances for fit-up of material for the required joints. If joints with backing are to be used, the material, width, thickness, and contour (if any), for such backing shall be shown.

2.2.4 Inspection. The following classes of inspection shall be indicated by letter classification added to the welding symbol or elsewhere on the drawing. The acceptance criteria for each type of inspection are defined in Clause 5:

(1) *Class A.* Cyclically loaded structures and statically loaded structures requiring inspection criteria greater than those of class B. This class of welds is not applicable to Annex A joints.

(2) *Class B.* Statically loaded. This class of welds is not applicable to Annex A joints.

(3) *Class C.* Ballistically loaded. This class of welds applies to joints which have been designed to withstand a ballistic threat in structures that are used in military applications.

Any joint requiring additional inspection requirements shall be identified on the drawings.

2.3 Allowable Stresses

The allowable stresses in welds and connections shall not exceed those given in Table 2.1. Special consideration is required where either

- (1) Dissimilar titanium grades are joined, or
- (2) The weld filler metal has not been selected in accordance with Table 4.2.

It should be noted that some combinations of weld metal and base metal may introduce additional issues that need to be assessed before acceptance of the design, examples of such conditions are described in the commentary.

Designs exceeding the loading and fatigue life conditions in Figure 2.9 and alternative or special weld configurations not listed in Table 2.3 shall be permitted subject to agreement with the Engineer, and supported by experimental data or engineering analysis or both.

Part B *Weld Lengths and Areas*

2.4 Groove Welds

2.4.1 Effective Length. The maximum effective weld length of any groove weld, regardless of orientation,

shall be the width of the part joined, perpendicular to the direction of tensile or compressive stress. For groove welds transmitting shear, the effective length is the length specified.

2.4.2 Complete Joint Penetration (CJP) Groove Welds.

The weld size of a complete joint penetration groove weld shall be the thickness of the thinner part joined. Weld reinforcement shall not be used when calculating weld size.

2.4.3 Partial Joint Penetration (PJP) Groove Welds.

Weld reinforcement shall not be used when calculating weld size.

2.4.4 Effective Area. The effective area shall be the product of the effective weld length multiplied by the weld size.

2.5 Fillet Welds

2.5.1 Maximum Weld Size. The maximum fillet weld size permitted along edges of material shall be as shown in Figure 2.1 and detailed in the following subclauses:

(1) The thickness of the base metal, for metal less than 1/4 in [6 mm] in thickness.

(2) 1/16 in [1.5 mm] less than the thickness of base metal, for metal 1/4 in [6 mm] or more in thickness, unless the weld size is designated on the drawing or the weld is designated on the drawing to be built out to obtain full throat thickness. The distance between the edge of the base metal and toe of the weld may be less than 1/16 in [1.5 mm], provided the edge is clearly visible and the weld size clearly verifiable.

2.5.1.1 The effective length of a straight fillet weld (not curved) shall be the overall length of the full-size fillet, including end returns with lengths no greater than the width of the narrower member. No reduction in effective length need be made for either the start or the crater of the weld if the weld is of full size throughout its length.

2.5.1.2 The effective length of a curved fillet weld shall be measured along the centerline of the effective throat. If the effective length of a fillet weld in a hole or slot leads to an effective area greater than the area found from 2.6.1, then the effective length of the fillet weld about the curve shall be used.

2.5.1.3 The minimum effective length of a fillet weld shall be at least four times the weld size, or the weld size shall be considered not to exceed one fourth its effective length.

2.5.1.4 The minimum length of an intermittent fillet weld shall be 1-1/2 in [38 mm] or four times the weld size, whichever is greater.

2.5.2 Effective Area. The effective area of the fillet weld shall be the product of the effective weld length and the effective throat. Stress in a fillet weld shall be considered as shear applied to this area, for any direction of applied load.

2.5.3 Effective Throat. For fillet welds between parts meeting at angles between 80° and 100° the effective throat (E) shall be taken as the shortest distance from the joint root to the weld face of a 90° diagrammatic weld (see Figure 2.8). For welds in acute angles between 60° and 80° and for welds in obtuse angles greater than 100°, the weld leg size required to provide the specified effective throat shall be calculated to account for geometry.

2.5.4 Fillets in Holes or Slots. Fillet welds in holes or slots in lap joints may be used to transfer shear, to prevent buckling, or to prevent separation of lapped parts. These fillet welds may overlap previous parts of the weld, subject to the provisions of 2.5.1.2. Fillet welds in holes or slots shall not be considered plug and slot welds.

2.5.5 Fillets in Skewed T-Joints. Fillet welds may be used in skewed T-joints having a dihedral angle of not less than 60° nor more than 120° (see Figure 2.2, details A and B).

2.5.6 Size and Spacing of Holes and Slots. Minimum spacing and dimensions of holes or slots when fillet welding is used shall conform to the requirements of 2.6.

2.6 Plug and Slot Welds

2.6.1 Effective Area. The effective area shall be the nominal area of the hole or slot in the plane of the faying surfaces. Plug and slot welds shall be designed to resist shear loads parallel to their effective area.

2.6.2 Minimum Plug Hole Diameter. The hole diameter for a plug weld shall be no less than that specified in Table 2.2.

2.6.3 Minimum Spacing of Plug Welds. The minimum center-to-center spacing of plug welds shall be four times the diameter of the hole.

2.6.4 Maximum Slot Length. The length of the slot for a slot weld shall not exceed ten times the thickness of the base metal. The width of the slot shall be no less than that specified in Table 2.2.

2.6.5 Slot Ends. The ends of the slot shall be semicircular or shall have the corners rounded to a radius not less than the thickness of the part containing it, except those ends which intersect an edge of the part.

2.6.6 Minimum Spacing of Slot Welds. The minimum spacing of lines of slot welds in a direction transverse to

their length shall be four times the width of the slot. The minimum center-to-center spacing in a longitudinal direction on any line shall be two times the length of the slot.

2.6.7 Fill Depth. The depth of fill of plug or slot welds in metal 5/8 in [16 mm] in thickness or less shall be equal to the thickness of the material. In metal over 5/8 in [16 mm] in thickness, it shall be at least one-half the thickness of the material, but not less than 5/8 in [16 mm].

Part C

Structural Details

2.7 Filler Plates

Wherever it is necessary to use filler plates in joints required to transfer applied force, the filler plates and the connecting welds shall conform to the requirements of 2.7.1 or 2.7.2, as applicable.

2.7.1 Thin Filler Plates. A filler plate less than 1/4 in [6 mm] thick (see Figure 2.3) shall not be used to transfer loads, but shall be kept flush with the welded edges of the load-carrying part. The weld sizes along such edges shall be increased over the required sizes by an amount equal to the thickness of the filler plate.

2.7.2 Thick Filler Plates. Any filler plate 1/4 in [6 mm] or more in thickness (see Figure 2.4) shall extend beyond the edges of the base metal. It shall be welded to the part on which it is fitted, and the joint shall have sufficient strength to transmit the load into the base metal as an eccentric load. The welds joining the base metal to the filler plate shall be sufficient to transmit the load from the base metal and shall be long enough to avoid over stressing the filler plate along the toe of the weld.

2.8 Backing Removal

In statically loaded structures, backing need not be removed. In cyclically loaded structures, backing transverse to the direction of computed stress shall be removed and the joint finished smooth. Backing parallel to the direction of the computed stress or not subject to detrimental fatigue problems as a result of the computed stress need not be removed. In ballistic structures backing shall be removed.

2.9 Lap Joints

2.9.1 Minimum Amount of Lap. The minimum amount of lap shall be five times the thickness of the thinner part, but not less than 1 in [25 mm] (see Figure 2.5).

2.9.2 Double Fillet Welded. Lap joints shall be double-fillet welded (see Figure 2.5), except where deflection of the joint is sufficiently restrained to prevent it from opening under load. Under this condition joints may be single fillet welded.

2.9.3 Double Plug or Slot Welds. To prevent buckling or separation the parts shall be connected by at least two transverse lines of plug or slot welds.

2.10 Transitions of Butt Joints

2.10.1 Thickness Transition. Butt joints between axially aligned members of different thicknesses, and subject to tensile stress greater than one-third of the allowable design tensile stress, shall be made in such a manner that the slope of the transition does not exceed 1 in 2-1/2 with the surface of either part (see Figure 2.6). The transition shall be accomplished by sloping the weld surface, or by sloping the weld surface and chamfering, or by chamfering the thicker part.

2.10.2 Width Transition. Butt joints between parts having different widths shall have a smooth transition between offset edges. The transition shall be accomplished by tapering the wider part (see Figure 2.7), radius-ing the wider part, sloping the weld metal, or by any combination of these. The slope of the transition shall be no more than 1 in 2-1/2 with the edge of either part. Alternatively, the width shall be transitioned with a 24 in [600 mm] minimum radius that is tangent to the narrower part of the center of the butt joints (see Figure 2.7).

2.11 Connections or Splices

2.11.1 Where Only Welds Carry Load. Connections or splices made with fillet or plug welds, except as noted in 2.11.2, shall be designed for an average of the sum of the calculated stress and the strength of the member, but not less than 75% of the strength of the member.

2.11.2 Where Both Bearing Surface and Welds Carry Load. If members subjected to compression only are spliced and full-milled bearing is provided, then the splice material and its welding shall be arranged to hold all parts in alignment and shall be proportioned to carry 50% of the computed stress in the member.

2.12 Combinations of General Types of Welds

If two or more general types of welds (groove, fillet, plug, slot) are combined in a single connection, their allowable capacity shall be computed with reference to the axis of the group in order to determine the allowable capacity of the combination. Fillet welds reinforcing groove welds shall have a combined effective size (see Figure 2.8) based on the throat of the combination.

2.13 Skewed T-Joints

Skewed T-joints which have angles between members less than 80° shall be qualified in accordance with Clause 3 to determine actual effective throat or effective weld size. These types of joints shall be considered PJP groove welds unless the WPS and procedure qualifications show that CJP groove welds can be achieved with the welding methods being used.

Part D *Cyclically Loaded Structures*

2.14 General

These requirements apply to members and connections subject to cyclic load of frequency and magnitude sufficient to initiate cracking and progressive failure by fatigue. The provisions of this part are applied to minimize the possibility of fatigue failure.

2.15 Region of Applicability

These requirements are applicable to cases where the number of applied cycles is expected to exceed 1000 and the range of stress is expected to exceed 4 ksi [27 MPa]. The requirements do not apply to welds in M51 material where the number of cycles is not expected to exceed 3500. The requirements do not apply to welds in M52 material where the number of cycles is not expected to exceed 1500. The Engineer may determine additional regions where this part is to be applied and, alternatively, may determine additional combinations of stress and cycles that exempt members and connections from its application. The M numbers for titanium materials can be found in Table 4.1.

2.16 Allowable Stresses

Except as modified by 2.17 and 2.18, allowable unit stresses in welds shall not exceed those listed in Table 2.1.

2.17 Combined Stresses

In the case of axial stress combined with bending, the maximum combined stress shall be that for concurrent applied load cases.

2.18 Cyclic Load Stress Range

The allowable stress range (fatigue) for structures subject to cyclic loading shall be as provided in Table 2.3 and Figure 2.9 for the applicable condition and cyclic life.

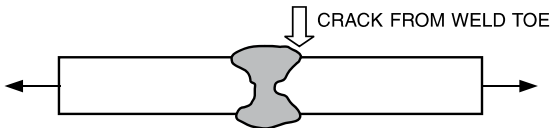
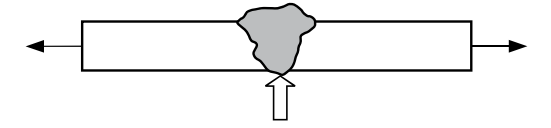
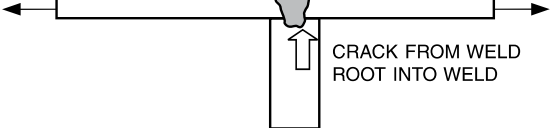
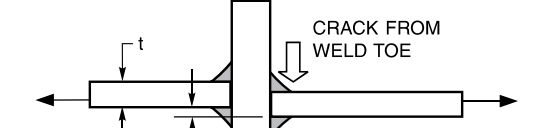
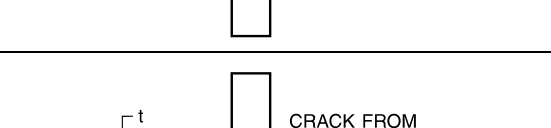
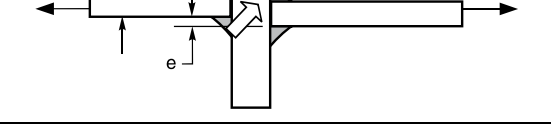
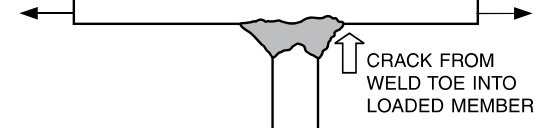
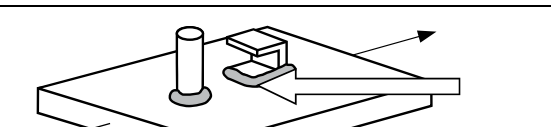
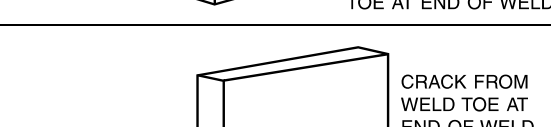
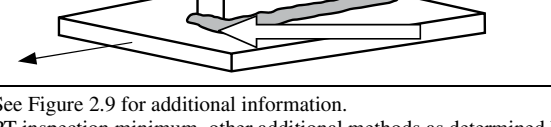
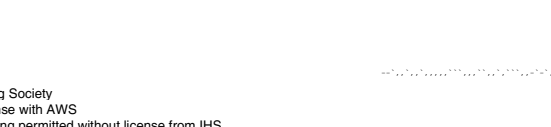
Table 2.1
Allowable Stresses in Connections (see 2.3 and 2.16)

Type of Weld	Stress in Weld		Allowable Connection Stress
Complete joint penetration groove welds	Tension normal to the effective area		90% of base metal
	Compression normal to the effective area		90% of base metal
	Tension or compression parallel to the axis of the weld		Same as base metal
	Shear on the effective area		$0.36 \times$ nominal yield strength of base metal, except shear stress on base metal shall not exceed $0.40 \times$ yield strength of base metal
Partial joint penetration groove welds	Compression normal to effective area	Joint not designed to bear	$0.60 \times$ nominal yield strength of base metal
		Joint designed to bear	Same as base metal
	Tension or compression parallel to the axis of the weld		Same as base metal
	Shear parallel to axis of weld		$0.36 \times$ nominal yield strength of base metal
	Tension normal to effective area		$0.36 \times$ nominal yield strength of base metal, except tensile stress on base metal shall not exceed $0.60 \times$ yield strength of base metal
Fillet welds	Shear on effective area		$0.36 \times$ nominal yield strength of base metal
	Tension or compression parallel to axis of weld		Same as base metal
Plug and slot welds	Shear parallel to faying surfaces (on effective area)		$0.36 \times$ nominal yield strength of base metal

Table 2.2
**Minimum Diameter of Hole for Plug Welds
or Width of Slot for Slot Welds (see 2.6.2 and 2.6.4)**

Material Thickness, T	Minimum Hole Diameter or Slot Width
1/8 in [3 mm] or greater	2.5T

Table 2.3
Fatigue Stress Provisions (see 2.3 and 2.18)

Shape of Detail	Description	Category ^a
	Shop CJP weld in flat position, smooth toes 30° angles or less ^b	100
	CJP weld made in field or out of flat position ^b	80
	CJP weld from one side without backing, root controlled by ^b	71
	Same as above without NDT	45
	Connection to attachment through butt weld root	71
	Cruciform or T-joint, complete joint penetration welds, misalignment less than $e = 0.15t$	71
	As above with partial joint penetration or fillet welds from both sides	63
	Cruciform or T-joint with crack from weld root using weld throat area to determine stress	45
	Transverse non-load-carrying attachment	80
	Non-load-carrying stud or clip	80
	Longitudinal gusset of length L along stress direction, $L < 12 \text{ in [300 mm]}$	56

^a See Figure 2.9 for additional information.

^b PT inspection minimum, other additional methods as determined by the Engineer.

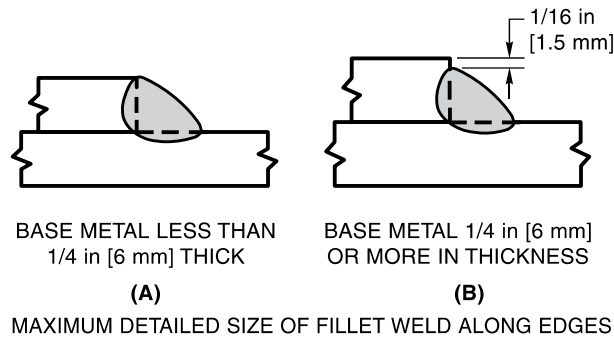
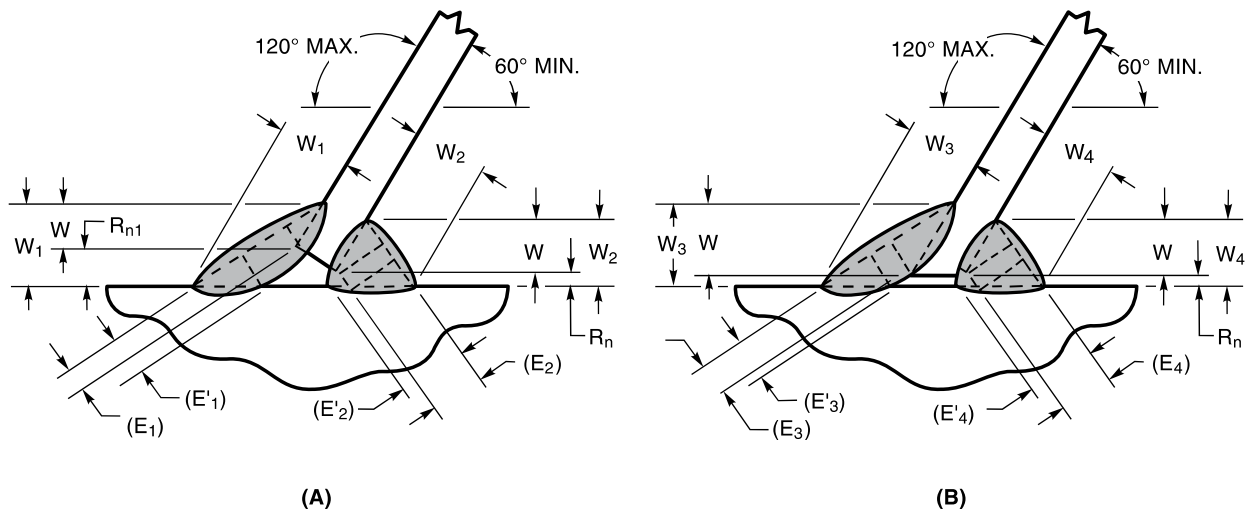


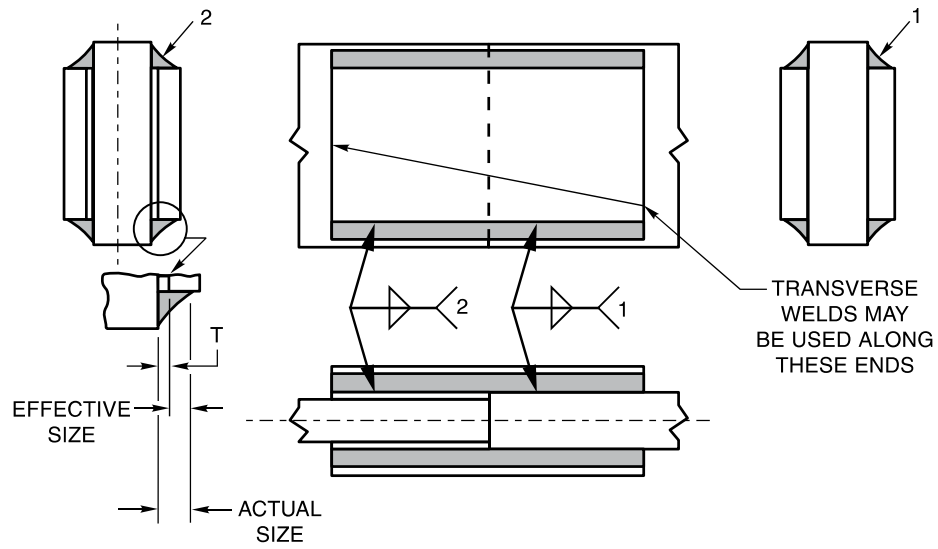
Figure 2.1—Maximum Fillet Weld Size Along Edges in Lap Joints (see 2.5.1)



Notes:

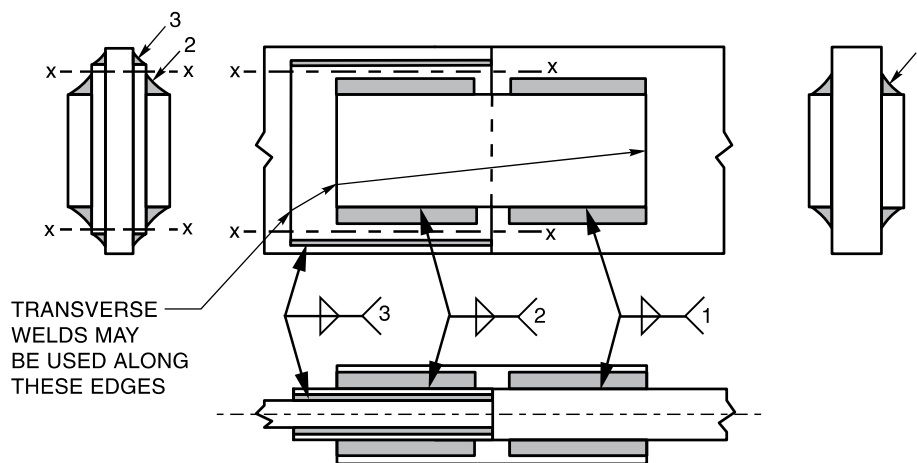
1. (E_n), (E'_n) = Effective throats dependent on magnitude of gap (R_n) (see 2.5.5). Subscript (n) represents 1, 2, 3, or 4.
2. Angles smaller than 60° may be used; however, in such cases, the weld is considered to be a partial joint penetration groove weld.

Figure 2.2—Fillets in Skewed T-Joints (see 2.5.5)



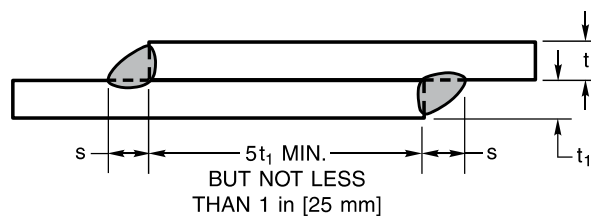
Note: The effective area of weld 2 shall equal that of weld 1, but its size shall be its effective size plus the thickness of the filler plate T .

Figure 2.3—Thin Filler Plates (see 2.7.1)



Note: The effective areas of welds 1, 2, and 3 shall be adequate to transmit the design force, and the length of welds 1 and 2 shall be adequate to avoid overstress of filler plate in shear along planes x-x.

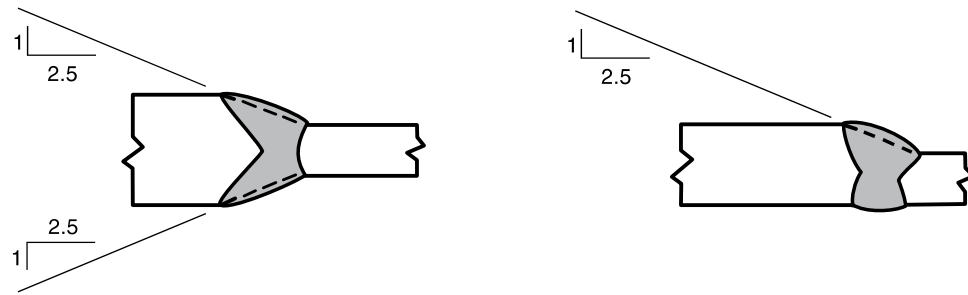
Figure 2.4—Thick Filler Plates (see 2.7.2)



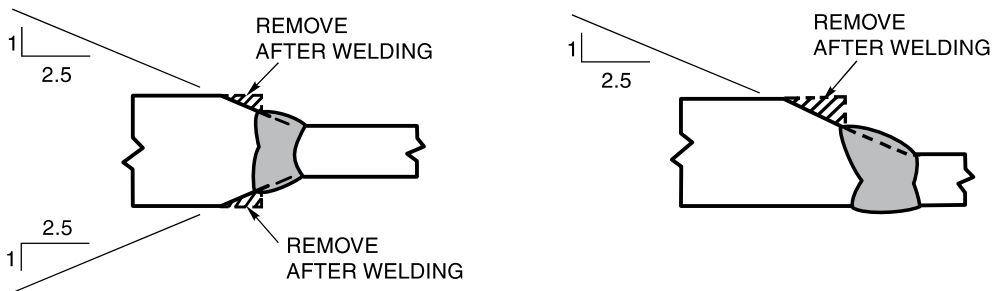
Notes:

1. s = as required.
2. $t > t_1$.

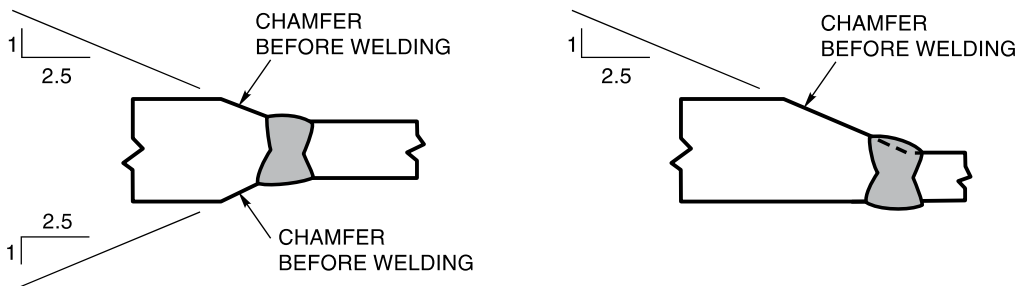
Figure 2.5—Minimum Amount of Lap and Double Fillet Weld (see 2.9.1 and 2.9.2)



(A) TRANSITION BY SLOPING WELD SURFACE



(B) TRANSITION BY SLOPING WELD SURFACE AND CHAMFERING



(C) TRANSITION BY CHAMFERING THICKER PART

Notes:

1. Groove may be of any permitted or qualified type and detail.
2. Transition slopes shown are the maximum permitted.

Figure 2.6—Thickness (see 2.10.1)

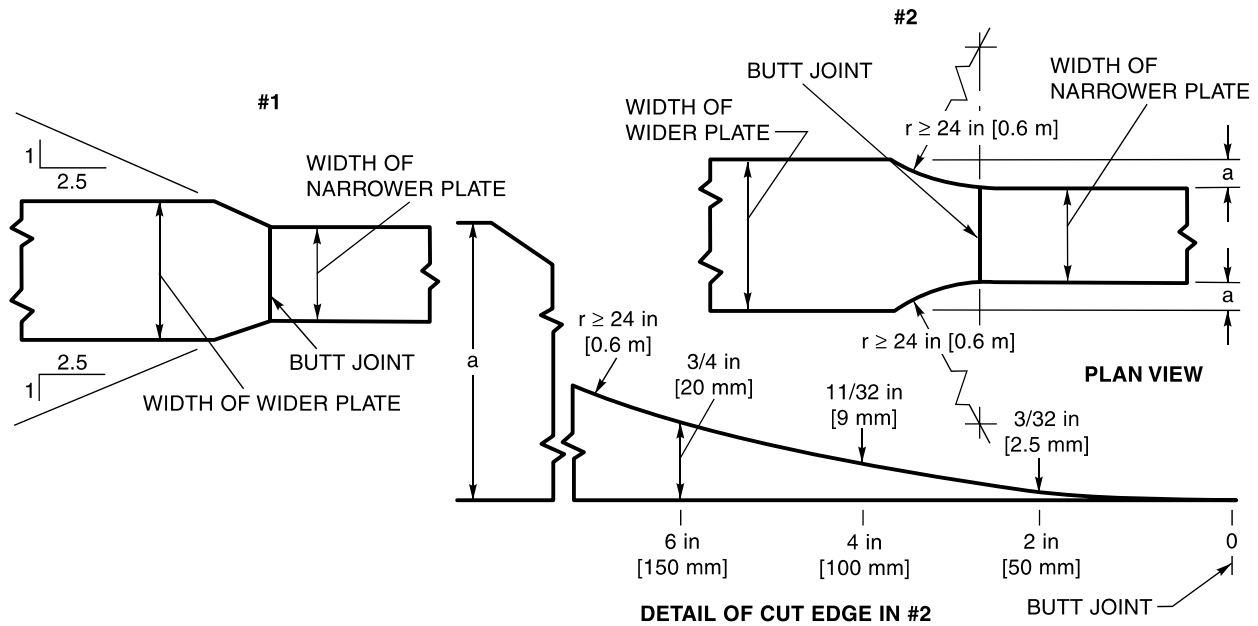
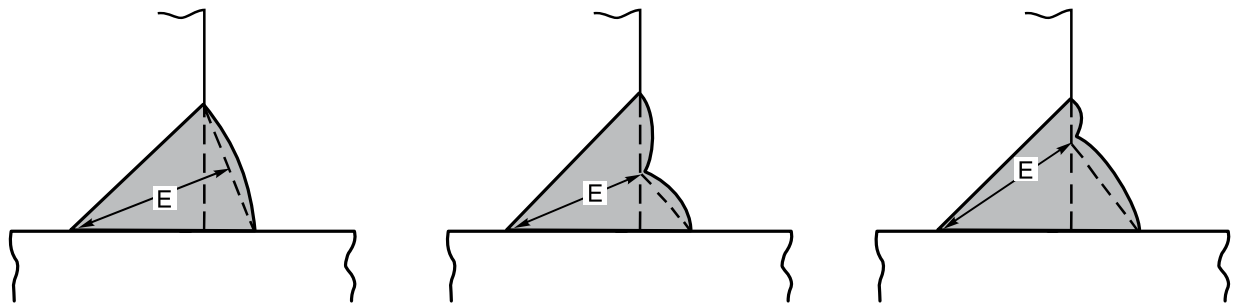
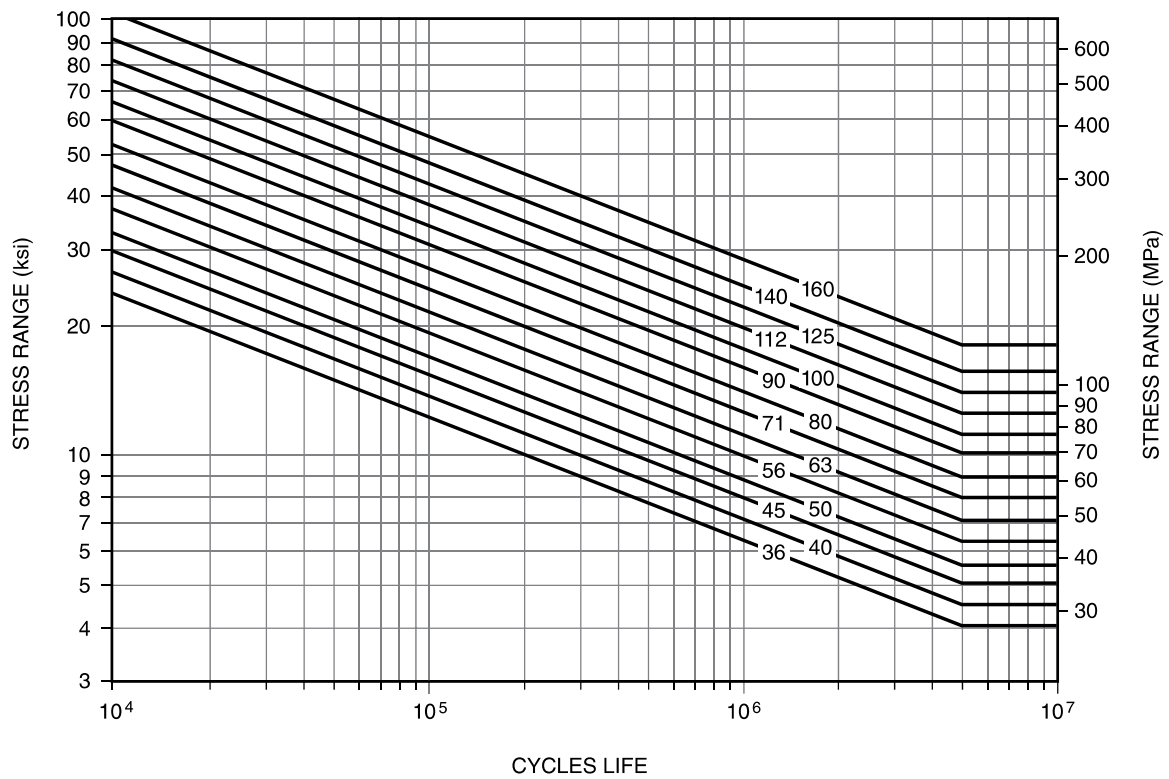


Figure 2.7—Plan Views of Width Transitions (see 2.10.2)



Note: The effective throat of a weld is the minimum distance from the root of the weld joint to its face less any reinforcement.

Figure 2.8—Effective Throat (see 2.5.3 and 2.12)



Note: Additional information regarding the use of this table may be found in the commentary for Clause 2.

Figure 2.9—Cyclic Load Stress Range (see 2.3 and 2.18)

3. Qualification

3.1 Scope

3.1.1 The requirements for the qualification and testing of welding procedure specifications (WPSs) and welding personnel using the GMAW (gas metal arc welding), GTAW (gas tungsten arc welding), PAW (plasma arc welding), LBW (laser beam welding), or EBW (electron beam welding) process are described in Parts A, B, C, and D below with the exception of the additional requirements specific to ballistic qualification that are detailed in Annex A. Other welding processes may be qualified using the provisions of this code, with the Engineer's approval.

(1) **Part A—General Requirements.** This part covers the general requirements for the qualification of a WPS and for the qualification of welding personnel.

(2) **Part B—Types of Tests and Test Methods.** This part details the type of destructive test methods, non-destructive test methods, or both, including acceptance criteria, to be used to assess both WPS and welding personnel performance qualification.

(3) **Part C—WPS Qualification.** This part covers the detail test requirements for the qualification of a WPS.

(4) **Part D—Performance Qualification.** This part covers the detail test requirements for performance qualification tests required by the code to determine the ability of welding personnel to produce sound welds.

Part A *General Requirements*

3.2 General

The qualification requirement of this code is intended to demonstrate understanding of the special needs and tools

required by a fabricator to work with structural titanium alloys and to assure that the fabrication procedures used in production consistently meet a recognized quality standard. To accomplish this objective, each Contractor or fabricator shall, prior to the start of production, perform the following which shall be documented to become part of an auditable trail:

(1) Qualify and record the essential variables and test results needed to compile a PQR (Procedure Qualification Record) to be used to define WPSs (Welding Procedure Specifications) in accordance with Clause 3, Part C using material, equipment, cleaning and preparation methods, welding conditions, etc., that will be contained in the WPS.

(2) Prepare written WPSs in accordance with 3.3.

(3) Qualify the welders, welding operators, and tack welders in accordance with Clause 3, Part D.

(4) Certify and maintain records of all tests and procedures on forms as shown in Annex E or similar, and make available such records to those authorized to examine them.

(5) Provide all welders, welding operators, tack welders and quality control personnel with access to the relevant WPSs.

3.3 Qualification of WPSs

3.3.1 The Engineer shall accept (1) and (2) below. Option 3 may be accepted at the Engineer's discretion.

(1) WPSs that have been properly documented and qualified in accordance with Clause 3, Part C.

(2) WPSs with previous and properly documented qualification that meets the requirements of Clause 3, Part C.

(3) WPSs with previous and properly documented qualification that meet the requirements of other codes.

3.4 Qualification of Welding Personnel

3.4.1 Qualification Requirements. The Engineer shall accept (1) and (2) below. Option 3 may be accepted at the Engineer's discretion.

(1) Welding personnel that have been qualified in accordance with Clause 3, Part D.

(2) Welding personnel with previous and properly documented qualifications that meet the requirements of Clause 3, Part D.

(3) Welding personnel with previous and properly documented qualification that meet the requirements of other codes.

3.4.2 Period of Effectiveness. The welder's, welding operator's, or tack welder's qualification shall be requalified every 5 years either in accordance with 3.4.1 or by providing volumetric and visual evidence of a welding quality level involving titanium alloys that meets the requirements of this code for the qualification of welding personnel. The qualification shall lapse immediately if (1) the welder, welding operator, or tack welder is not engaged in a welding process for which he is qualified for a period exceeding 6 months, or (2) there is some specific reason to question the individual's ability.

3.5 Common Requirements for WPS and Welding Personnel Performance Qualification

3.5.1 Records. Records developed which form part of a body of supporting evidence applicable to the contract shall be retained as defined by the contract.

3.5.2 Position of Test Welds. Each WPS, welder, welding operator, and tack welder shall be qualified by positioning and welding the test assembly in the manner stated below and as shown in Figure 3.1 through Figure 3.6 for the positions for which the test assembly is to be qualified.

3.5.2.1 Groove Welds—Plate (with and without backing)—(Illustrated in Figure 3.3). When making

the qualification tests for both complete and partial penetration groove welds in plate they shall be welded in one or more of the positions outlined below as required by Table 3.1:

(1) *Position 1G (Flat).* The test plates shall be placed in an approximately horizontal plane and the weld metal deposited from the upper side [see Figure 3.3(A)].

(2) *Position 2G (Horizontal).* The test plates shall be placed in an approximately vertical plane with the groove approximately horizontal [see Figure 3.3(B)].

(3) *Position 3G (Vertical).* The test plates shall be placed in an approximately vertical plane with the groove approximately vertical [see Figure 3.3(C)].

(4) *Position 4G (Overhead).* The test plates shall be placed overhead in an approximately horizontal plane, and the weld metal deposited from the under side [see Figure 3.3(D)].

3.5.2.2 Groove Welds—Pipe (with and without Backing) (Illustrated in Figure 3.4). The term pipe, as used herein, shall include all square or round tubular shapes. In making the qualification tests for groove welds, the test pipe shall be welded in the following positions as defined in Table 3.1:

(1) *Position 1G (Pipe Horizontal-Rotated).* The test pipe shall be placed with its axis approximately horizontal and the groove approximately vertical. The pipe shall be rotated during welding so the weld metal is deposited in the flat position [see Figure 3.4(A)].

(2) *Position 2G (Pipe Vertical-Fixed).* The test pipe shall be placed with its axis approximately vertical and the groove approximately horizontal. The pipe shall not be rotated during welding [see Figure 3.4(B)].

(3) *Position 5G (Pipe Horizontal-Fixed).* The test pipe shall be placed with its axis approximately horizontal and the groove approximately vertical. The pipes shall not be rotated during welding [see Figure 3.4(C)].

(4) *Position 6G (Pipe Inclined-Fixed).* The test pipe shall be inclined at approximately 45°. The pipe shall not be rotated during welding [see Figure 3.4(D)].

3.5.2.3 Fillet Welds—Plate (Illustrated in Figure 3.5). When making the qualification tests for fillet welds on plate they shall be welded in one or more of the positions outlined below as required by Table 3.1:

(1) *Position 1F (Flat).* The test plates shall be so placed that each fillet weld is deposited with its axis approximately horizontal and its throat approximately vertical [see Figure 3.5(A)].

(2) *Position 2F (Horizontal)*. The test plates shall be so placed that each fillet weld is deposited on the upper side of a horizontal surface and against a vertical surface [see Figure 3.5(B)].

(3) *Position 3F (Vertical)*. The test plates shall be placed in approximately vertical planes, and each fillet weld deposited on vertical surfaces [see Figure 3.5(C)].

(4) *Position 4F (Overhead)*. The test plates shall be so placed that each fillet weld is deposited on the under side of a horizontal surface and against a vertical surface [see Figure 3.5(D)].

3.5.2.4 Fillet Welds—Pipe (Illustrated in Figure 3.6). The term pipe, as used herein, shall include all square or round tubular shapes. When making the qualification tests for a fillet weld on pipe they shall be welded in one or more of the positions outlined below as required by Table 3.1:

(1) *Position 1F (Pipe Inclined-Rotated)*. The test pipe shall be placed with its axis at approximately 45° and rotated during welding so that the filler metal is deposited in the flat position [see Figure 3.6(A)].

(2) *Position 2F (Pipe Vertical-Fixed)*. The test pipe shall be placed with its axis approximately vertical. The filler metal shall be placed on the outer surface of the pipe at its juncture with the upper side of the abutting plate or pipe. The assembly shall not be rotated during welding [see Figure 3.6(B)].

(3) *Position 2F-Rotated (Pipe Horizontal-Rotated)*. The test pipe shall be placed with its axis approximately horizontal and rotated during welding so that filler metal is deposited in the horizontal position [see Figure 3.6(C)].

(4) *Position 4F (Overhead-Fixed)*. The test pipe shall be placed with its axis approximately vertical. The filler metal shall be placed against the outer surface of the pipe at its juncture with the abutting plate or pipe. The assembly shall not be rotated during welding [see Figure 3.6(D)].

(5) *Position 5F (Pipe Horizontal-Fixed)*. The test pipe shall be placed with its axis approximately horizontal and with the welding joint vertical. The assembly shall not be rotated during welding [see Figure 3.6(E)].

3.5.2.5 Restricted Access Welds. For restricted access welds and those welds not covered by 3.5.2.1 to 3.5.2.4 the position(s) to be used for qualification shall be agreed upon with the Engineer.

Part B

Types of Tests, Test Methods, and Acceptance Criteria

3.6 Types of Tests, Test Methods, and Acceptance Criteria Tests

When required by Table 3.5 and Table 3.6, the tests, test methods, and acceptance criteria described in Part B are intended to determine the mechanical properties and soundness of welds made in accordance with the WPS or the soundness of welds made by a welder, welding operator, or tack welder.

The provisions of AWS B4.0 or AWS B4.0M, *Standard Methods for Mechanical Testing of Welds*, may be used for the testing of welds made for WPS or performance qualification. However, in instances where the provisions of AWS B4.0 and AWS D1.9 are in conflict, AWS D1.9 shall take precedence.

3.7 Visual Examination

Visual inspection of the weld surfaces shall be performed in accordance with 3.7.1. The acceptance criteria are given in 3.7.2.

3.7.1 Surface Examination Methods (Visual)

3.7.1.1 Before machining the weldments for testing, the weld face and weld root shall be visually examined when possible.

3.7.2 Surface Acceptance Criteria (Visual)

3.7.2.1 Groove Welds, Plate, and Pipe. The visual examination of the test weldment shall satisfy the following acceptance criteria:

(1) Both the face and root surfaces shall be free of cracks.

(2) All craters shall be filled to the full cross section of the weld except as permitted in 3.7.2.1(4).

(3) The edges of the weld shall blend smoothly with the base metal such that the contact angle as defined in Figure 3.7 is less than 90°.

(4) Underfill shall not exceed 10% of the design weld thickness or 1/32 in [0.8 mm], whichever is less, provided the undersize condition does not exceed 10% of the weld length.

(5) The root shall show (a) complete fusion for complete joint penetration groove welds, or (b) fusion equal

to or greater than the weld size specified for partial joint penetration groove welds.

(6) The maximum root reinforcement on single sided groove welds in plate and pipe shall not exceed the lesser of 1/8 in [3 mm] or 1/4 of the thickness of the thinnest member.

(7) Root concavity shall not be allowed for WPS and welder/operator qualification with the exception of the weld restart region which may be locally concave by 1/32 in [0.8 mm] with a maximum diameter of concavity of 3/8 in [10 mm]. No more than three areas of concavity (associated with the restart region) are allowed in any linear 14 in [400 mm] of the test coupon.

(8) For complete joint penetration welds, the total weld thickness shall be equal to or greater than the thickness of the base metal.

(9) The color of the weld and HAZ is defined in Clause 5, Table 5.3. Color shall be used as acceptance criteria when specified by the Owner. When color is invoked for acceptance, mechanical cleaning (wire brushing, polishing, etc.) or cosmetic welding to remove coloration shall be cause for rejection.

(10) Face reinforcement shall not exceed the lesser of 3/16 in [5 mm] or 50% of base material thickness whichever is less.

(11) Undercut at the weld toes shall not exceed the lesser of 1/32 in [0.8 mm] or 25% of the thickness of the thinner member being welded.

3.7.2.2 Fillet Welds for Plate or Pipe. The visual examination of the test weldment shall satisfy the following acceptance criteria:

- (1) The surface of the weld shall be free from cracks.
- (2) All craters shall be filled to the full cross section of the weld except as permitted in 3.7.2.2(4).
- (3) The edges of the weld shall blend smoothly with the base metal such that the radius at the weld toes is greater than 3/8 in [10 mm].
- (4) Undersize shall not exceed 10% or 1/32 in [0.8 mm], whichever is less, provided the undersize condition does not exceed 10% of the weld length.
- (5) Weld size shall meet the requirements of the WPS.
- (6) The weld shall exhibit complete fusion in the root.
- (7) The color of the weld and HAZ is defined in Clause 5, Table 5.3. Color shall be used as acceptance criteria when specified by the Owner. When color is

invoked for acceptance, mechanical cleaning (wire brushing, polishing, etc.) or cosmetic welding to remove coloration shall be cause for rejection.

(8) Undercut at the weld toes shall not exceed the lesser of 1/32 in [0.8 mm] or 25% of the thickness of the thinner member being welded.

3.8 Radiographic Examination

3.8.1 Radiographic Examination Procedure. Radiographic examination shall be in accordance with the requirements of Clause 5. All welds shall be examined for 100% of their length (excluding starting weld tab and run off weld tab).

3.8.2 Radiographic Examination—Acceptance Criteria. Acceptability shall be based on Table 5.2.

3.9 Macroexamination and Microexamination

Macroexamination and microexamination of the weld shall be performed in accordance with 3.9.1 to determine whether the sample weldments pass the acceptance criteria detailed in 3.9.2.

3.9.1 Macroexamination and Microexamination Methods (Visual). Macroexamination of the transverse cross sections of the weld at 5X power shall be conducted after the sections have been polished. Microexamination shall be conducted after etching with a suitable etchant to give a clear definition of the weld and heat-affected zone (HAZ) areas. Typical etching solutions and procedures are given in Annex G.

Microexamination shall be performed when specified in the contract at a magnification power agreed with the Engineer.

3.9.2 Macro and Micro Acceptance Criteria (Visual)—Groove Welds, Plate and Pipe. The visual examination of the test weldment shall satisfy the following acceptance criteria:

- (1) The face examined shall be visually free of cracks.
- (2) The weld shall show complete fusion in the root.
- (3) The total weld thickness shall be equal to or greater than the required weld size.

3.10 Tension Tests—Groove Welds

3.10.1 Specimens. Transverse tension test specimens shall conform to one of the types illustrated in Figure 3.9, Figure 3.10, or Figure 3.11. “All weld” longitudinal test specimens shall conform to one of the types illustrated in Figure 3.12.

For partial joint penetration groove welds in plate and pipe, the unfused material on the root side of the joint shall be removed by machining to the thickness of the weld size.

3.10.1.1 Reduced Section Transverse Test Specimens—Plate. Reduced section specimens from plate conforming to the requirements given in Figure 3.9 shall be used for tension tests on all thicknesses of plate.

(1) A single specimen of full plate thickness shall be used for thicknesses up to and including 0.75 in [19 mm].

(2) For plate thicknesses greater than 0.75 in [19 mm], single or multiple specimens may be used.

(3) When multiple specimens are necessary because of the limitations of the testing equipment, the entire thickness shall be mechanically cut into the minimum number of approximately equal size specimens that can be tested in the available equipment. Each specimen (slice) shall be tested, and collectively shall represent a single required tension test.

3.10.1.2 Reduced Section Transverse Test Specimens—Pipe. For pipe having an outside diameter greater than 3 in [76 mm], reduced section specimens conforming to the requirements given in either Figure 3.9 or Figure 3.10 shall be used for tension tests on all thicknesses.

(1) A single specimen of the full thickness shall be used for pipe whose wall thicknesses is less than or equal to 0.75 in [19 mm].

(2) For a pipe whose wall thicknesses is greater than 0.75 in [19 mm], single or multiple specimens may be used.

(3) When multiple specimens are necessary because of the limitations of the testing equipment, the entire thickness shall be mechanically cut into the minimum number of approximately equal size specimens that can be tested in the available equipment. Each specimen (slice) shall be tested, and collectively shall represent a single required tension test.

3.10.1.3 Full-Section Transverse Test Specimens—Pipe. For pipe having an outside diameter of 1.0 in [25 mm] or less, full-section specimens conforming to

the requirements given in Figure 3.11 shall be used for tension tests.

3.10.1.4 Reduced Section All-Weld Test Specimen—Plate. Reduced section all-weld test specimens from plate conforming to the requirements given in Figure 3.12 shall be used for tension tests of all plate thickness in order that the gauge diameter contains all weld metal.

(1) A single specimen shall be used for plate thicknesses up to and including 1 in [25 mm].

(2) For plate thicknesses greater than 1 in [25 mm], single or multiple specimens may be used.

(3) When multiple specimens are necessary because of the limitations of the testing equipment, the entire thickness shall be mechanically cut into the minimum number of approximately equal slices that can be tested in the available equipment. Each specimen (slice) shall be tested, and collectively, shall represent a single required test.

3.10.2 Tension Test Procedure. The test specimen shall be tested in conformance with ASTM E 8, *Standard Test Method for Tension Testing of Metallic Materials*.

3.10.3 Acceptance Criteria—Transverse Tension Tests—Plate and Pipe

3.10.3.1 The ultimate tensile strength shall be no less than the minimum values stated for the applicable grade of parent material in the fully annealed condition, as shown in Table 4.1. When multiple specimens are used, as allowed in 3.10.1.1, and 3.10.1.2 each specimen (slice) shall meet the requirement.

3.10.3.2 If base metals of different tensile strengths are used, the specified minimum tensile strength of the lower strength base metal, as shown in Table 4.1, applies.

3.10.4 Acceptance Criteria—All Weld Tension Tests—Plate

3.10.4.1 The tensile strength shall not be less than 90% of the values for the applicable grade of parent material stated in Table 4.1. When multiple specimens are used, as allowed in 3.10.1.4 each specimen (slice) shall meet the same requirements.

3.11 Bend Tests—Groove Welds—Plate and Pipe

3.11.1 Specimens. Bend specimens are of five types, depending on whether the axis of the weld is transverse

or parallel to the longitudinal axis of the specimen and which surface (side, face, or root) is on the convex (outer) side of the bent specimen. Longitudinal bend specimens may be used in lieu of transverse bend specimens for testing combinations of base and filler materials which differ markedly in bending properties. Bend test specimens shall conform to one of the types shown in Figure 3.13, Figure 3.14, or Figure 3.15. The cut surfaces shall be designated as the sides of the specimen. The original surfaces of the specimen shall be called the face and root surfaces, the face surface having the greater width of weld.

For partial joint penetration groove welds in plate and pipe, the excess material on the root side of the joint shall be removed by machining to the thickness of the weld size.

A supporting PQR for a complete joint penetration groove weld of the same welding position in which the partial joint penetration groove weld is made is acceptable for qualification, providing all essential variables remain within their limits of qualification.

3.11.1.1 Transverse Side Bend Specimen. The weld is transverse to the longitudinal axis of the specimen which is bent so that the side surface with the larger discontinuity, if any, becomes the convex surface of the bent specimen. Transverse side bend specimens shall conform to the dimensions shown in Figure 3.13.

3.11.1.2 Transverse Face Bend Specimen. Transverse face bend test specimens shall conform to the dimensions shown in Figure 3.14. They shall be bent so that the face surface becomes the convex surface of the bent specimen. Pipe less than or equal to 4 in [100 mm] in outside diameter shall have face bend specimens prepared as described in 3.11.1.4.

3.11.1.3 Transverse Root Bend Specimen. Transverse root bend test specimens shall conform to the dimensions shown in Figure 3.14. They shall be bent so that the root surface becomes the convex surface of the bent specimen. Pipe less than or equal to 4 in [100 mm] in outside diameter shall have root bend specimens prepared as described in 3.11.1.4. In specimens taken from partial joint penetration groove welds, the weld specimen shall be cut and tested at the plane coincident with the base of the weld preparation.

3.11.1.4 Subsize Transverse Face and Root Bend Specimen. For pipe 4 in [100 mm] or less in outside diameter, the width of the specimen may be 3/4 in [19 mm], measured around the outside surface. Alternatively, for pipe less than 2-3/8 in [60 mm] in outside diameter, the width of the specimen may be that obtained by cutting the pipe into quarter sections, less the allow-

ance for cutting. The other dimensions shall be as shown in Figure 3.14.

3.11.1.5 Longitudinal Face Bend Specimen. The weld is parallel to the longitudinal axis of the specimen which is bent so that the face surface becomes the convex surface of the bent specimen. Longitudinal face bend test specimens shall conform to the dimensions shown in Figure 3.15.

3.11.1.6 Longitudinal Root Bend Specimen. The weld is parallel to the longitudinal axis of the specimen which is bent so that the root surface becomes the convex surface of the bent specimen. Longitudinal root bend test specimens shall conform to the dimensions shown in Figure 3.15. In specimens taken from partial joint penetration groove welds, the weld size shall be measured from the bottom of the weld preparation to the material surface, and the weld assembly shall be cut to and tested at the plane coincident with the base of the weld preparation.

3.11.2 Test Procedures—Bend Tests—Plate and Pipe

3.11.2.1 Bend Test Fixture. A wraparound fixture (Figure 3.16) shall be used. The face surface of the specimen is turned toward the outer roller for face bend tests, the root surface for root bend tests, and the side with the larger discontinuity, if any, for side bend tests. The specimen shall be wrapped around the center roller by a 180° movement of the outer roller.

3.11.3 Acceptance Criteria—Bend Tests—Pipe and Plate

3.11.3.1 The weld and heat-affected zone of a transverse weld bend specimen shall be completely within the bent portion of the specimen after bending.

3.11.3.2 The convex surface of the bend test specimen shall be visually examined for surface discontinuities. For acceptance, the surface shall not contain any discontinuities exceeding the following dimensions:

- (1) 1/8 in [3 mm] measured in any direction on the surface.
- (2) 3/8 in [10 mm] the sum of the greatest dimensions of all discontinuities exceeding 1/32 in [0.8 mm], but less than or equal to 1/8 in [3 mm].
- (3) 1/4 in [6 mm]—the maximum corner crack, except where that corner crack results from inclusions or other fusion type discontinuity, then the 1/8 in [3 mm] maximum shall apply.

Specimens with corner cracks exceeding 1/4 in [6 mm] with no evidence of fusion type discontinuity shall be discarded and a replacement test specimen from the original weldments shall be tested.

3.12 Chemical Analysis

Chemical analysis or reference to the manufacturers certificates shall be used to determine the amount of Carbon, Oxygen, Hydrogen, Nitrogen, Aluminum, Vanadium, Iron, and Titanium present within the filler wire and parent material.

3.12.1 Analysis Procedure. The chemical analysis of weld metal shall be conducted using a sample extracted as detailed in 3.12.2. All chemical analysis techniques shall be in accordance with ASTM E 1447 for hydrogen and ASTM E 1409 for Oxygen and Nitrogen.

3.12.2 Weld Metal Sample Removal When it is required, by 3.12.1, to analyze the weld metal the following steps shall be undertaken:

- (1) A length of weld shall be cut from the joint.
- (2) The end faces of the section polished and etched to determine the likely base/weld metal interface.

The base metal shall be removed from the weld deposit by any nonthermal cutting process.

3.12.3 Acceptance Criteria—Chemical Analysis. The Engineer shall use the unique filler metal and base metal chemical compositions for the weld being analyzed as a basis for establishing acceptance limits.

Part C *WPS Qualification*

3.13 General WPS Qualification

WPS qualification shall be conducted by the Contractor performing the production welding. The WPS qualification tests required in Part C are devised to determine the mechanical properties and soundness of the welds made with a specific WPS. Results of these tests are used to establish WPS welding parameters that define the limitations of essential variables applicable to production welding under this code.

3.13.1 Procedure Qualification Record. The specific values of conditions involved in qualifying a WPS shall be recorded in a form called the Procedure Qualification Record (PQR). The essential variables for the specific welding process shall be recorded on this form. Suggested forms for these records are given in Annex E.

3.13.2 WPS. The WPS shall list the group numbers of the base metals to be joined, the filler metal(s) to be used, the range of preheat and postweld heat treatments, thick-

nesses, and other variables associated with the welding process as defined in the PQR.

Suggested forms for these records are given in Annex E.

3.13.3 Combination of WPSs. More than one WPS may be used in a single production joint, provided each WPS is qualified either separately or in combination with the other WPS(s) within the position and thickness limits specified in Table 3.1 and Table 3.5, respectively.

3.14 Limits of Qualified Positions for WPSs

To reduce the number of WPS qualifications that may be required, qualification in certain welding positions also qualifies for other welding positions as shown in Table 3.1.

3.15 Limitation of Essential Variables—WPS Qualification

Changes greater than the limits set in Table 3.3 shall be considered essential changes in a WPS and shall require qualification of the altered WPS.

3.16 Tests—WPS Qualification

3.16.1 Number and Type of Examinations. The number and type of examinations shall be determined in accordance with Table 3.5. Test methods and acceptance criteria for each test shall be as directed by Clause 3, Part B. Any additional testing may be added at the discretion of the Engineer or Contractor.

3.16.2 Test Specimens for WPS Qualification. Sample weldments of sufficient size to obtain the length/number of test specimens required by Table 3.5, as applicable, shall be prepared in accordance with the WPS. Where it is impractical to obtain all the required specimens from one weldment multiple weldments may be used.

3.16.2.1 Test Specimens—Groove Welds—Plate. The location of test specimens shall conform to Figure 3.17.

3.16.2.2 Partial Joint Penetration Groove Welds—Plate or Pipe. A sample weld shall be made using the type of groove design and WPS to be used in construction except that when a WPS has been qualified for a complete joint penetration groove weld and is applied to the welding conditions of a partial joint penetration groove weld, then three macroetch cross section test specimens are required for visual examination.

3.16.2.3 Test Specimens—Groove Welds—Hollow Section or Pipe. The location of test specimens shall conform to Figure 3.18 and Figure 3.19 as applicable.

3.16.2.4 Test Specimens—Fillet Welds—Hollow Section or Pipe. The location of test specimens shall conform to Figure 3.20, Figure 3.21, and Figure 3.22.

3.16.2.5 Test Specimens—Plug and Slot Welds. The location of the test specimens shall conform to Figure 3.23.

3.17 Retests

If any destructive test specimen of all those tested fails to meet the test requirements for qualification, then two retests of that particular type of test specimen may be performed with specimens cut from the same test weldment, or from an additional weldment made in accordance with the WPS being qualified. Both retest specimens shall meet the test requirements for the WPS to be qualified.

Part D *Performance Qualification*

3.18 General Performance Qualification

The qualification tests described in Part D are specially devised to determine the ability of a welder, welding operator, or tack welder to produce sound welds in accordance with the WPS. These qualification tests are not intended as a guide for selecting the WPS to be used for welding during construction. The test welds shall be made in accordance with the requirements of a WPS.

3.18.1 Definitions. For purposes of this code the following shall apply collectively and be considered welding personnel:

- (1) A welder is a person who uses a manual or semi-automatic process.
- (2) A welding operator is a person who operates automatic equipment and program-guided systems, but has a degree of control over setting the values of the welding conditions. The welding operator may also adjust the path of the equipment along a weld joint.
- (3) A tack welder is a person who, under the direction of a fitter, or as a fitter, tack welds an assembly in order to hold the parts together until the final welds are made.

3.18.2 Identification of Welders, Welding Operators, and Tack Welders. Each qualified welder, welding operator, and tack welder shall be assigned an identifying number, letter or symbol by the Contractor or fabricator which shall be used to identify the work of that person.

3.18.3 Records of Tests. The essential variables (as defined in Table 3.2) of the performance qualification test and the test results obtained by each welder, welding operator, or tack welder shall be recorded on a Record of Performance Qualification Tests. A suggested form for these records is given in Annex E.

3.18.4 Position of Test Weld. A Contractor who does production welding in a special orientation may make the tests for performance qualification in this specific orientation. Such qualifications are valid only for the positions actually tested, except that an angular deviation of $\pm 15^\circ$ is permitted in the inclination of the weld axis and the rotation of the weld face, as defined in Figure 3.1 or Figure 3.2.

3.18.5 A welder, welding operator, or tack welder who satisfactorily completes a test weldment that meets the criteria for WPS qualification in Clause 3, Part C shall be considered qualified to weld joints within the type and position limitations for the qualification test weld described in Table 3.2 and subject to the limitation of variables for welders, welding operators, or tack welders in 3.18, 3.19, 3.20, or 3.21, as applicable.

3.19 Limits of Qualified Positions for Performance

To reduce the number of welding performance qualifications that may be required, qualification under certain conditions also qualifies for other conditions as shown in Table 3.2.

3.20 Test Plate Weldment Types

Test weldment types shall be determined in accordance with this subclause and its subclauses. Satisfactory completion of a given test made using the welding parameters of a qualified WPS shall qualify the welder, welding operator, or tack welder as directed by this subclause.

3.20.1 Groove Weld Qualification Test

3.20.1.1 Plate. Each half of the test plate assembly shall have minimum dimensions of 5 in [125 mm] by 14 in [350 mm] with the groove preparation along the

14 in [350 mm] dimension. The welded joint (from one or more test assemblies) shall be of sufficient length to allow the removal of all of the required test specimens. The location of destructive test specimens and stop and restart locations shall be in accordance with Figure 3.17.

3.20.1.2 Pipe. Each section of the test assembly shall have a minimum length of 8 in [200 mm]. The welded joint (from one or more test assemblies) shall be of sufficient length to allow the removal of all of the required test specimens. The location of destructive test specimens shall be in accordance with Figure 3.18 or Figure 3.19, as applicable.

3.20.2 Fillet Weld Qualification Test

3.20.2.1 Plate. One section of the test assembly shall have minimum dimensions of 6 in × 12 in [150 mm × 300 mm] and the other section minimum dimensions of 3 in × 12 in [75 mm × 300 mm] with the square face along the 12 in. [300 mm] dimension. The welded joint (from one or more test assemblies) shall be of sufficient length to allow the removal of all of the required test specimens. The location of the destructive test specimens and stop/start locations shall be in accordance with Figure 3.20.

3.20.2.2 Pipe. Each section of the test assembly shall have a minimum length of 3 in [75 mm]. The welded joint (from one or more test assemblies) shall be of sufficient length to allow the removal of all of the required test specimens. The location of the destructive test specimen and stop/start locations shall be in accordance with Figure 3.21.

3.20.2.3 Plate to Pipe/Hollow Section. The plate section of the test assembly shall be at least 2 in [50 mm] larger than the outside dimensions of the pipe/hollow section. The welded joint (from one or more test assemblies) shall be of sufficient length to allow the removal of all of the required test specimens. The location of the destructive test specimens and stop-start position shall be in accordance with the relative position of Figure 3.22.

3.20.3 Tack Weld Qualification

3.20.3.1 Tack Weld—Fillet. The test assembly for fillet tack welds shall be in accordance with the requirements of 3.20.2.1, 3.20.2.2, or 3.20.2.3.

3.20.3.2 Tack Weld—Groove. The test assembly required for a production groove joint with a root gap shall be in accordance with the requirements of 3.20.1.1, or 3.20.1.2 for groove weld qualification test. In the case of production groove joints without a root gap, the test assembly shall be in accordance with the requirements of 3.20.2.1 or 3.20.2.2.

3.20.4 Special Weld Qualification Test

3.20.4.1 Special Welds. The test assembly for special welds and the acceptance criteria shall be agreed upon between the Contractor and the Engineer.

3.21 Limitation of Essential Variables—Welder, Welding Operator, and Tack Welder Performance Qualification

For the qualification of a welder, the following rules shall apply:

3.21.1 Qualification established with any one of the titanium alloys permitted by this code shall be considered as qualification to weld or tack weld any of the other titanium alloys with the process used in the qualification.

3.21.2 A welder shall be qualified for each welding process used.

3.21.3 A change in the approved filler metal or shielding gas combinations shall require requalification.

3.21.4 A change in the position in which welding is performed as defined in 3.18.4 and outside the limitations of Table 3.2 shall require requalification.

3.21.5 A change from one size grouping shown in Table 3.6 to another shall require requalification.

3.21.6 When the plate is in the 3G or 3F vertical position, or the pipe is in the 5G or 6G position, a change in the direction of vertical welding shall require requalification.

3.21.7 The omission of permanent backing material in complete joint penetration groove welds welded from one side shall require requalification as indicated in Figure 3.24.

3.21.8 The omission of inert gas backing shall require requalification.

3.22 Tests—Performance Qualification

3.22.1 Required Tests. The number and type of nondestructive/destructive examinations shall be determined in accordance with Table 3.6. Test methods and acceptance criteria shall be as directed by Clause 3, Part B.

3.23 Retests

3.23.1 The performance test may be terminated at any stage of the testing procedure, whenever it becomes apparent to the testing authority conducting the tests that the welder, welding operator, or tack welder does not have the required skill to produce satisfactory results.

3.23.2 In case a welder, welding operator, or tack welder fails to meet the requirements of one or more weld tests, a retest may be allowed under the following conditions:

3.23.2.1 An immediate retest may be made consisting of two test specimens of each type on which the welder, welding operator, or tack welder failed. All retest specimens shall meet all the specified requirements.

3.23.2.2 A complete performance qualification retest may be made at a later date for any failed qualification tests, provided there is evidence that the welder, welding operator, or tack welder has had further training or practice.

Table 3.1
WPS Qualification—Type of Weld and Position Limitations (see 3.13.3 and 3.14)

Qualification Test		Type of Weld and Position of Welding Qualified ^a			
		Plate		Tube	
Weld	Plate or Pipe Positions ^a	Groove	Fillet	Groove	Fillet
Plate Groove	1G	1G,	1F	1G ^b	1F ^b
	2G	1G, 2G	1F, 2F	1G ^b , 2G ^b	1F ^b , 2F ^b
	3G	1G, 3G	1F, 3F	1G ^b , 2G ^b	1F ^b , 2F ^b
	4G	1G, 4G	1F, 4F	1G ^b	1F ^b , 4F ^b
Plate Fillet	1F	—	1F	—	—
	2F	—	1F 2F	—	—
	3F	—	1F 3F	—	—
	4F	—	1F 4F	—	—
Tube Groove	1G	1G	1F	1G	1F
	2G	1G, 2G	1F, 2F	1G, 2G	1F, 2F
	5G	1G, 3G, 4G	1F, 3F, 4F	1G, 5G	1F, 4F, 5F
	6G	1G, 2G, 3G, 4G	1F, 2F, 3F, 4F	1G, 2G, 5G, 6G	1F, 2F, 4F, 5F
Tube Fillet	1F	—	1F	—	1F
	2F, 2FR	—	1F, 2F	—	1F, 2F
	4F	—	1F, 2F, 4F	—	1F, 2F, 4F
	5F	—	1F, 2F, 3F, 4F	—	1F, 2F, 4F, 5F

^a See Figure 3.3, Figure 3.4, Figure 3.5, and Figure 3.6.

^b Qualifies for welding pipe or tubing over 24 in [610 mm] in diameter.

Table 3.2
Welder, Welding Operator, and Tack Welder Performance Limitations
(see 3.18.3, 3.18.5, 3.19, 3.21.4, and Table 3.1)

Qualification Test	Plate or Pipe Positions ^b	Type of Weld and Position of Welding Qualified ^b			
		Plate		Pipe	
Weld	Plate or Pipe Positions ^b	Groove ^a	Fillet ^c	Groove	Fillet ^c
Plate-Groove Complete Joint Penetration	1G	1G	—	1G ^a	—
	2G	1G, 2G	—	1G ^a , 2G ^a	—
	3G	1G, 3G	—	—	—
	4G	1G, 4G	—	—	—
	3G and 4G	All	—	—	—
Plate-Fillet	1F	—	1F	—	1F ^a
	2F	—	1F, 2F	—	1F ^a , 2F ^a
	3F	—	3F	—	5F ^a
	4F	—	4F	—	4F ^a
Tube-Groove Complete Joint Penetration	1G	1G	—	1G	—
	2G	1G, 2G	—	1G, 2G	—
	5G	1G, 3G, 4G	—	1G, 2G, 5G	—
	6G	All	—	All ^b	—
Tube Fillet	1F	—	1F	—	1F
	2F, 2FR	—	1F, 2F	—	1F, 2F
	4F	—	1F, 2F, 4F	—	1F, 2F, 4F
	5F	—	All	—	All

^aQualifies for welding pipe or tubing over 24 in [610 mm] in diameter.

^bSee Figure 3.3, Figure 3.4, Figure 3.5, and Figure 3.6.

^cWelders requiring qualification for fillet welding shall also possess a groove weld qualification in any position and thickness.

Table 3.3
Limitations of Essential Variables: of a WPS^a (see 3.15)

Essential Variable (Changes outside these limits require requalification)	GMAW	GTAW (Manual)	GTAW (Mechanized)	Manual PAW	Mechanized PAW	EBW	LBW
Welding Process							
A change in the welding process, i.e., from GMAW to GTAW	X	X	X	X	X	X	X
Base Metal Alloy							
A change from one material M number (Note b) to another except as detailed in Table 3.4	X	X	X	X	X	X	X
Base Metal Thickness							
A change in thickness beyond the limitations of the qualified range as shown in Table 3.5	X	X	X	X	X	X	X
Filler Metal							
A change from one filler metal grade to another (Note c)	X	X	X	X	X	X	X
The addition or deletion of filler metal		X	X	X	X	X	X
A change in the method by which filler metal is added (Note f)		X	X	X	X	X	X
Electrode/Filler Metal							
An increase or decrease in the nominal filler metal diameter	X	by >0.035 in [>1 mm]	by >0.02 in [>0.5 mm]	by >0.035 in [>1 mm]	by >0.02 in [>0.5 mm]	by >0.02 in [>0.5 mm]	by >0.02 in [>0.5 mm]
An increase or decrease in the nominal filler metal volume feed rate (Note e)			>20%		>20%	>20%	>20%
The addition or deletion of resistance heating of the filler wire			X		X	X	X
Travel Speed							
An increase or decrease in the specified travel speed	>15%	>15%	>15%	>15%	>15%	X	X
Electrical Parameters							
An increase or decrease in the specified amperage	>15%	>20%	>20%	>20%	>20%	X	X
An increase or decrease in the specified voltage	>15%	>15%	>15%	>15%	>15%	>2%	X
A change in the beam or beam focus current from that qualified						>5%	
A change in the beam pulsing frequency or duration from that qualified						X	

(Continued)

Table 3.3 (Continued)
Limitations of Essential Variables: of a WPS^a (see 3.15)

Essential Variable (Changes outside these limits require requalification)	GMAW	GTAW (Manual)	GTAW (Mechanized)	Manual PAW	Mechanized PAW	EBW	LBW
A change in the filament type, size, or shape						X	
Shielding							
A change in shielding gas from a single gas to any other single gas or to a mixture of gases	X	X	X	X	X	X	X
A change in the specified nominal percentage composition of a gas mixture	X	X	X	X	X	X	X
A change in shielding gas concept (Note g)	X	X	X	X	X		X
An increase in the total flow rate	>50%	>50%	>30%	>50%	>30%		>30%
A decrease in the total flow rate	>20%	>20%	>10%	>20%	>10%		>10%
A change of shielding environment from vacuum to inert gas							X
An increase in vacuum pressure						X	
The deletion of, or a change in composition of or a decrease exceeding 10% in the trailing gas flow rate	X	X	X	X	X	X	X
The addition, deletion, a 5% flow rate change for any gas used in the process, or a change in the orientation of the plasma removing gas jet relative to the workpiece (e.g., coaxial transverse to the beam)							X
Plasma							
A change in plasma orifice diameter				X	X		
A change in electrode tip geometry				X	X		
A change in plasma gas flow				X	>10%		
A change in plasma gas composition				X	X		
A change in secondary (shield) gas flow				>10%	>10%		
A change in secondary (shield) gas composition				X	X		
A change in electrode "set back"				X	X		
A change in torch angle				X	X		
A change in torch type				X	X		

(Continued)

Table 3.3 (Continued)
Limitations of Essential Variables: of a WPS^a (see 3.15)

Essential Variable (Changes outside these limits require requalification)	GMAW	GTAW (Manual)	GTAW (Mechanized)	Manual PAW	Mechanized PAW	EBW	LBW
Welding Power Source							
A change from nonpulsed to pulsed type and vice versa	X	X	X	X	X		
A change from AC to DC or vice versa	X	X	X	X	X		
A change in the type of AC “wave form”		X	X	X	X		
A change from DCEP to DCEN and vice versa	X	X	X	X	X		
Number of Weld Passes							
For a specified groove area, a change >25% in the number of passes specified (Note h)	X	X	X	X	X		
Technique							
A change from stringer-bead technique to a weave-bead technique	X	X	X	X	X		
A change from multiple pass per side to single pass per side						X	X
A change exceeding $\pm 5\%$ in gun to work piece distance, or axis of beam angle related to work						X	
A change exceeding $\pm 20\%$ in oscillation length or width from that qualified, or the addition of a cosmetic wash pass						X	
A change from single sided welds to double sided or vice versa						X	X
Welding Position							
A change in position in which welding is done exceeding the limitations of Table 3.1	X	X	X	X	X	X	X
Direction of Welding							
A change from push to pull and vice versa	X		X		X	X	X
A change in torch angle	>10°	> $\pm 15^\circ$	> $\pm 5^\circ$	> $\pm 15^\circ$	> $\pm 5^\circ$	> $\pm 5^\circ$	> $\pm 5^\circ$
Vertical welding: For any pass from upward to downward or vice versa	X	X	X	X	X	X	X
Groove Type							
A change in the type of groove	X	X	X	X	X	X	X

(Continued)

Table 3.3 (Continued)
Limitations of Essential Variables: of a WPS^a (see 3.15)

Essential Variable (Changes outside these limits require requalification)	GMAW	GTAW (Manual)	GTAW (Mechanized)	Manual PAW	Mechanized PAW	EBW	LBW
A decrease of 5° or more in the specified groove angle	X	X	X	X	X		
A change in the M number of the backing	X	X	X	X	X	X	X
Fit-Up Tolerances							
Changes involving the following:							
A decrease in the groove angle by	>5°	>5°	>5°	>5°	>5°		
A change in the root opening (when backing is not used) by	>1/16 in [1.5 mm]	>1/32 in [0.8 mm]	>1/32 in [0.8 mm]	>1/32 in [0.8 mm]	>1/32 in [0.8 mm]		
An increase in the root face (when not back machined) by:	>1/16 in [1.5 mm]	>1/32 in [0.8 mm]	>1/32 in [0.8 mm]	>1/32 in [0.8 mm]	>1/32 in [0.8 mm]		
An increase in fit up gap beyond that used in the qualification test						X	X
Cleaning							
A change in the type of cleaning used (mechanical, chemical, etc.)							
(1) in initial joint preparation	X	X	X	X	X	X	X
(2) in interpass cleaning of weld beads	X	X	X	X	X	X	X
Backing							
A change from permanent backing to temporary or no backing	X	X	X	X	X	X	X
Back-Machining							
Omission, but not inclusion of	X	X	X	X	X	X	X
Interpass Temperature							
Increase from specified maximum	X	X	X	X	X	X	X
Postweld Heat Treatment (PWHT) (See Note d)							
Addition or deletion of PWHT	X	X	X	X	X	X	X
Change in nominal PWHT temperature	>±18°F [≥±10°C]	>±18°F [≥±10°C]	>±18°F [≥±10°C]	>±18°F [≥±10°C]	>±18°F [≥±10°C]	>±18°F [≥±10°C]	>±18°F [≥±10°C]
Change of furnace atmosphere	X	X	X	X	X	X	X

^a An "X" indicates applicability for the process; a shaded area indicates nonapplicability.

^b Grade numbers are shown in Table 4.1.

^c Filler metal grades are detailed in AWS A5.16.

^d PWHT is not required for welding personnel qualification tests involving material numbers M51, M52, M53, and M54 (Grades 1, 2, 3, 5, 9, and 23).

^e Filler metal volume feed rate is calculated by multiplying the wire cross sectional area in inches [mm] by the filler wire feed speed in inches per minute [mm/min].

^f From leading edge of the weld pool to the trailing or side of the weld pool.

^g A change in shielding gas concept would include the deletion but not addition of a trailing shield or other gas related concept that may effect the inert gas protection of a weld.

^h If the area of the groove is changed, it is permissible to change the number of passes in proportion to the area.

Table 3.4
Limitations of Variables for Base Materials (see Table 3.3 and 4.3.2)

Base Material M Number and Grade for Test Plate	Base Material M Number and Grade Qualified						
	M51 (Grade 1)	M51 (Grade 2)	M52 (Grade 3)	M53 (Grade 9)	M54 (Grade 5)	M54 (Grade 23)	Armor Grades
M51 (Grade 1)	X						
M51 (Grade 2)	X	X					
M52 (Grade 3)			X				
M53 (Grade 9)				X			
M54 (Grade 5)					X		
M54 (Grade 23)					X	X	
Armor Grades							X ^a

^aMIL-DTL-46077—Armor Plate, Titanium, Weldable.

Table 3.5
Number and Type of Test Specimens and Range of Thickness Qualified—WPS Qualification
(see 3.6, 3.13.3, 3.16.1, 3.16.2, and Table 3.3)

Joint Type ^f	Nominal Plate/Pipe Thickness (T) and Diameter (D), ^a in [mm]	Minimum Length of Weld Joint, ^c in [mm]	Surface Visual Inspection	Macro Exam	Radiography	Transverse Tensile	Root Bend ^b	Face Bend ^b	Side Bend	Weld Metal Chemical Analysis ^e	Plate/Pipe Thickness and Diameter Qualified, in [mm]
Plate Groove	1/8 ≤ T ≤ 3/8 [3 ≤ T ≤ 10]	14 [350]	Full	1	Full	2	2	2	—	—	1/8 to 1/2 [3 to 12] plate
	3/8 < T ≤ 1 [10 < T ≤ 25]	14 [350]	Full	1	Full	2	—	—	4	—	3/8 to 2 [10 to 50] plate
	T > 1 [T > 25]	14 [350]	Full	1	Full	2	—	—	4	—	1 [25] and greater plate
Plate Fillet	1/8 ≤ T ≤ 3/8 [3 ≤ T ≤ 10]	12 [300]	Full	3	N/A	N/A	N/A	N/A	N/A	—	1/8 to 1/2 [3 to 12] plate
	3/8 < T ≤ 1 [10 < T ≤ 25]	12 [300]	Full	3	N/A	N/A	N/A	N/A	N/A	—	3/8 to 2 [10 to 50] plate
	T > 1 [T > 25]	12 [300]	Full	3	N/A	N/A	N/A	N/A	N/A	—	1 [25] and greater plate
Pipe Groove	1/2 < D ≤ 1 T ≥ 0.125 [12 < D ≤ 25] [T ≥ 3]	12 [300]	Full	1	Full	2	2	2	—	—	1/2 < D ≤ 1 T ≥ 0.125 [12 < D ≤ 25] [T ≥ 3]
	1 < D ≤ 3 0.125 ≤ T ≤ 0.25 [25 < D ≤ 76] [3 ≤ D ≤ 6]	12 [300]	Full	1	Full	2	2	2	—	—	1 < D ≤ 3 0.125 ≤ T ≤ 0.25 [25 < D ≤ 76] [3 < D ≤ 6]
	1 < D ≤ 3 0.25 < T ≤ 0.5 [25 < D ≤ 76] [6 < T ≤ 12]	12 [300]	Full	1	Full	2	2	2	—	—	1 < D ≤ 3 0.25 ≤ T ≤ 0.5 [25 < D ≤ 76] [6 ≤ T ≤ 12]
	D > 3 0.125 ≤ T ≤ 0.216 [D > 76] [3 ≤ T ≤ 5.5]	12 [300]	Full	1	Full	2	2	2	—	—	D > 3 0.125 ≤ T ≤ 0.216 [D > 76] [3 ≤ T ≤ 5.5]
	0.216 < T ≤ 0.6 [D > 76] [5.5 < T ≤ 15]	12 [300]	Full	1	Full	2	2	2	—	—	D > 3 0.216 ≤ T ≤ 0.6 [D > 76] [5.5 ≤ T ≤ 15]

(Continued)

Table 3.5 (Continued)
Number and Type of Test Specimens and Range of Thickness Qualified—WPS Qualification
(see 3.6, 3.13.3, 3.16.1, 3.16.2, and Table 3.3)

Joint Type ^f	Nominal Plate/Pipe Thickness (T) and Diameter (D), ^a in [mm]	Minimum Length of Weld Joint, ^c in [mm]	Surface Visual Inspection	Macro Exam	Radiography	Transverse Tensile	Root Bend ^b	Face Bend ^b	Side Bend	Weld Metal Chemical Analysis ^e	Plate/Pipe Thickness and Diameter Qualified, in [mm]
Pipe Groove (Cont'd)	D > 3 T > 0.6 [D > 76] [T > 15]	12 [300]	Full	3	Full	2	2	2	—	—	D > 3 T > 0.6 [D > 76] [T > 15]
Pipe Fillet	1/2 < D ≤ 1 [12 < D ≤ 25]	12 [300]	Full	3	N/A	N/A	—	—	—	—	The thickness qualified shall be determined by reference to the limits set for plate fillet welds and 1/2 < D ≤ 1 [12 < D ≤ 25]
	1 < D ≤ 3 [25 < D ≤ 76]	12 [300]	Full	3	N/A	N/A	—	—	—	—	The thickness qualified shall be determined by reference to the limits set for plate fillet welds and 1 < D ≤ 3 [25 < D ≤ 76]
	D > 3 [D > 76]	12 [300]	Full	3	N/A	N/A	—	—	—	—	The thickness qualified shall be determined by reference to the limits set for plate fillet welds and D > 3 [D > 76]
Plug and Slot Weld	1/8 ≤ T ≤ 3/8 [3 ≤ T ≤ 10]	Special weld	Full	3	N/A	N/A	—	—	—	—	The thickness qualified shall be determined by reference to the limits set for plate fillet welds
	3/8 < T ≤ 1 [10 < T ≤ 25]	Special weld	Full	3	N/A	N/A	—	—	—	—	The thickness qualified shall be determined by reference to the limits set for plate fillet welds
	T > 1 [T > 25]	Special weld	Full	3	N/A	N/A	—	—	—	—	The thickness qualified shall be determined by reference to the limits set for plate fillet welds
Special Welds	To be agreed between the contracting parties										

^a The nominal pipe diameter is not equal to outside diameter for D < 14 in [D < 450 mm].

^b For nominal thickness greater than 0.6 in [15 mm] face and root bend specimens may be replaced with an equal number of side bend specimens.

^c The minimum length may be calculated cumulatively from several test pieces.

^d Relates to the nominal size of the smaller pipe for pipe fillet and complete joint penetration pipe T-welds.

^e Weld metal chemical analysis shall be completed when required by the contract.

^f Fillet, complete penetration T-joint, plug and slot welds shall be supplemented with a complete joint penetration groove weld approval.

Table 3.6
Number and Type of Test Specimens and Range of Thickness Qualified for Welder, Welding Operator, and Tack Welder Qualification (see 3.6, 3.21.5, and 3.22.1)

Joint Type	Nominal Plate/Pipe Thickness (T) and Diameter (D), ^a in [mm]	Minimum Length of Weld Joint, ^c in [mm]	Surface Visual Inspection	Macro Exam	Radiography	Transverse Tensile	Root Bend ^b	Face Bend ^b	Side Bend	Plate/Pipe Thickness and Diameter Qualified, in [mm]
Plate Groove	1/8 ≤ T ≤ 3/8 [3 ≤ T ≤ 10]	14 ^e [350]	Full	—	Full	2	2	2	—	1/8 to 1/2 [3 to 12] plate
	3/8 < T ≤ 1 [10 < T ≤ 25]	14 ^e [350]	Full	—	Full	2	—	—	4	3/8 to 2 [10 to 50] plate
	T > 1 [T > 25]	14 ^e [350]	Full	—	Full	2	—	—	4	≥ 1 [25] plate
Plate Fillet	1/8 ≤ T ≤ 3/8 [3 ≤ T ≤ 10]	12 [300]	Full	3	—	—	—	—	—	1/8 to 1/2 [3 to 12] plate
	3/8 < T ≤ 1 [10 < T ≤ 25]	12 [300]	Full	3	—	—	—	—	—	3/8 to 2 [10 to 50] plate
	T > 1 [T > 25]	12 [300]	Full	3	—	—	—	—	—	≥ 1 [25] plate
Pipe Groove	1/2 < D ≤ 1 T ≥ 0.125 [12 < D ≤ 25] [T ≥ 3]	12 [300]	Full	—	Full	2	2	2	—	1/2 < D ≤ 1 T ≥ 0.125 [12 < D ≤ 25] [T ≥ 3]
	1 < D ≤ 3 0.125 ≤ T ≤ 0.25 [25 < D ≤ 76] [3 ≤ D ≤ 6]	12 [300]	Full	—	Full	2	2	2	—	1 < D ≤ 3 0.125 ≤ T ≤ 0.25 [25 < D ≤ 76] [3 < D ≤ 6]
	1 < D ≤ 3 0.25 < T ≤ 0.5 [25 < D ≤ 76] [6 < T ≤ 12]	12 [300]	Full	—	Full	2	2	2	—	1 < D ≤ 3 0.25 ≤ T ≤ 0.5 [25 < D ≤ 76] [6 ≤ T ≤ 12]
	D > 3 0.125 ≤ T ≤ 0.216 [D > 76] [3 ≤ T ≤ 5.5]	12 [300]	Full	—	Full	2	2	2	—	D > 3 0.125 ≤ T ≤ 0.216 [D > 76] [3 ≤ T ≤ 5.5]
	D > 3 0.216 < T ≤ 0.6 [D > 76] [5.5 < T ≤ 15]	12 [300]	Full	—	Full	2	2	2	—	D > 3 0.216 ≤ T ≤ 0.6 [D > 76] [5.5 ≤ T ≤ 15]

(Continued)

Table 3.6 (Continued)
**Number and Type of Test Specimens and Range of Thickness Qualified for Welder,
Welding Operator, and Tack Welder Qualification (see 3.6, 3.21.5, and 3.22.1)**

Joint Type	Nominal Plate/Pipe Thickness (T) and Diameter (D), ^a in [mm]	Minimum Length of Weld Joint, ^c in [mm]	Surface Visual Inspection	Macro Exam	Radiography	Transverse Tensile	Root Bend ^b	Face Bend ^b	Side Bend	Plate/Pipe Thickness and Diameter Qualified, in [mm]
Pipe Groove (Cont'd)	D > 3 T > 0.6 [D > 76] [T > 15]	12 [300]	Full	—	Full	2	—	—	4	D > 3 T > 0.6 [D > 76] [T > 15]
Pipe Fillet	1/2 < D ≤ 1 [12 < D ≤ 25]	12 [300]	Full	3	—	—	—	—	—	The thickness qualified shall be determined by reference to the limits set for plate fillet welds and 1/2 < D ≤ 1 [12 < D ≤ 25]
	1 < D ≤ 3 [25 < D ≤ 76]	12 [300]	Full	3	—	—	—	—	—	The thickness qualified shall be determined by reference to the limits set for plate fillet welds and 1 < D ≤ 3 [25 < D ≤ 76]
	D > 3 [D > 76]	12 [300]	Full	3	—	—	—	—	—	The thickness qualified shall be determined by reference to the limits set for plate fillet welds and D > 3 [D > 76]
Plug and Slot Weld	1/8 ≤ T ≤ 3/8 [3 ≤ T ≤ 10]	Special weld	Full	3	—	—	—	—	—	The thickness qualified shall be determined by reference to the limits set for plate fillet welds
	3/8 < T ≤ 1 [10 < T ≤ 25]	Special weld	Full	3	—	—	—	—	—	The thickness qualified shall be determined by reference to the limits set for plate fillet welds
	T > 1 [T > 25]	Special weld	Full	3	—	—	—	—	—	The thickness qualified shall be determined by reference to the limits set for plate fillet welds
Special Welds	To be agreed between the contracting parties									

^a The nominal pipe diameter is not equal to outside diameter for D < 14 in [350 mm].

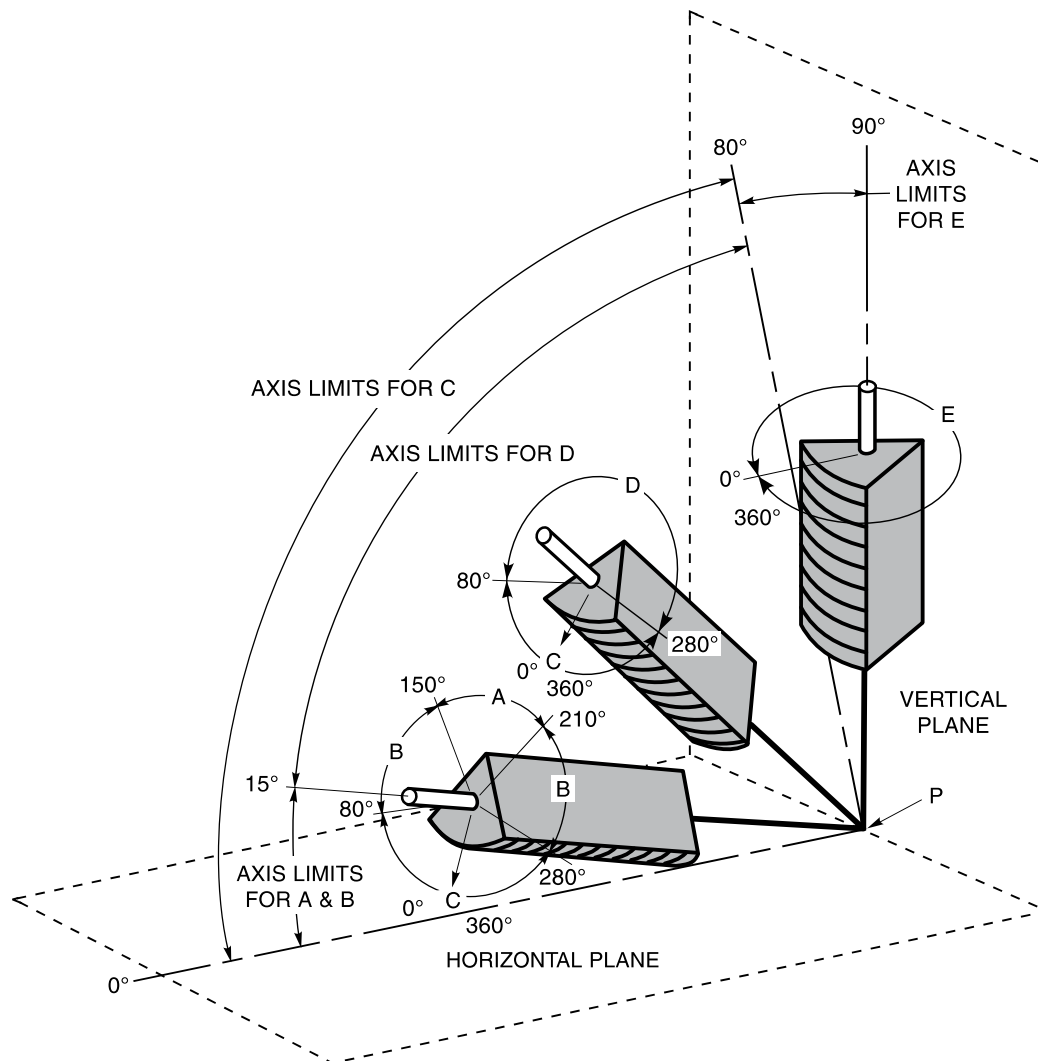
^b For nominal thickness greater than 0.6 in [15 mm] face and root bend specimens may be replaced with an equal number of side bend specimens.

^c The minimum length may be calculated cumulatively from several test pieces.

^d Relates to the nominal size of the smaller pipe for pipe fillet and complete joint penetration pipe T-welds.

^e The 14 in minimum includes 4 in [100 mm] of discard material that may be run-on/off tabs.

Tabulation of Positions of Groove Welds			
Position	Diagram Reference	Inclination of Axis	Rotation of Face
Flat	A	0° to 15°	150° to 210°
Horizontal	B	0° to 15°	80° to 150° 210° to 280°
Overhead	C	0° to 80°	0° to 80° 280° to 360°
Vertical	D	15° to 80°	80° to 280°
	E	80° to 90°	0° to 360°



Notes:

1. The horizontal reference plane is always taken to lie below the weld under consideration.
2. The inclination of axis is measured from the horizontal reference plane toward the vertical reference plane.
3. The angle of rotation of the face is determined by a line perpendicular to the theoretical face of the weld which passes through the axis of the weld. The reference position (0°) of rotation of the face invariably points in the direction opposite to that in which the axis angle increases. When looking at point P, the angle of rotation of the face of the weld is measured in a clockwise direction from the reference position (0°).

Figure 3.1—Positions of Groove Welds (see 3.5.2 and 3.18.4)

Tabulation of Positions of Fillet Welds			
Position	Diagram Reference	Inclination of Axis	Rotation of Face
Flat	A	0° to 15°	150° to 210°
Horizontal	B	0° to 15°	125° to 150° 210° to 235°
Overhead	C	0° to 80°	0° to 125° 235° to 360°
Vertical	D	15° to 80°	125° to 235°
	E	80° to 90°	0° to 360°

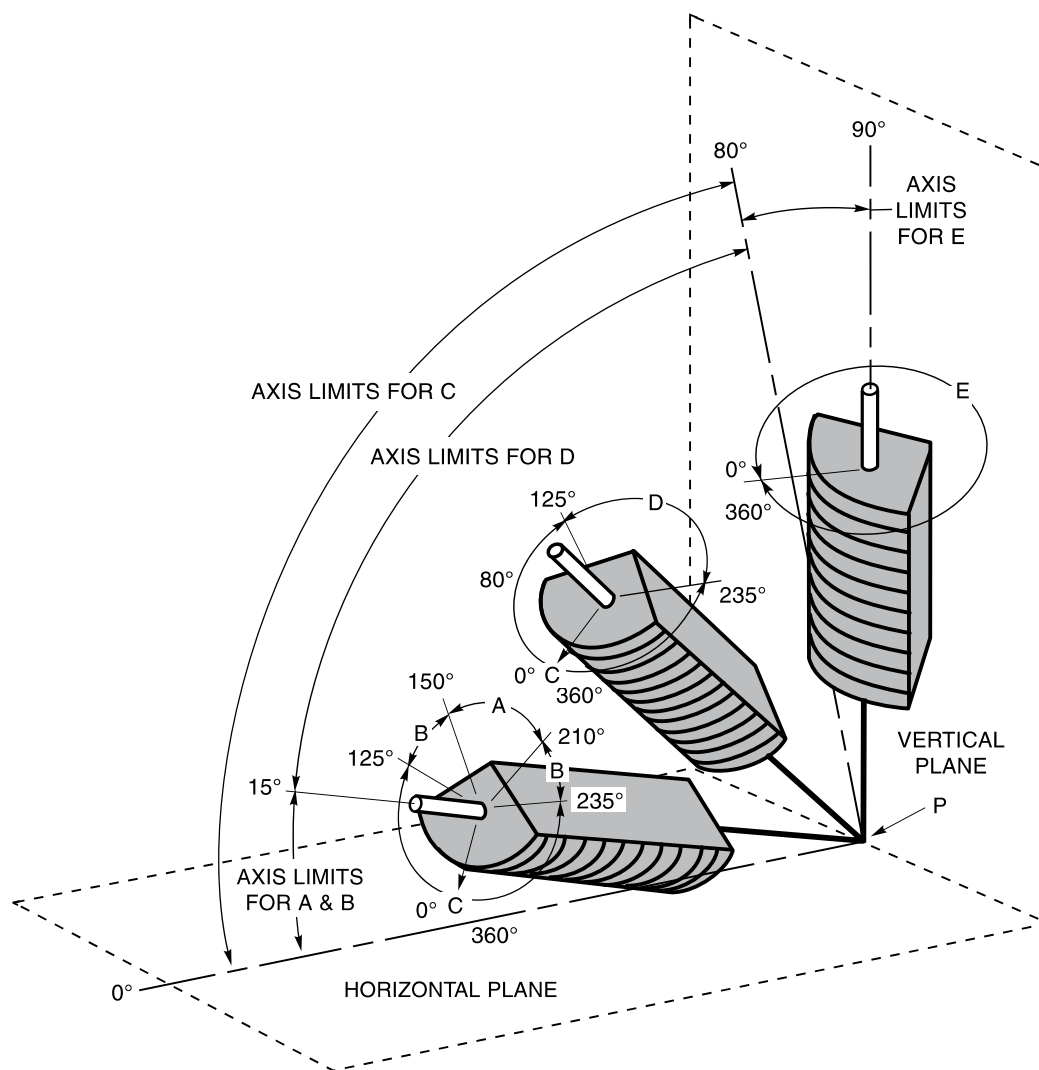
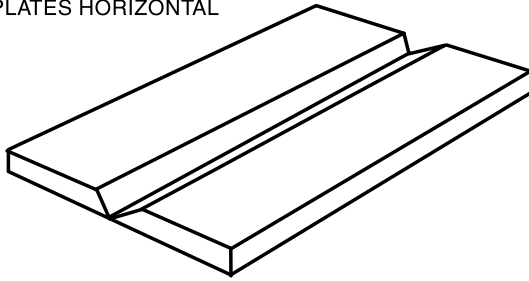
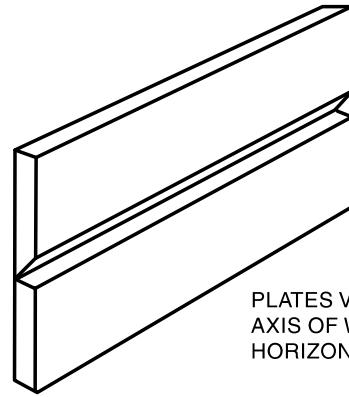


Figure 3.2—Positions of Fillet Welds (see 3.5.2 and 3.18.4)

PLATES HORIZONTAL

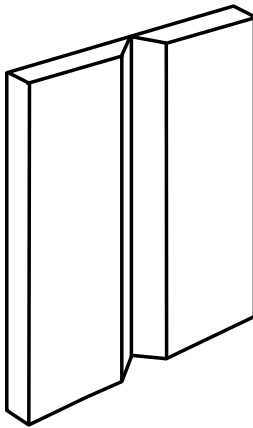


(A) FLAT WELDING TEST POSITION 1G



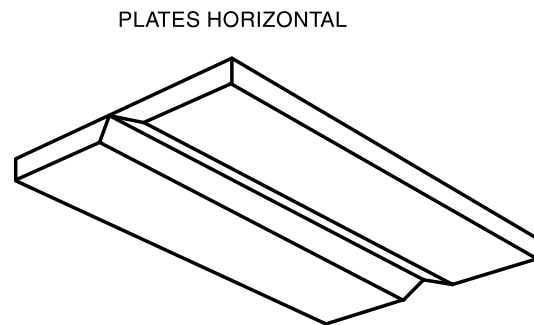
PLATES VERTICAL;
AXIS OF WELD
HORIZONTAL

(B) HORIZONTAL WELDING TEST POSITION 2G



PLATES VERTICAL;
AXIS OF WELD
VERTICAL

(C) VERTICAL WELDING TEST POSITION 3G



PLATES HORIZONTAL

(D) OVERHEAD WELDING TEST POSITION 4G

Figure 3.3—Position of Test Plates for Groove Welds (see 3.5.2 and 3.5.2.1)

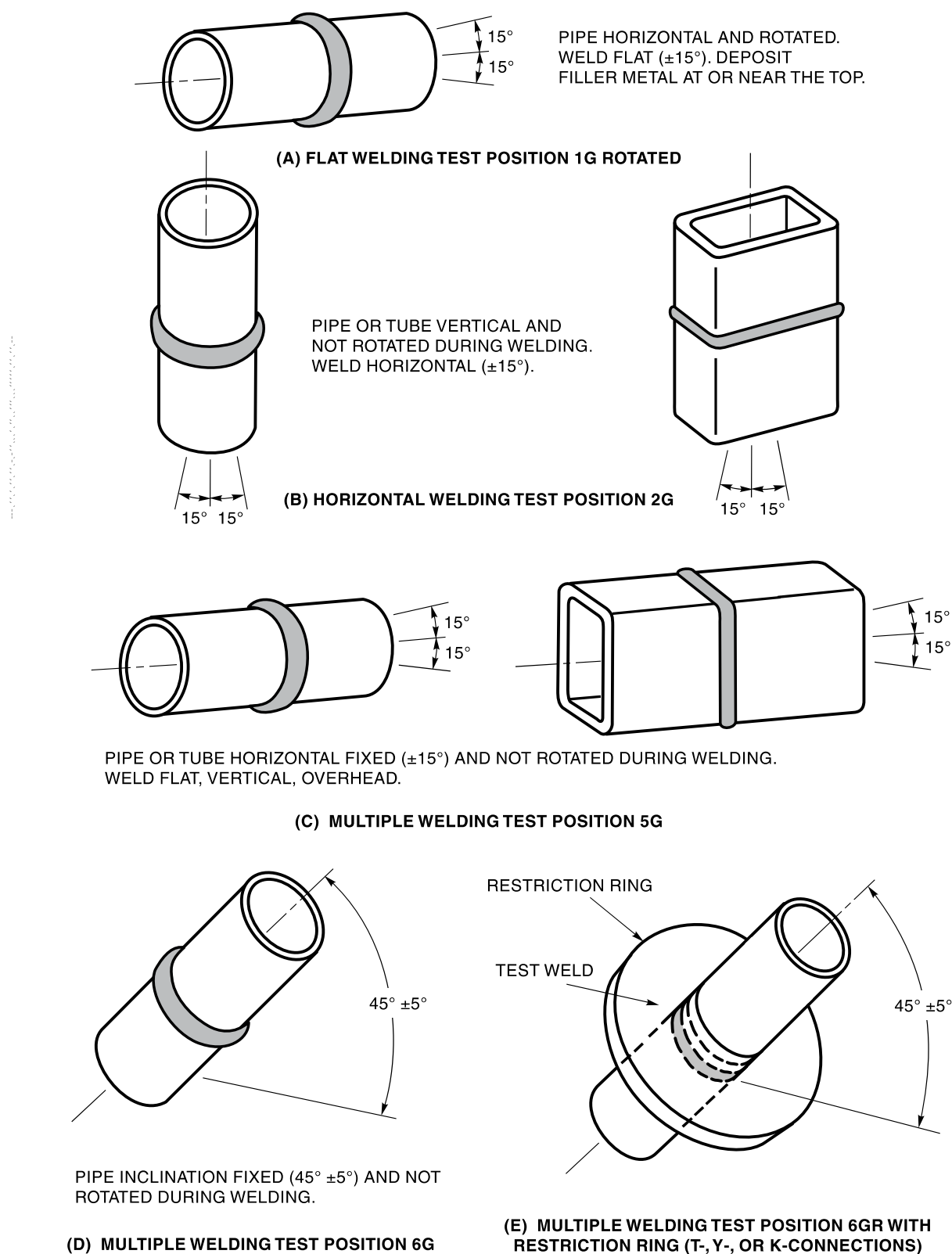


Figure 3.4—Positions of Groove Welds in Pipe or Tubing (see 3.5.2 and 3.5.2.2)

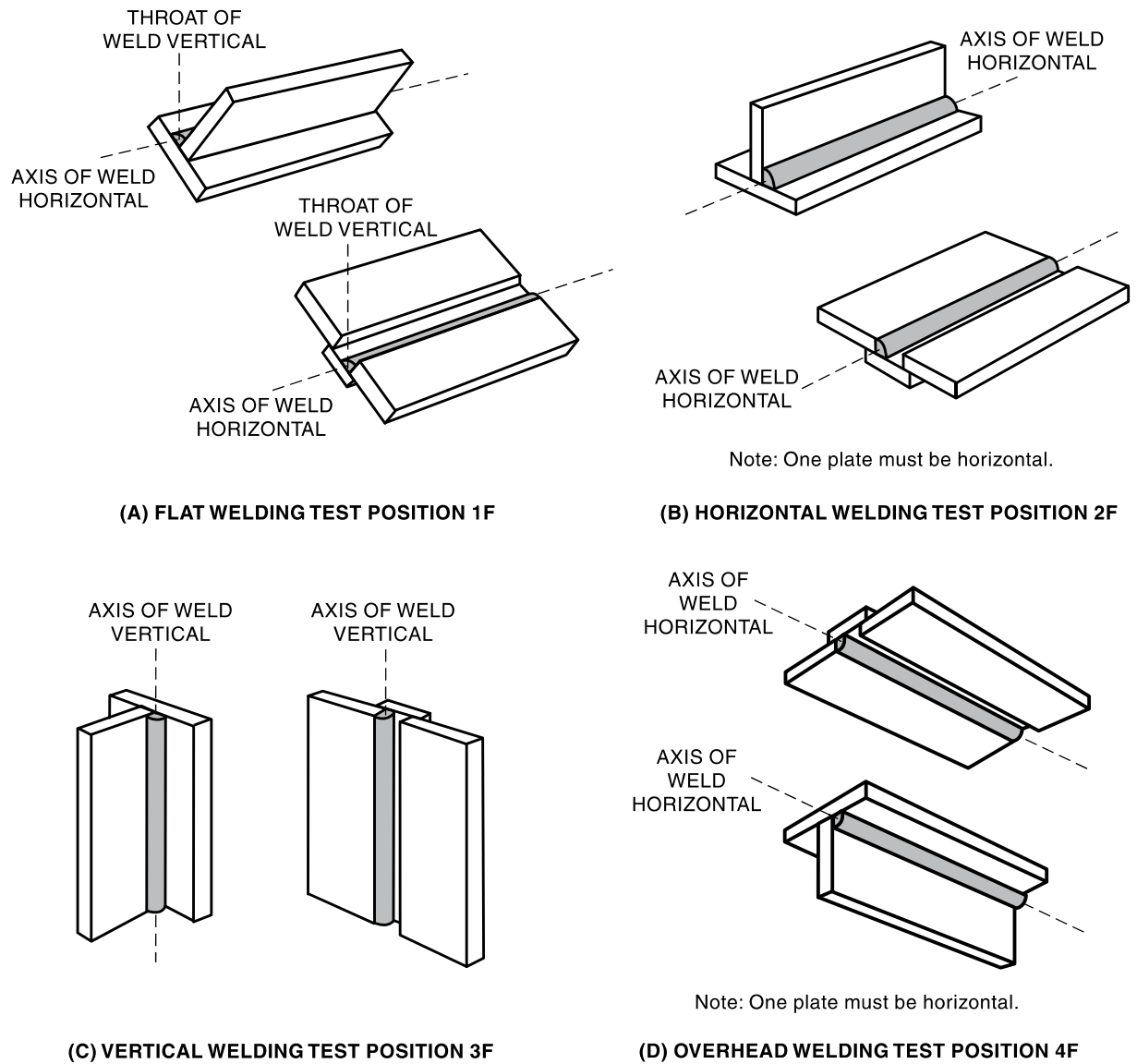


Figure 3.5—Positions of Test Plates for Fillet Welds (see 3.5.2 and 3.5.2.3)

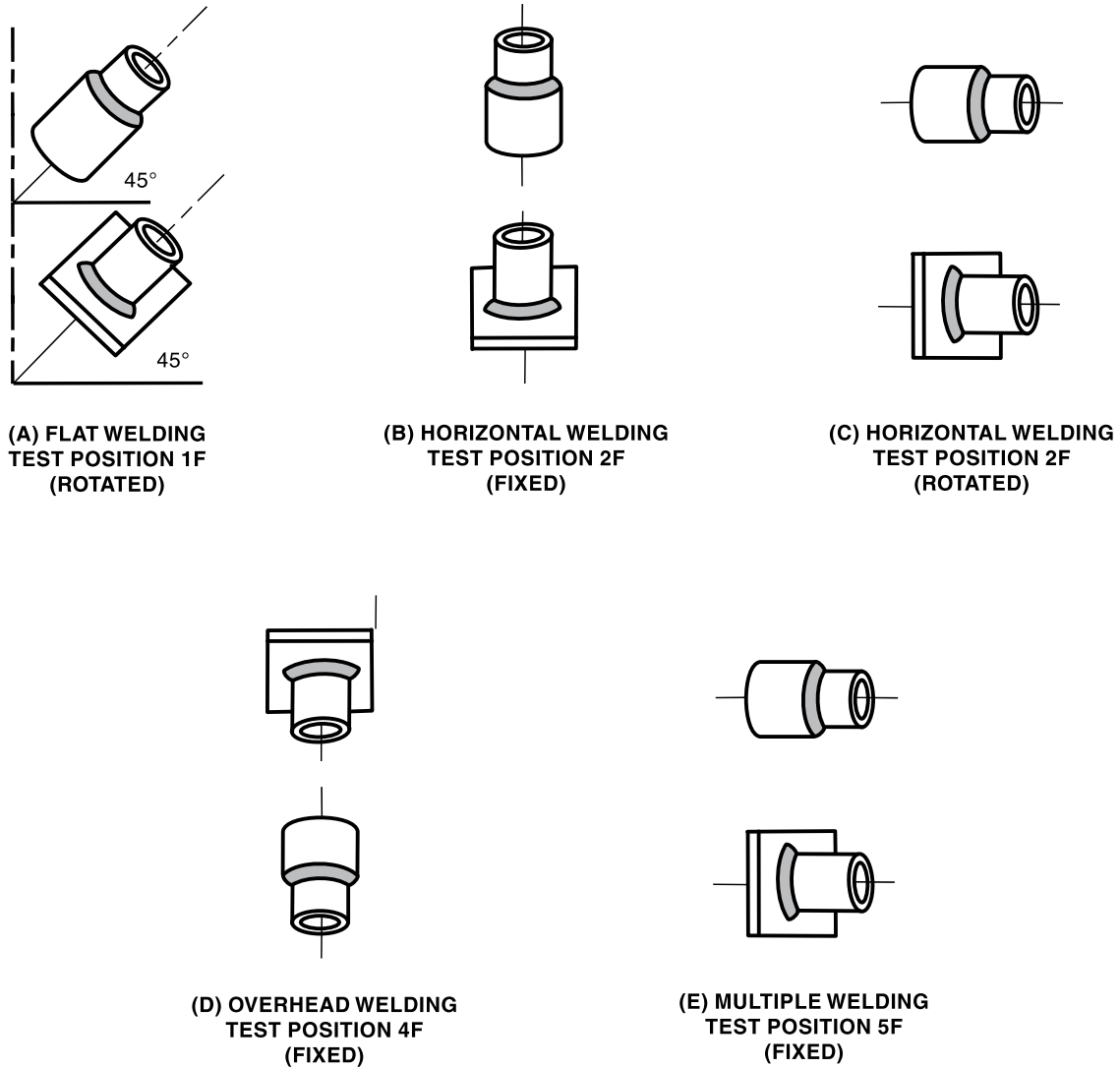


Figure 3.6—Positions of Test Pipes for Fillet Welds (see 3.5.2 and 3.5.2.4)

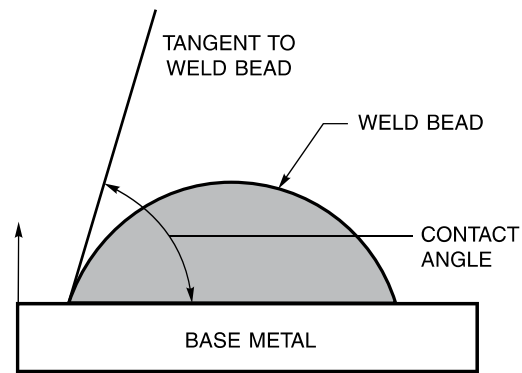
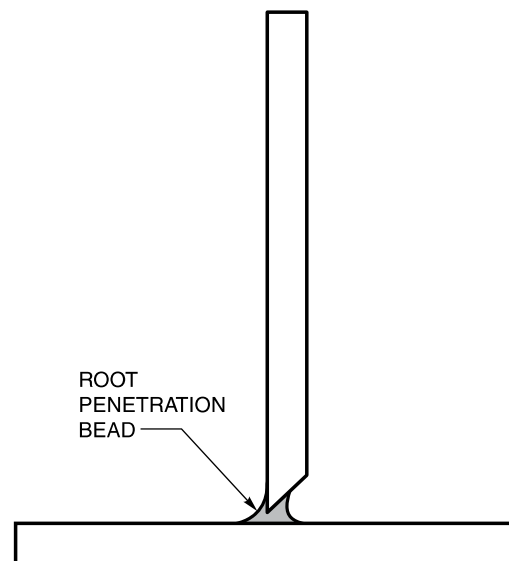
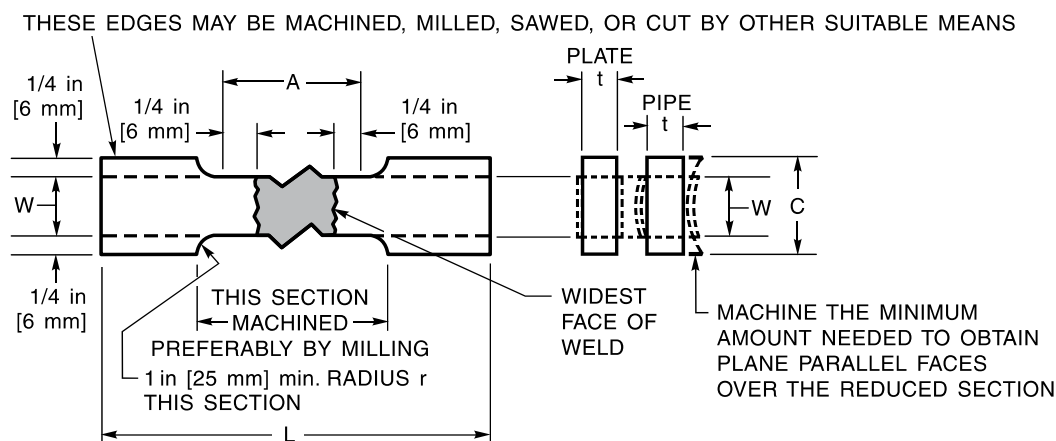


Figure 3.7—Weld Contact Angle Definition (see 3.7.2.1)



Note: The root penetration bead shown on the left hand side shall be fully penetrated and concave with a vertical leg length greater than the original root gap (note this weld has been made from the right hand side). Undercut on the penetration side shall not exceed that allowed in 3.7.2.3.

Figure 3.8—Root Fusion Requirements for Complete Penetration T-Joints in Material Numbers M51, M52, M53, and M54 (Grades 1, 2, 3, 5, 9, and 23) (see 3.7.2.3)



Dimensions (in)				
	Test Plate		Test Pipe	
	Thickness ≤ 0.75 in	Thickness > 0.75 in	3 in or Smaller Diameter ^f	Greater than 3 in Diameter of Larger Job Size Pipe
A—Length of reduced section	Widest face of weld + 1/2, 2-1/4 min.		Widest face of weld + 1/2 in	
L—Overall length, min. ^a	As required by testing equipment		As required by testing equipment	
W—Width of reduced section ^{b,c}	$1-1/2 \pm 0.125$	1 ± 0.125	$1/2 \pm 0.125$	$3/4 \pm 0.05$
C—Width of grip section, min. ^{c,d}	2	1-1/2	1 approx.	1-1/4 approx.
t—Specimen thickness ^{e,f}	Thickness	Thickness/n (Note 7)	Maximum possible with plane parallel faces within length A	
r—Radius of fillet, min.	1	1	1	1

Dimensions [mm]				
	Test Plate		Test Pipe	
	Thickness ≤ 19 mm	Thickness > 19 mm	75 mm or Smaller Diameter ^f	Greater than 75 mm Diameter of Larger Job Size Pipe
A—Length of reduced section	Widest face of weld + 13 mm, 57 mm min.		Widest face of weld + 13 mm	
L—Overall length, min. ^a	As required by testing equipment		As required by testing equipment	
W—Width of reduced section ^{b,c}	38 ± 3	25 ± 3	13 ± 3	19 ± 1.3
C—Width of grip section, min. ^{c,d}	51	38	25 approx.	32 approx.
t—Specimen thickness ^{e,f}	Thickness	Thickness/n	Maximum possible with plane parallel faces within length A	
r—Radius of fillet, min.	25	25	25	25

^a The ends of the reduced section shall not differ in width by more than 0.004 in [0.102 mm]. Also, there may be gradual decrease in width from the ends to the center, but the width of either end shall not be more than 0.015 in [0.381 mm] larger than the width at the center.

^b Narrower widths (W and C) may be used when necessary. In such cases, the width of the reduced section should be as large as the width of the material being tested permits. If the width of the material is less than W, the sides may be parallel throughout the length of the specimen.

^c For standard plate-type specimens, the ends of the specimen shall be symmetrical with the center line of the reduced section within 0.25 in [6 mm] except for referee testing, in which case the ends of the specimen shall be symmetrical with the center line of the reduced section within 0.10 in [2.5 mm].

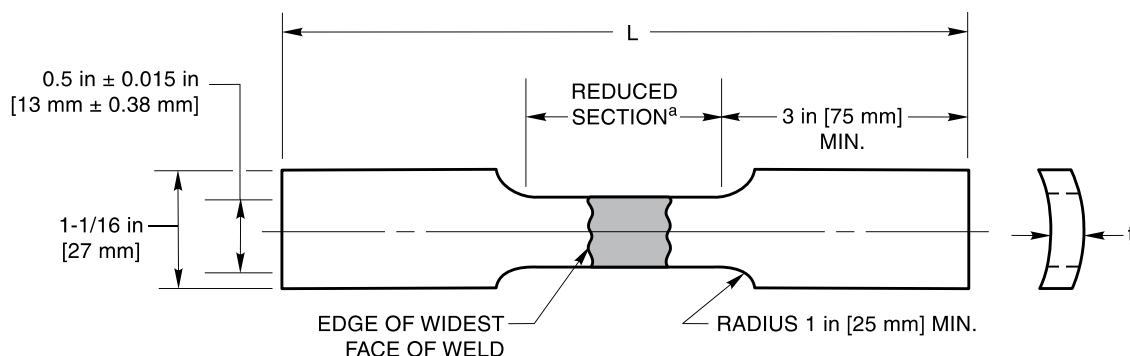
^d The dimension t is the thickness of the specimen as provided for in the applicable material specifications. The minimum nominal thickness of 1-1/2 in [38 mm] wide specimens shall be 3/16 in [5 mm] except as permitted by the product specification.

^e For plates over 0.75 in [19 mm] thick, specimens may be cut into the minimum number (n) of approximately equal strips not exceeding 0.75 in [19 mm] in thickness. Test each strip and each strip must meet the tensile requirements.

^f Refer to 3.10.1.1(2) for alternate test specimen.

Note: It is desirable, if possible, to make the length of the grip section large enough to allow the specimen to extend into the grips a distance equal to two-thirds or more of the length of the grips.

Figure 3.9—Reduced Section Tension Specimens—Plate and Pipe
(see 3.10.1, 3.10.1.1, and 3.10.1.2)



^a The length of the reduced section shall not be less than the width of the welds plus two "t."

Notes:

1. Cross-sectional area = $0.5 \times "t."$
2. Test specimen thickness (t) shall be within the material thickness range allowed by the applicable material specification for the schedule/diameter of pipe being tested.
3. The specimen reduced section shall be parallel within 0.010 in [0.254 mm]. Specimen width may be gradually tapered provided the ends are no more than 0.010 in [0.254 mm] wider than the center.
4. Weld reinforcement shall be removed so that weld thickness does not exceed the base metal thickness.
5. Specimen edges shall not be arc or flame cut.

Figure 3.10—Alternate Reduced Section Tension Specimen for Pipe (3 in [76 mm] Diameter or Less) or Tubing (see 3.10.1 and 3.10.1.2)

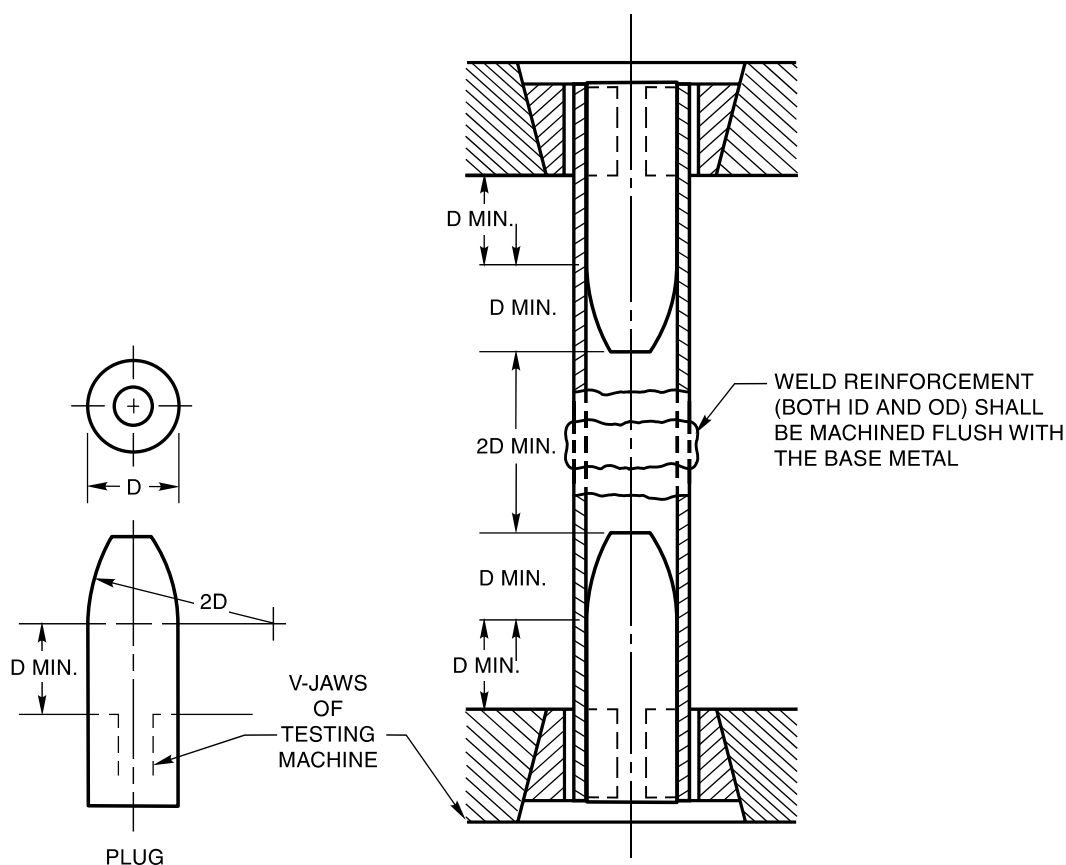
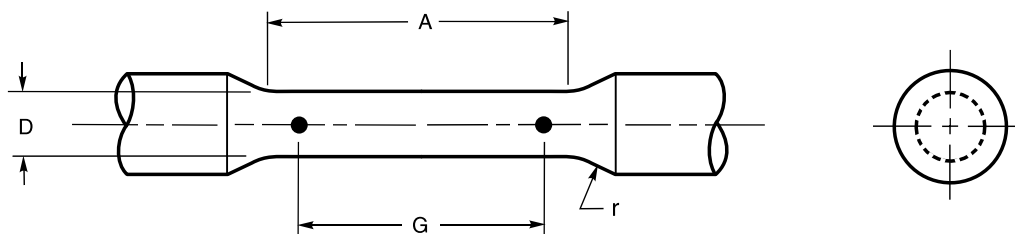


Figure 3.11—Full Section Tension Specimens—Small Diameter, 1 in [25 mm] Outside Diameter or Less, Pipe or Tubing (see 3.10.1 and 3.10.1.3)



Dimensions (in)			
	Standard Specimen	Small-Size Specimens Proportional to Standard	
Nominal Diameter	0.500 in Round	0.350 in Round	0.250 in Round
G—Gage length	2.000 ± 0.005	1.400 ± 0.005	1.000 ± 0.005
D—Diameter ^a	0.500 ± 0.010	0.350 ± 0.007	0.250 ± 0.005
r—Radius of fillet, min.	3/8	1/4	3/16
A—Length of reduced section, ^b min.	2-1/4	1-3/4	1-1/4

Dimensions [mm] per ASTM E 8M			
	Standard Specimen	Small-Size Specimens Proportional to Standard	
Nominal Diameter	12.5 mm Round	9 mm Round	6 mm Round
G—Gage length	62.5 ± 0.1	45.0 ± 0.1	30.0 ± 0.1
D—Diameter, ^a	12.5 ± 0.2	9.0 ± 0.1	6.0 ± 0.1
r—Radius of fillet, min.	10	8	6
A—Length of reduced section, ^b min.	75	54	36

^a The reduced section may have a general taper from the ends towards the center, with the ends not more than 1% larger in diameter than the center (controlling dimension).

^b If desired, the length of the reduced section may be increased to accommodate an extensometer of any convenient gage length. Reference marks for the measurement of elongation should be spaced at the indicated gage length.

Note: The gage length and fillets shall be as shown, but the ends may be of any form to fit the holders of the testing machine in such a way that the load shall be axial. If the ends are to be held in wedge grips, it is desirable, if possible, to make the length of the grip section great enough to allow the specimen to extend into the grips a distance equal to two-thirds or more of the length of the grips.

Figure 3.12—Reduced All-Weld Tensile Specimens (see 3.10.1 and 3.10.1.4)

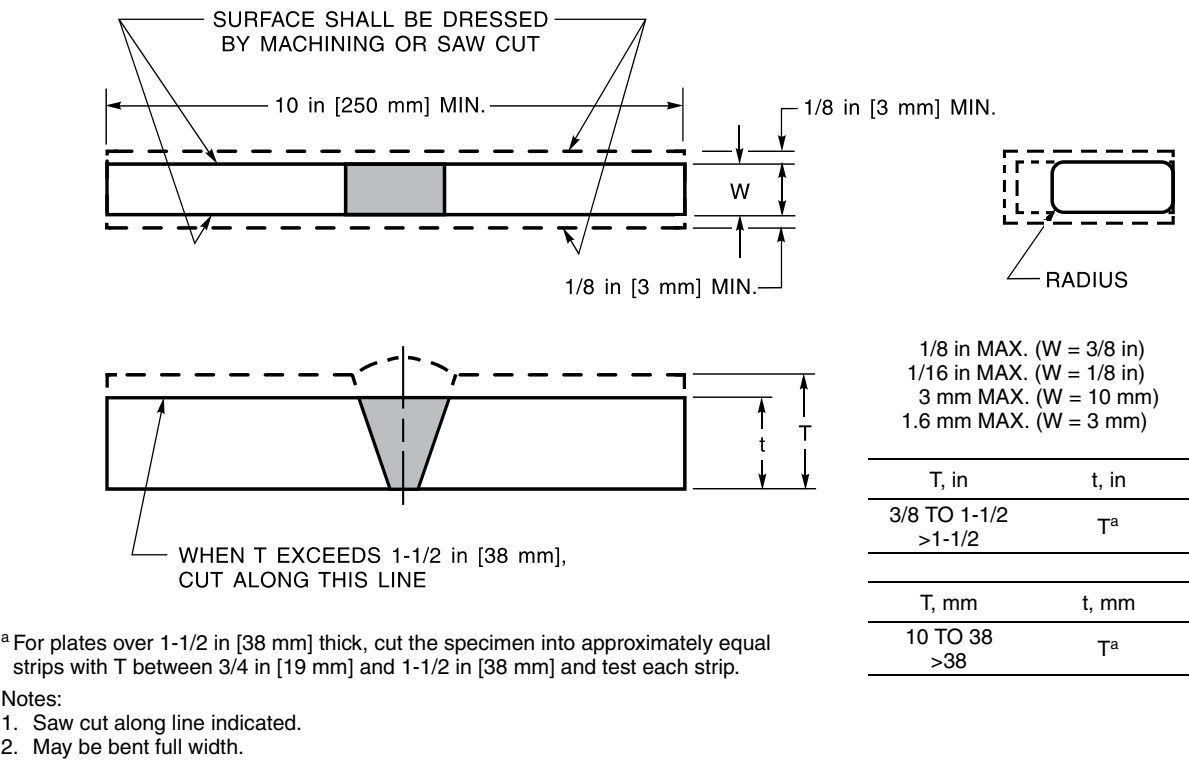
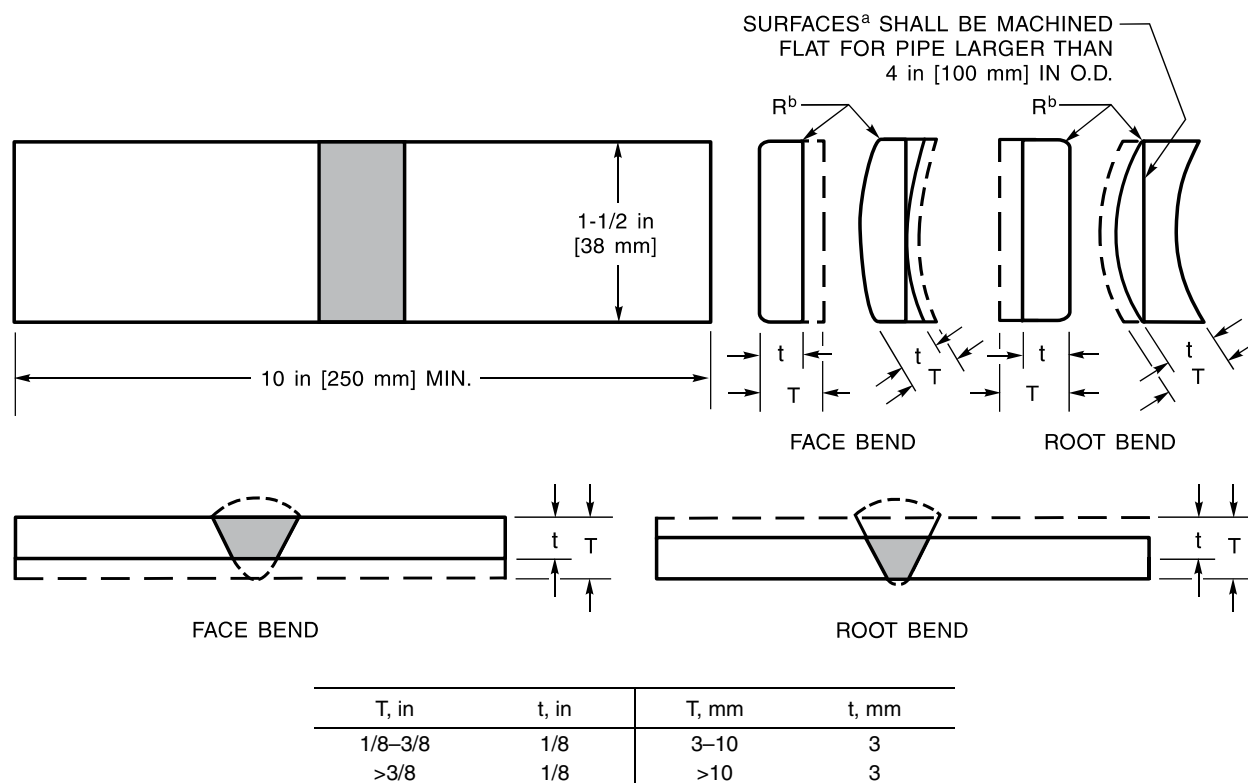


Figure 3.13—Transverse Side Bend Specimens (see 3.11.1 and 3.11.1.1)



^a Surfaces shall be machined flat for pipe larger than 4 in [100 mm] O.D. Curvature shall remain where pipe is 4 in [100 mm] or less O.D.

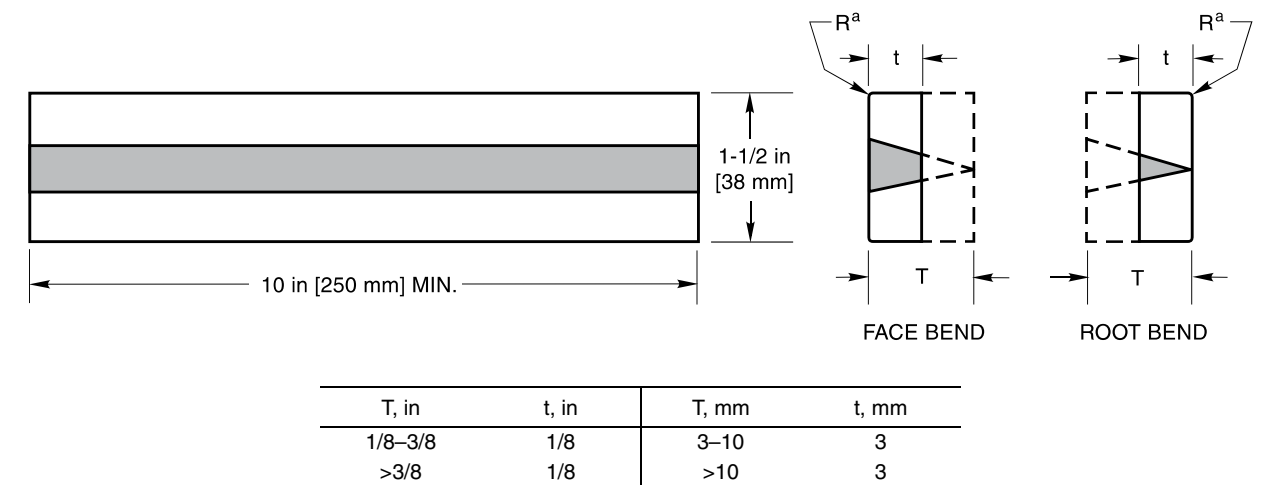
^b $R = 1/2 t$ max. for $<1/4$ in [6 mm].

$R = 1/8$ in [3 mm] max. for $t > 1/4$ in [6 mm].

Notes:

1. Weld reinforcement and backing strip or backing ring, if any, shall be removed flush with the surface of the specimen. If a recessed ring is used, this surface of the specimen may be machined to a depth not exceeding the depth of the recess to remove the ring, except that in such cases the thickness of the finished specimen shall be that specified above. Do not flame-cut titanium.
2. If the pipe being tested is 4 in [100 mm] outside diameter or less, the width of the bend specimen may be $3/4$ in [19 mm], measured around the outside surface. Alternatively, if the pipe being tested is less than 2 in [51 mm] pipe size (2.375 in [60.3 mm] outside diameter), the width of the bend specimens may be that obtained by cutting the pipe into quarter sections, less an allowance for saw cuts or machine cutting.

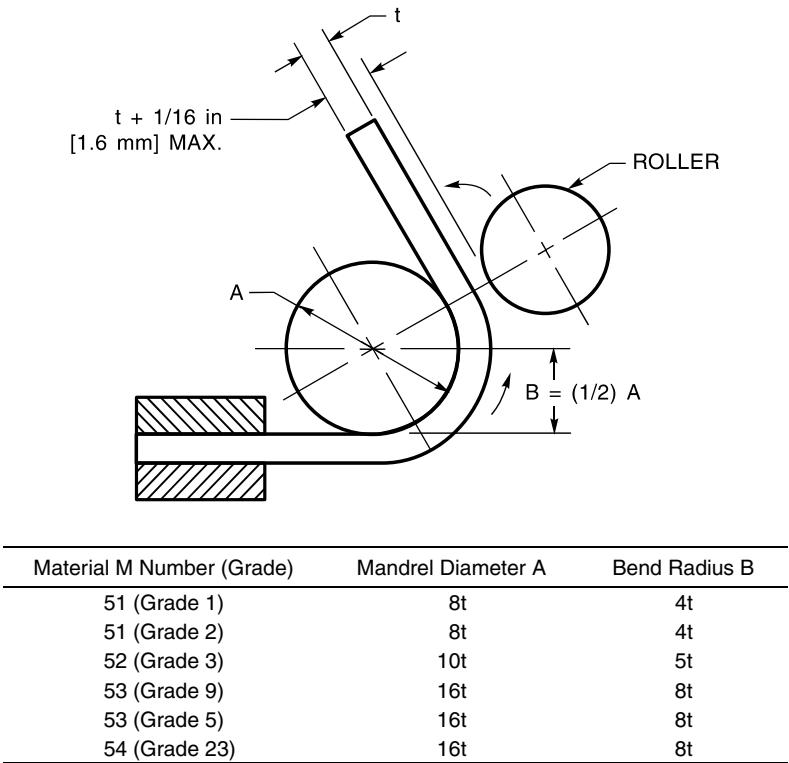
Figure 3.14—Transverse Face and Root Bend Specimens
(see 3.11.1, 3.11.1.2, 3.11.1.3, and 3.11.1.4)



^aR = 1/2 t max. for <1/4 in [6 mm].
 R = 1/8 in [3 mm] max. for t >1/4 in [6 mm].

Note: Weld reinforcements and backing strip or backing ring, if any, shall be removed essentially flush with the undisturbed surface of the base material. If a recessed strip is used, this surface of the specimen may be machined to a depth not exceeding the depth of the recess to remove the strip, except that in such cases the thickness of the finished specimen shall be that specified above.

Figure 3.15—Longitudinal Face and Root Bend Specimens (see 3.11.1, 3.11.1.5, and 3.11.1.6)



- Notes:
1. Dimensions not shown are the option of the designer. The essential consideration is to have adequate rigidity so that the fixture parts will not spring.
 2. The specimen shall be firmly clamped on one end so that there is no sliding of the specimen during the bending operation.
 3. Test specimens shall be removed from the fixture when the outer roll has been removed 180° from the starting point.
 4. The test fixture mandrel shall be at least 0.25 in [6 mm] wider than the specimen being tested.

Figure 3.16—Wraparound Guided Bend Jig (see 3.11.2.1)

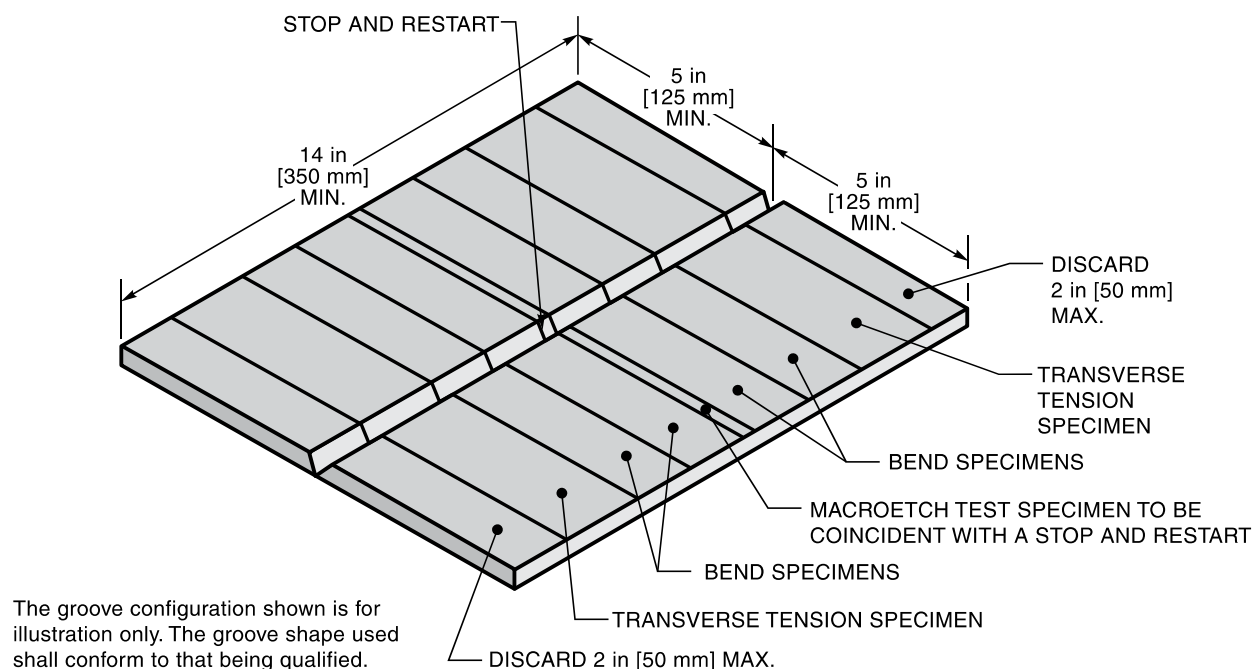
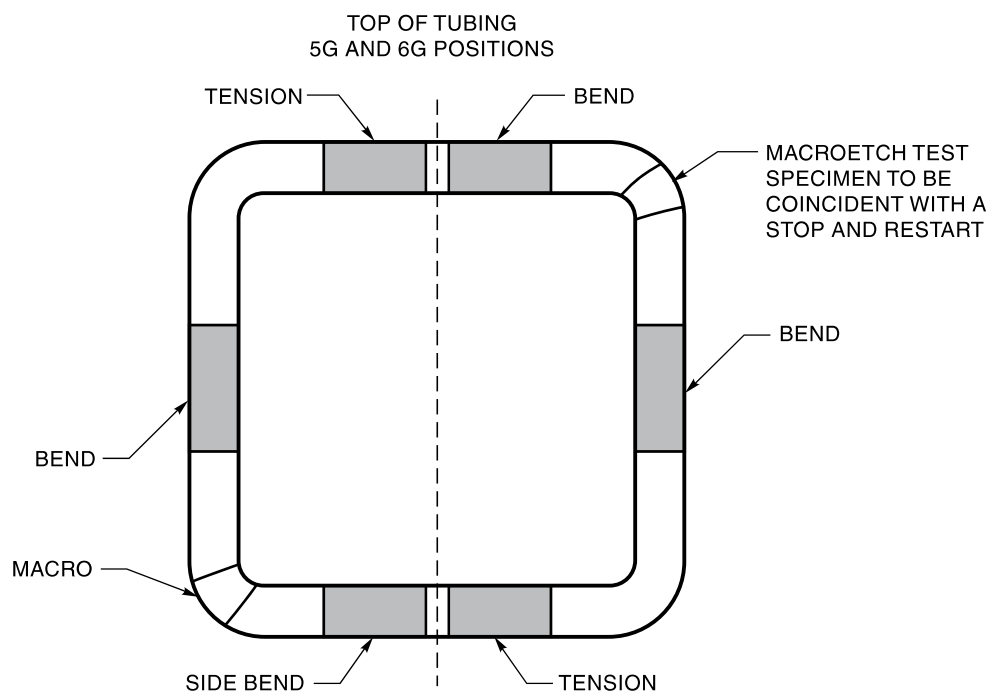
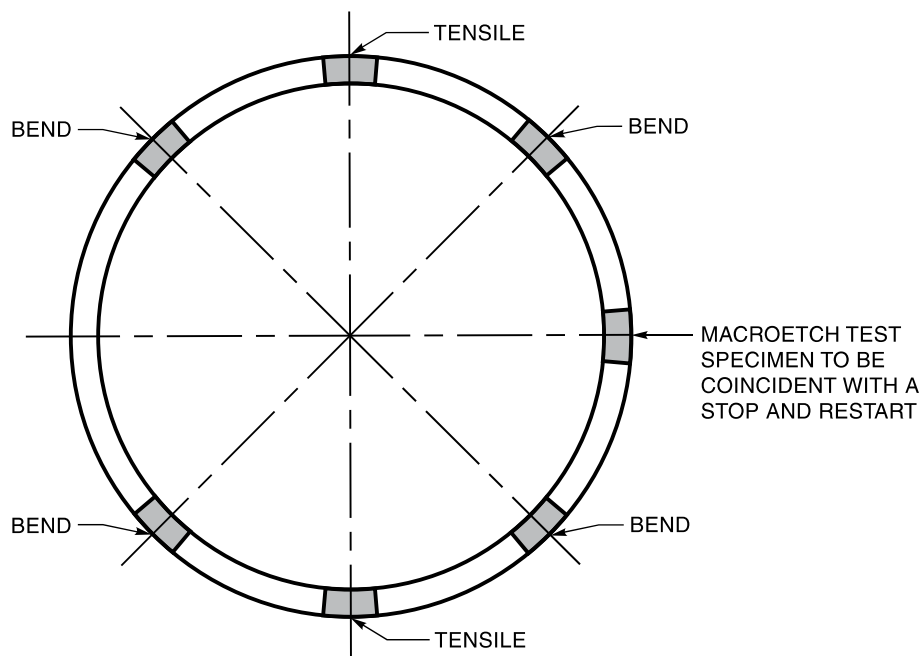


Figure 3.17—Plate—Relative Location of Test Specimens
(for WPS Qualification, see 3.16.2.1; for Performance Qualification, see 3.20.1.1)



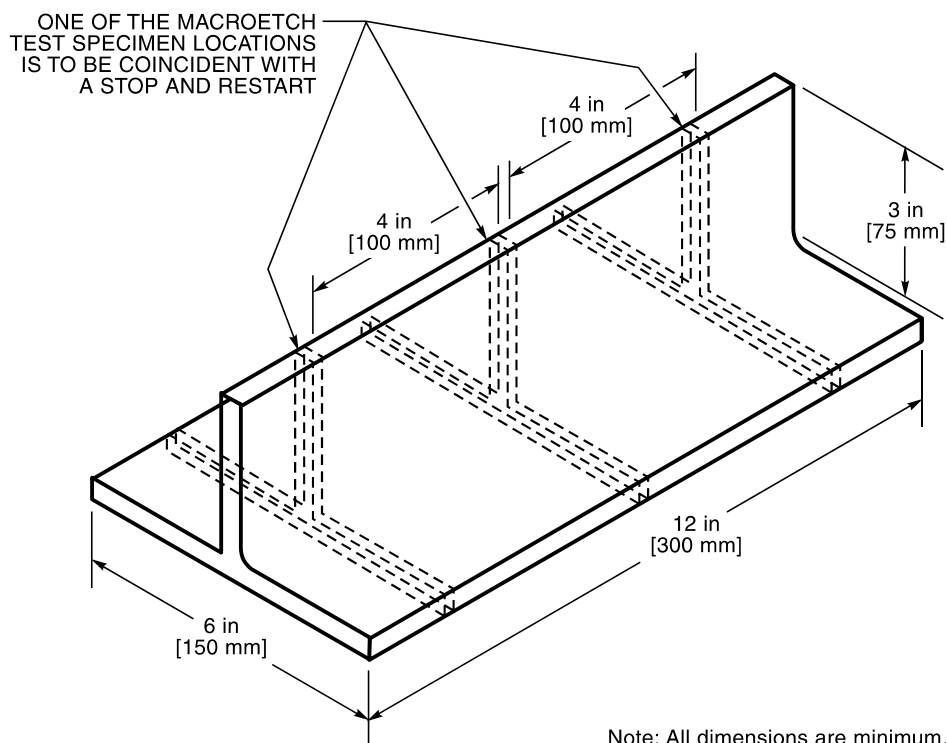
Note: Test weldment shall be 16 in [400 mm] minimum length.

Figure 3.18—Box Tubing—Relative Location of Test Specimens for WPS and Performance Qualifications (see 3.16.2.3 and 3.20.1.2, respectively)



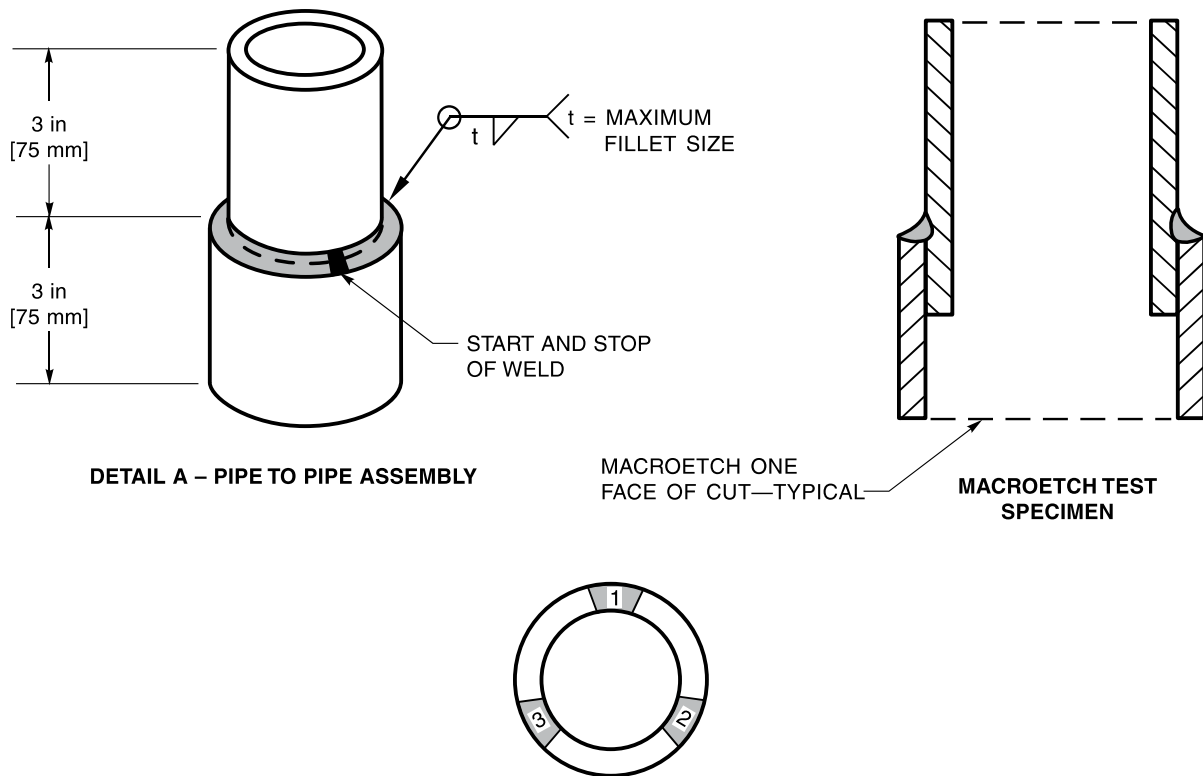
Note: Test weldment shall be 16 in [400 mm] minimum length.

Figure 3.19—Relative Location of Test Specimens
(for WPS and Performance Qualification, see 3.16.2.3 and 3.20.1.2, respectively)



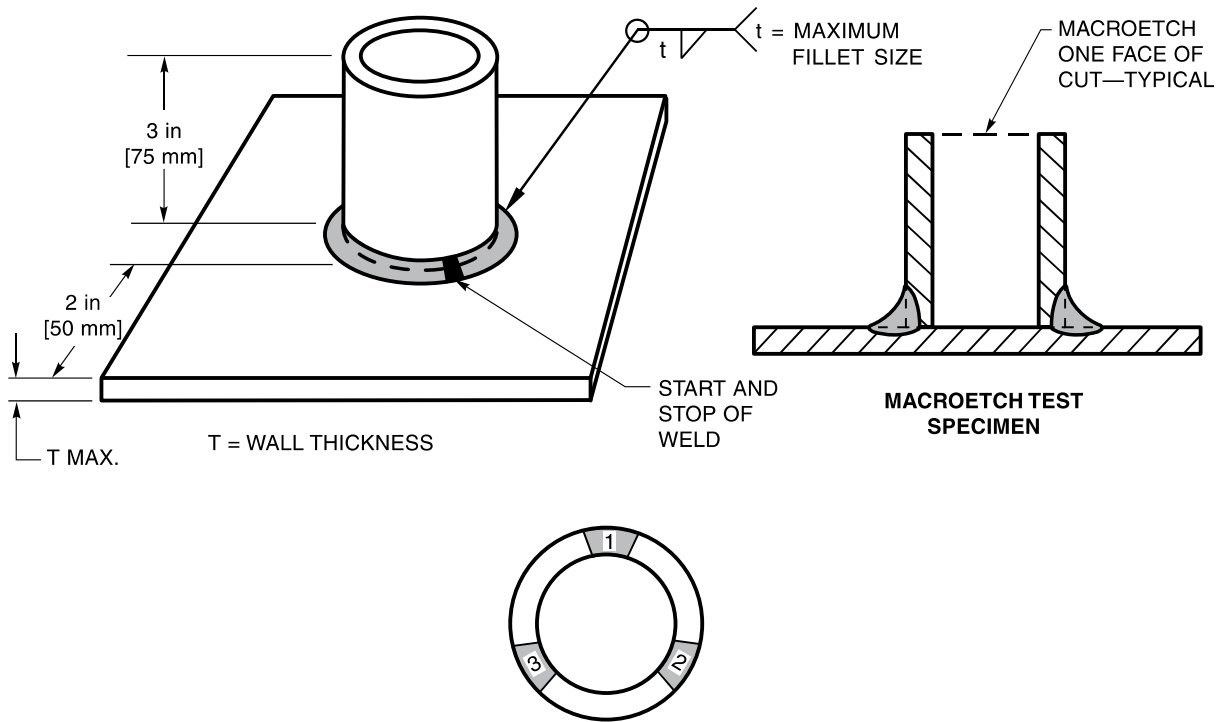
Note: All dimensions are minimum.

Figure 3.20—Fillet Weld—Relative Location of Test Specimens
(for WPS and Performance Qualification, see 3.16.2.4 and 3.20.2.1, respectively)



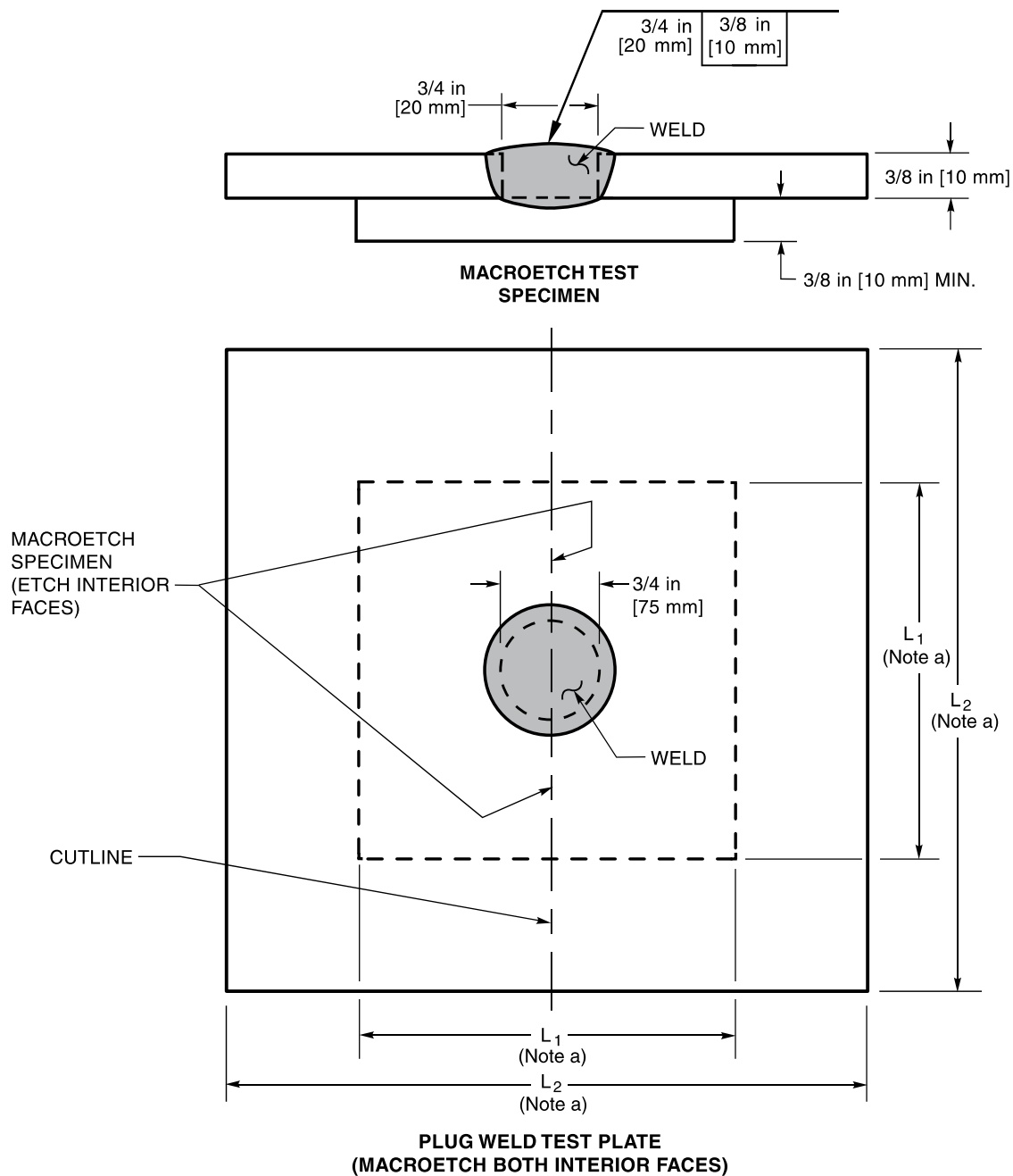
Note: Location of macro sections: One of the sections is to be coincident with the stop and restart.

**Figure 3.21—Fillet Weld Pipe—Relative Location of Test Specimens
(for WPS and Performance Qualification, see 3.16.2.4 and 3.20.2.2, respectively)**



Note: Location of macro sections: One of the sections is to be coincident with the stop and restart.

**Figure 3.22—Fillet Weld Plate to Pipe—Relative Location of Test Specimens
(for WPS and Performance Qualification, see 3.16.2.4 and 3.20.2.3, respectively)**



^a L₁ = 2 in [50 mm] min. (welder, welding operator, and tack welder).
 L₂ = 3 in [75 mm] min. (welder, welding operator, and tack welder).

Figure 3.23—Plug Weld Macroetch Test Plate—Welder, Welding Operator, and Tack Welder Qualification (see 3.16.2.5)

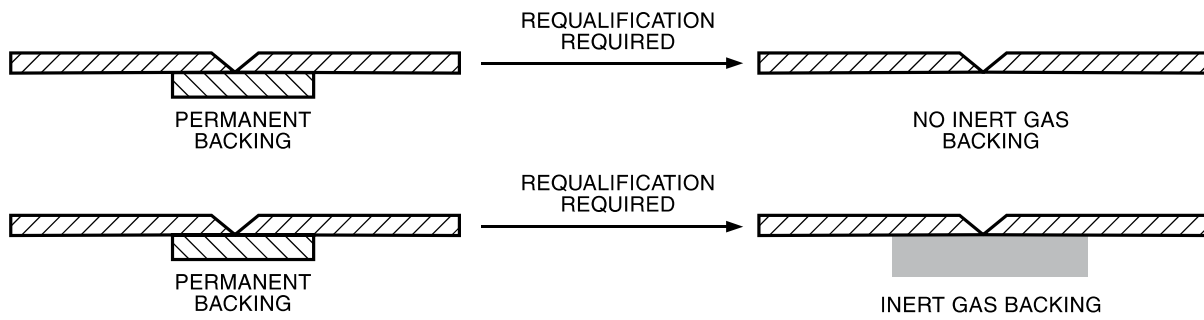


Figure 3.24—Requirements for Requalification Based on the Replacement of Permanent Backing with an Inert Gas Backing and Vice Versa for CJP Welds (see 3.21.7)

4. Fabrication

4.1 Scope

This clause contains the requirements for the preparation, assembly, and workmanship of welded titanium structures.

4.2 Processes

This code provides requirements for these processes:

- (1) GMAW—gas metal arc welding
- (2) GTAW—gas tungsten arc welding
- (3) PAW—plasma arc welding
- (4) EBW—electron beam welding
- (5) LBW—laser beam welding

4.3 Base Metals

4.3.1 Specifications. Base metal shall conform to a specification listed in Table 4.1.

4.3.2 Group Designations. Base metals are grouped to reduce the number of WPSs as allowed by Table 3.4.

4.3.3 Unlisted Material. When an alloy is not listed in Table 4.1, then it shall be qualified in accordance with the requirements of Clause 3.

4.4 Filler Metal

4.4.1 Selection. Filler metal shall conform to AWS A5.16/A5.16M, *Specification for Titanium and Titanium-Alloy Welding Electrodes and Rods*, or AMS 4954, *Titanium Alloy, Welding Wire, 6Al-4V*, or AMS 4956, *Titanium Alloy Welding Wire, 6Al-4V, Extra Low Interstitial Environment Controlled Packaging*. Table 4.2 lists filler alloys recommended for various base metal alloys.

Before making welds between two different alloys, subsection 2.3 should be consulted before selecting a filler metal.

4.4.2 Certification. The filler metal shall meet the requirements of AWS A5.16/A5.16M.

4.4.3 Storage. Filler metals shall be stored in unopened containers, in a dry place, adequately protected from the weather until needed at the fabrication site. Recommendations of the manufacturer concerning special protection during storage and use shall be followed.

4.5 Tungsten Electrodes

Tungsten electrodes shall conform to AWS A5.12/A5.12M, *Specification for Tungsten and Tungsten Alloy Electrodes for Arc Welding and Cutting*.

4.6 Shielding Gases

A gas or gas mixture used for shielding shall be purchased in accordance with AWS A5.32/A5.32M. When requested by the Engineer, the Contractor shall furnish the gas manufacturer's certification that the gas or gas mixture meets the dew point requirements. When mixed at the welding site, suitable meters shall be used for proportioning the gases. Percentage of gases shall conform to the requirements of the qualified WPS.

4.7 Welding and Cutting Equipment

Welding and cutting equipment shall be designed, manufactured, and maintained so that qualified welders, welding operators, tack welders, and other qualified personnel are able to follow the procedures and attain the results required in this code.

4.8 Backing

4.8.1 Position. Backing shall be in intimate contact with the root side of the parts being welded.

4.8.2 Removal. When backing is to be removed, then it shall be removed by machining, sawing or grinding.

4.8.3 Permanent Backing. Permanent backing shall be a bare titanium alloy of the same M-number as the parts joined unless specifically allowed by the Engineer and qualified in accordance with the requirements of Clause 3. The backing may be attached with intermittent fillet welds unless corrosion is a consideration, in which case it shall be attached with continuous fillet welds along both edges.

4.8.4 Temporary Backing. Temporary backing shall protect the weld pool and parent material from direct oxidation. If an inert gas purge is used, it shall conform to the requirements of 4.6.

4.9 Preheat and Interpass Temperatures

Welding shall not be performed when the temperature of the weld joint is below 60°F [16°C] or ambient air temperature, whichever is greater, unless otherwise qualified in accordance with Clause 3. The maximum interpass temperature shall be as stated on the qualified WPS. The minimum interpass temperature shall not be less than the minimum preheat temperature.

4.10 Welding Environment

Welding shall not be performed in an environment detrimental to the welding of titanium alloys. Examples of these detrimental environments are windy conditions, when structure surfaces are wet or exposed to precipitation, or when welders, welding operators, or tack welders are exposed to such conditions. Temporary structures may be used to eliminate detrimental environments.

4.11 Compliance with Design

The dimensions and locations of welds shall be those shown on the engineering design drawings.

4.12 Preparation of Base Metal

4.12.1 Edge Condition. All surfaces to be welded shall be free from detrimental oxides, nitrides, carbides, abrasive particles, paint, grease, lubricants, and moisture.

Surfaces and edges to be welded shall be smooth, uniform, and free from fins, tears, and cracks that may entrap moisture, dirt, or other deleterious substances.

4.12.2 Grinding. When grinding, care shall be taken to select non-loading type abrasives specifically intended for use on titanium, and the abrasives shall be maintained free of lubricants and other foreign material.

4.12.3 Re-entrant Corners. Unless otherwise specified on the drawing or by the Engineer, re-entrant corners cut in base metal shall have a fillet radius of no less than 3/4 in [19 mm]. The fillet and its adjacent cuts shall meet without offset or cutting past the point of tangency.

4.12.4 Beam Copes and Weld Access Holes. Radii of beam copes and weld access holes shall provide a smooth transition free of notches, past the points of tangency between adjacent surfaces. The size of all weld access holes required to facilitate welding operations shall be adequate for deposition of sound weld metal. In built-up shapes, all beam copes and weld access holes shall be shaped free of notches or sharp reentrant corners except that when fillet web-to-flange welds are used in built-up shapes, access holes may terminate perpendicular to the flange. Fillet welds shall not be returned through weld access holes unless approved by the Engineer.

4.12.5 Weld Removal. Machining, sawing, grinding, and plasma arc gouging may be used to remove temporary welds or unacceptable work or metal. Other processes may be used if approved by the Engineer. This also applies to double welded joints that may require the removal (from the second side) of base metal or root weld metal in order to form the required second side weld preparation. The excavated area shall comply with 4.12.1 and 4.12.2.

4.13 Assembly

4.13.1 Abutting parts to be joined by groove welds shall be properly aligned. A mismatch not exceeding 10% of the thickness of the thinner part, but in no case more than 1/8 in [3 mm], may be allowed as a departure from the theoretical alignment.

4.13.2 Complete Joint Penetration Groove Welds

4.13.2.1 The following types of welds are considered to be complete joint penetration groove welds:

(1) All groove joints welded from both sides with the root of the first weld “back-cut” to sound metal before welding the second side

(2) All groove joints welded from one side using an integral or removable backing

- (3) All groove joints welded with inert gas backing

4.13.3 Partial Joint Penetration Groove Welds

4.13.3.1 For single sided partial penetration joints where materials at the root of the joint are not in intimate contact, or the thickness of either material is less than 1/2 in [12 mm], an inert gas backing shield shall be used unless qualified in accordance with the requirements of Clause 3.

4.13.4 Groove Tolerances

4.13.4.1 Groove joints which vary from those shown on the engineering drawings and WPSs by more than the following tolerances shall require the Engineer's approval, correction, or rejection:

- (1) Root face $\pm 1/32$ in [0.8 mm]
- (2) Root opening $\pm 1/32$ in [0.8 mm] with temporary backing
- (3) Root opening + 1/16 in [1.5 mm] with integral backing or permanent titanium backing
- (4) Groove angle of $+10^\circ$, -2.5°
- (5) Root opening for square butt joints that are plasma arc welded shall not be more than 2% of the thinner member to be welded up to 1/2 in [12 mm], not more than 3% of the thinner member to be welded for greater than 1/2 in [12 mm], with a maximum of not more than 0.030 in [0.6 mm].

4.13.5 Fillet and Lap Welds

4.13.5.1 Parts to be joined by fillet welds shall be brought into contact and an inert gas shield applied to the back face of the joint.

4.13.5.2 The separation between faying surfaces of lap joints and of butt joints lying on a backing shall be subject to the same requirements for inert gas shielding as fillet welds.

4.13.6 Fixtures and Alignment

4.13.6.1 Members to be welded shall be brought into correct alignment and held in position by the use of fixtures, strong-backs, bolts, clamps, wedges, guy lines, struts, or other suitable devices until the welding has been completed. The use of fixtures is recommended when practicable. The fixtures shall have sufficient stiffness and strength to counteract the forces resulting from the temperature changes in the weldment. Similarly, tack welds shall have sufficient effective throat or weld size and length to develop the necessary strength.

4.14 Tack Welds and Temporary Welds

Tack and temporary welds shall be made by any welding process in accordance with a qualified WPS by a qualified welder. Tack welds shall be subject to the same quality requirements, once incorporated into the final weld, as the final welds. All welds shall be made automatically or with filler metal of the same composition as detailed in the WPS. Temporary welds shall be removed by mechanical means, and the excavated area shall comply with the requirements of 4.12.1 and 4.12.2.

4.14.1 Unacceptable craters existing in tack welds that are to be incorporated into permanent welds shall be removed by mechanical means and filled using a qualified WPS.

4.14.2 Temporary welds shall be subject to the same WPS and quality requirements as final welds. Their possible effects on the material properties shall be considered in the design process.

4.15 Dimensional Tolerances

The following dimensional tolerances shall govern the work:

4.15.1 Straightness of Columns. Permissible variations from straightness of welded columns and primary truss members, regardless of cross section, shall not exceed:

Column lengths of 45 ft [14 m] and under:

$$1/8 \text{ in} \times \frac{\text{Total length, in feet}}{10}$$

$$3 \text{ mm} \times \frac{\text{Total length, in meters}}{3}$$

but not over 3/8 in [10 mm]

Column lengths over 45 ft [14 m]:

$$3/8 \text{ in} + 1/8 \text{ in} \times \frac{\text{Total length, in feet,} - 45}{10}$$

$$10 \text{ mm} + 3 \text{ mm} \times \frac{\text{Total length, in meters,} - 14}{3}$$

4.15.2 Straightness of Beams and Girders. Variations in straightness at any point along either flange of welded beams or girders regardless of cross section, where there is no specified sweep, shall not exceed:

$$1/8 \text{ in} \times \frac{\text{Total length, in feet}}{10}$$

$$3 \text{ mm} \times \frac{\text{Total length, in meters}}{3}$$

4.15.3 Camber of Beams and Girders. Departures from the specified camber at any point along welded beams or girders (as fabricated members before placement in the structure), regardless of cross section, shall not exceed -0 , $+1/4$ in [6 mm] or:

$$-0, +1/4 \text{ in} \times \frac{\text{Total length, in feet}}{10}$$

$$-0, +6 \text{ mm} \times \frac{\text{Total length, in meters}}{3}$$

but not to exceed $3/4$ in [19 mm] or:

$$-0, +1/8 \text{ in} \times \frac{\text{Distance to nearest end, in feet}}{10}$$

$$-0, +3 \text{ mm} \times \frac{\text{Distance to nearest end, in meters}}{3}$$

4.15.4 Deviation Between Web and Flange. Lateral deviation between the centerline of the web and the centerline of the flange of built-up H or I members at the contact surface shall not exceed $1/4$ in [6 mm].

4.15.5 Warpage of Flanges. The combined warpage and tilt of a flange of welded beams and girders shall be determined by measuring the offset at the toe of the flange from a line normal to the plane of the web through the intersection of the centerline of the web with the outside surface of the flange plate as indicated in Figure 4.2. This offset shall not exceed 1% of the total flange width or $1/4$ in [6 mm], whichever is greater, except that abutting parts to be joined by groove welds shall fulfill the requirements of 4.13.1.

4.15.6 Depth Variation. Variation from the specified depth of members from outer flange surface to outer flange surface as shown in Figure 4.3, measured at the web centerline, shall not exceed:

For depths up to 36 in [0.9 m], inclusive	$\pm 1/8$ in [3 mm]
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For depths over 36 to 72 in [0.9 to 1.8 m], inclusive	$\pm 3/16$ in [5 mm]
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For depths over 72 in [1.8 m]	$\pm 5/16$ in [8 mm]
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4.15.7 Web Flatness. Variation from flatness of webs is determined by measuring the distance between the web and a straight edge whose length is not less than the least clear dimension, d , of a web panel as indicated in Figure 4.4. The unit of measure of deviation from flatness is the length unit, in or mm. Variations from flatness of webs with least panel dimension d shall not exceed $d/100$.

4.15.7.1 In girders which have been punched and reamed for a bolted-field splice or connection, deviations of two times those allowed in 4.15.7, shall be acceptable, provided that, when the bolted splice or connection is completed, the final assembly is in accordance with 4.15.7.

4.15.8 Weld Joint Fit-Up Tolerances

4.15.8.1 The ends of branch members which are to be welded with complete joint penetration welds shall be shaped by a mechanical operation to fit snugly with the main member. The edge shall be trimmed to produce a satisfactory welding edge as dictated by an approved WPS.

4.15.8.2 Where the parts to be joined by fillet welds cannot be brought into intimate contact, then the leg of the fillet weld shall be increased by the amount of the separation. Appropriate gas backing is required as defined in 4.13.5.

4.15.8.3 The separation between faying surfaces of lap joints or butt joints, or both, lying on a backing shall not exceed $1/16$ in [1.5 mm]. Where irregularities in rolled or extruded shapes, after straightening, prevent contact within the above limit, the procedure to be used to bring the separation within the limiting value shall be approved by the Engineer. The use of filler plates is prohibited, unless specified on the drawing or approved by the Engineer and made in accordance with 2.7.

4.15.8.4 Abutting parts to be joined by girth welds shall be carefully aligned. Girth welds shall not be closer together than the smaller of the pipe diameter or 3 ft [0.9 m]. There shall be no more than two girth welds in any 10 ft [3 m] interval of pipe, except as may be approved by the Engineer. Radial offset of abutting edges at a girth weld shall not exceed 30% of the wall thickness or $1/4$ in [6 mm], whichever is smaller. If the offset exceeds $1/8$ in [3 mm], the joint shall be welded from both sides. For joints that cannot be welded from both sides, the radial offset shall not exceed $1/8$ in [3 mm] or 30% of the wall thickness, whichever is less.

4.15.8.5 Longitudinal weld seams of adjoining sections of pipe shall be staggered a minimum of 90° .

4.15.8.6 Variations in welding partial joint penetration groove details from those shown on the detail drawings shall be in accordance with those shown in 4.13.4. In addition, variations from the joint detail for welds made from one side only without backing shall not exceed the following:

Root face	$\pm 1/32$ in [0.8 mm]
Root opening	$\pm 1/16$ in [1.5 mm]
Groove angle	$+10^\circ, -2-1/2^\circ$

4.15.8.7 Dimensional tolerances for complete joint penetration groove welds shall be as stated on the WPS.

4.16 Arc Strikes

Arc strikes outside the area of permanent welds should be avoided on any base metal. Cracks or blemishes caused by arc strikes shall be ground to a smooth contour and checked to ensure soundness.

4.17 Cleaning After Completion of Welds

4.17.1 Welds and 1/2 in [12 mm] of adjacent base material past the toe of the weld shall not be wire-brushed or otherwise cleaned, nor painted or otherwise covered before the weld is examined and approved.

4.18 Weld Termination

4.18.1 Extension bars, starting weld tabs, and run-off weld tabs shall be removed by mechanical cutting upon completion and cooling of the weld. The ends of the weld shall be made smooth and fit flush with the edges of the adjacent parts.

4.18.2 Weld terminations shall be prepared and finish welded to assure a smooth transition into the member.

4.18.3 Craters existing in weld terminations that will form part of a final weld shall be removed by grinding or rotary cutting methods prior to additional welding to correct the crater. Weld craters shall be filled to the full cross section of the weld or repaired in accordance with 4.21.

4.18.4 Weld terminations around the circumference of pipe and tube shall overlap the weld start by 5° or 1/2 in [12 mm], whichever is less.

4.19 Control of Distortion and Shrinkage

4.19.1 Sequence. On members or structures where excessive shrinkage or distortion could be expected, the Contractor shall prepare a written welding sequence for that member or structure which meets the quality requirements specified.

4.19.2 Direction of Welding. The direction of the general progression in welding on a member should usually be from points where the parts are relatively fixed in

position with respect to each other toward points where they have a greater relative freedom of movement.

4.19.3 Crack Prevention. In making welds under conditions of severe shrinkage restraint, the welding shall be completed to a point that will ensure freedom from cracking, before the joint is allowed to cool to a point below the preheat requirements of the WPS.

4.19.4 Corrections. In the case of members distorted beyond acceptable limits by welding, a correction procedure shall be formulated and submitted for approval by the Engineer.

4.20 Weld Profiles

4.20.1 Fillet Welds and Complete Joint Penetration Groove Weld in T-Joint. The faces of the welds shall be slightly convex, flat, or slightly concave as shown in Figure 4.1(A) and Figure 4.1(B), with none of the unacceptable profiles shown in Figure 4.1(C) (reference Clause 5 visual inspection requirements).

4.20.2 Groove Welds. Groove welds shall be made with minimum reinforcement unless otherwise specified. In the case of butt and corner joints, the weld face reinforcement and root melt-through height shall not exceed the values given in Figure 4.1(D) and Figure 4.1(E) unless otherwise specified in the contract documents and shall have a gradual transition to the plane of the base metal surface. The weld shall be free of discontinuities of the types shown for butt joints in Figure 4.1(F).

4.20.3 Flush Surfaces. Butt welds required to be flush shall be finished so as to not reduce the thicknesses of the thinner base metal or weld metal by more than 1/32 in [0.8 mm], or 5% of the material thickness, whichever is less. Remaining reinforcement shall not exceed 1/32 in [0.8 mm] in height. However, all reinforcement shall be removed where the weld forms part of a faying or contact surface. All reinforcement shall blend smoothly into the plate surfaces with transition areas free from undercut.

4.21 Repairs

4.21.1 Approval. Weld repair shall be performed in accordance with a defined and Engineer approved process.

4.21.2 Base Material. Approval of the Engineer shall be obtained prior to performing weld repair of base material.

4.21.3 Weld Material Repair. Weld repair shall be performed in accordance with an approved welding procedure. Repair of welds may be undertaken at the discretion

of the Contractor and two cycles of weld repair per defective area may be performed by the Contractor prior to approval of the Engineer.

4.21.4 Inspection. The repaired or replaced weld shall be inspected using the same technique and quality acceptance criteria applied to the original weld.

4.22 Anti-Spatter Compound

The use of anti-spatter compound is prohibited except when suitability can be demonstrated by successful WPS

testing qualified in accordance with the requirements of Clause 3.

4.23 Peening

Weld peening shall not be used unless approved by the Engineer.

4.24 Stress-Relief Treatment

The stress relief treatment procedure shall be approved by the Engineer prior to beginning the work.

Table 4.1
Strengths of Welded Titanium Alloys (see 3.10.3.1, 3.10.3.2, and 3.10.4.1)
and Products Available for Structure Applications (see 4.3.1 and 4.3.3)

Material Number (M)	Standard	Base Metal Specification	UNS Number	Thickness or O.D. in [mm]	Minimum As-Welded Tensile/Yield ksi [MPa]	Type of Base Metal
M51	ASTM	B 265	R50250	0.005–10.0 [0.12–250] incl.	35/25 [240/170]	Grade 1 strip, sheet, and plate
M51	ASTM	B 337	R50250	1/8–12.0 [3–300] incl.	35/25 [240/170]	Grade 1 seamless and welded pipe
M51	ASTM	B 338	R50250	≤3.5 [≤90] O.D.	35/25 [240/170]	Grade 1 seamless and welded tube
M51	ASTM	B 348	R50250	1/4–4.5 [6–115] incl.	35/25 [240/170]	Grade 1 hot rolled rounds and squares
M51	ASTM	B 348	R50250	1/4–3.5 [6–90] incl.	35/25 [240/170]	Grade 1 hot rolled hexagons and octagons
M51	ASTM	B 348	R50250	≤10.0 [≤250]	35/25 [240/170]	Grade 1 hot rolled flats
M51	ASTM	B 348	R50250	1/2–4.0 [12–100] incl.	35/25 [240/170]	Grade 1 cold finished rounds
M51	ASTM	B 348	R50250	>1/2 [>12]	35/25 [240/170]	Grade 1 cold finished hexagons, octagons and squares
M51	ASTM	B 348	R50250	3/8–4.5 [10–115] incl.	35/25 [240/170]	Grade 1 cold finished flats
M51	ASTM	B 265	R50400	0.005–10.0 [0.12–250] incl.	50/40 [345/275]	Grade 2 strip, sheet, and plate
M51	ASTM	B 337	R50400	1/8–12.0 [3–300] incl.	50/40 [345/275]	Grade 2 seamless and welded pipe
M51	ASTM	B 338	R50400	≤3.5 [≤90] O.D.	50/40 [345/275]	Grade 2 seamless and welded tube
M51	ASTM	B 348	R50400	1/4–4.5 [6–115] incl.	50/40 [345/275]	Grade 2 hot rolled rounds and squares
M51	ASTM	B 348	R50400	1/4–3.5 [6–90] incl.	50/40 [345/275]	Grade 2 hot rolled hexagons and octagons
M51	ASTM	B 348	R50400	≤10.0 [≤250]	50/40 [345/275]	Grade 2 hot rolled flats
M51	ASTM	B 348	R50400	1/2–4.0 [12–100] incl.	50/40 [345/275]	Grade 2 cold finished rounds
M51	ASTM	B 348	R50400	>1/2 [>12]	50/40 [345/275]	Grade 2 cold finished hexagons, octagons, and squares
M51	ASTM	B 348	R50400	3/8–4.5 [10–115] incl.	50/40 [345/275]	Grade 2 cold finished flats
M52	ASTM	B 265	R50550	0.005–10.0 [0.12–250] incl.	65/55 [450/380]	Grade 3 strip, sheet, and plate

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Table 4.1 (Continued)
Strengths of Welded Titanium Alloys (see 3.10.3.1, 3.10.3.2, and 3.10.4.1)
and Products Available for Structure Applications (see 4.3.1 and 4.3.3)

Material Number (M)	Standard	Base Metal Specification	UNS Number	Thickness or O.D. in [mm]	Minimum As-Welded Tensile/Yield ksi [MPa]	Type of Base Metal
M52	ASTM	B 337	R50550	1/8–12.0 [3–300] incl.	65/55 [450/380]	Grade 3 seamless and welded pipe
M52	ASTM	B 338	R50550	≤3.5 [≤90] O.D.	65/55 [450/380]	Grade 3 seamless and welded tube
M52	ASTM	B 348	R50550	1/4–4.5 [6–115] incl.	65/55 [450/380]	Grade 3 hot rolled rounds and squares
M52	ASTM	B 348	R50550	1/4–3.5 [6–90] incl.	65/55 [450/380]	Grade 3 hot rolled hexagons and octagons
M52	ASTM	B 348	R50550	≤10.0 [≤250]	65/55 [450/380]	Grade 3 hot rolled flats
M52	ASTM	B 348	R50550	1/2–4.0 [12–100] incl.	65/55 [450/380]	Grade 3 cold finished rounds
M52	ASTM	B 348	R50550	>1/2 [>12]	65/55 [450/380]	Grade 3 cold finished hexagons, octagons, and squares
M52	ASTM	B 348	R50550	3/8–4.5 [10–115] incl.	65/55 [450/380]	Grade 3 cold finished flats
M53	ASTM	B 265	R56320	0.005–10.0 [0.12–250] incl.	90/70 [620/480]	Grade 9 sheet, strip, and plate
M53	ASTM	B 337	R56320	1/8–12.0 [3–300] incl.	90/70 [620/480]	Grade 9 seamless and welded pipe
M53	ASTM	B 348	R56320	1/4–4.5 [6–115] incl.	90/70 [620/480]	Grade 9 hot rolled rounds and squares
M53	ASTM	B 348	R56320	1/4–3.5 [6–90] incl.	90/70 [620/480]	Grade 9 hot rolled hexagons and octagons
M53	ASTM	B 348	R56320	≤10.0 [≤250]	90/70 [620/480]	Grade 9 hot rolled flats
M53	ASTM	B 348	R56320	1/2–4.0 [12–100] incl.	90/70 [620/480]	Grade 9 cold finished rounds
M53	ASTM	B 348	R56320	>1/2 [>12]	90/70 [620/480]	Grade 9 cold finished hexagons, octagons, and squares
M53	ASTM	B 348	R56320	3/8–4.5 [10–115] incl.	90/70 [620/480]	Grade 9 cold finished flats
M54	ASTM	B 862	—	—	130/120 [895/825]	Grade 5 welded pipe
M54	ASTM	B 265	R56400	0.01–10.0 [0.25–250] incl.	130/120 [895/825]	Grade 5 sheet, strip, and plate
M54	ASTM	B 348	R56400	1/4–4.5 [6–115] incl.	130/120 [895/825]	Grade 5 hot rolled rounds and squares

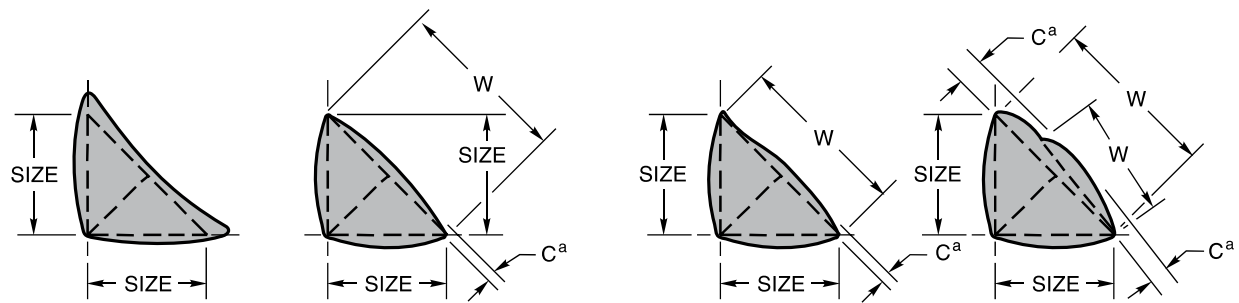
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Table 4.1 (Continued)
Strengths of Welded Titanium Alloys (see 3.10.3.1, 3.10.3.2, and 3.10.4.1)
and Products Available for Structure Applications (see 4.3.1 and 4.3.3)

Material Number (M)	Standard	Base Metal Specification	UNS Number	Thickness or O.D. in [mm]	Minimum As-Welded Tensile/Yield ksi [MPa]	Type of Base Metal
M54	ASTM	B 348	R56400	1/4–3.5 [6–90] incl.	130/120 [895/825]	Grade 5 hot rolled hexagons and octagons
M54	ASTM	B 348	R56400	≤10.0 [≤250]	130/120 [895/825]	Grade 5 hot rolled flats
M54	ASTM	B 348	R56400	1/2–4.0 [12–100]	130/120 [895/825]	Grade 5 cold finished rounds
M54	ASTM	B 348	R56400	>1/2 [≥12]	130/120 [895/825]	Grade 5 cold finished hexagons, octagons, and squares
M54	ASTM	B 348	R56400	3/8–4.5 [10–115]	130/120 [895/825]	Grade 5 cold finished flats
M54	ASTM	B 381	R56400	All	130/120 [895/825]	F-5 forgings
M54	ASTM	B 367	—	—	—	Castings
M54	ASTM	B 862	—	—	130/120 [895/825]	Grade 23 welded pipe
M54	ASTM	B 348	R56402	1/4–4.5 [6–115]	120/110 [895/825]	Grade 23 hot rolled rounds and squares
M54	ASTM	B 348	R56402	1/4–3.5 [6–90]	120/110 [895/825]	Grade 23 hot rolled hexagons and octagons
M54	ASTM	B 348	R56402	≤10.0 [≤250]	120/110 [895/825]	Grade 23 hot rolled flats
M54	ASTM	B 348	R56402	1/2–4.0 [12–100]	120/110 [895/825]	Grade 23 cold finished rounds
M54	ASTM	B 348	R56402	>1/2 [≥12]	120/110 [895/825]	Grade 23 cold finished hexagons, octagons, and squares
M54	ASTM	B 348	R56402	3/8–4.5 [10–115]	120/110 [895/825]	Grade 23 cold finished flats
M54	ASTM	B 381	R56402	All	120/110 [895/825]	F-23 forgings
M54	ASTM	B 367	—	—	—	Castings

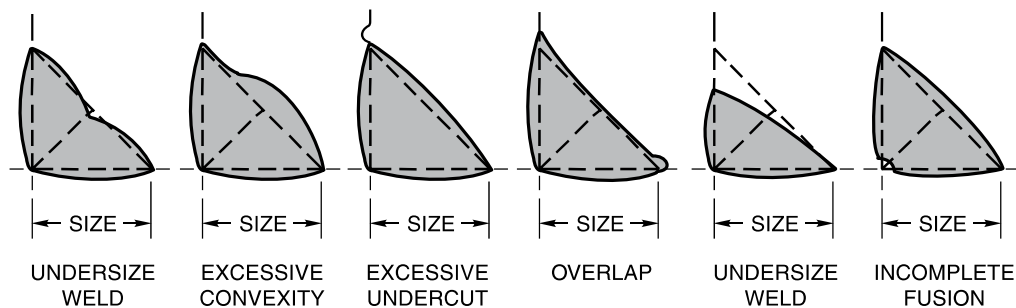
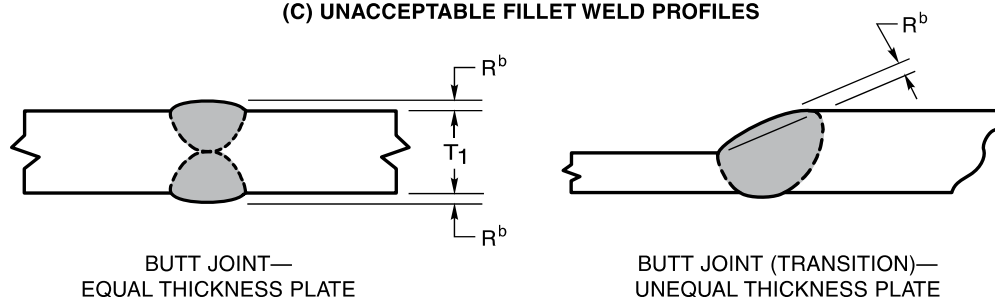
Table 4.2
Recommended Titanium Alloy Filler Metals for
Structural Welding of Various Base Titanium Alloys (see 4.4.1)

Base Material M Number	Filler Material Grade					
	AWS A5.16 ERTi-1	AWS A5.16 ERTi-2	AWS A5.16 ERTi-3	AWS A5.16 ERTi-5	AWS A5.16 ERTi-9 and AWS A5.16 ERTi-9ELI	AWS A5.16 ERTi-23
51 (Grade 1)	X					
51 (Grade 2)	X	X				
52 (Grade 3)			X			
53 (Grade 9)					X	
54 (Grade 5)				X		X
54 (Grade 23)						X
Armor (ref Annex A)				X		X

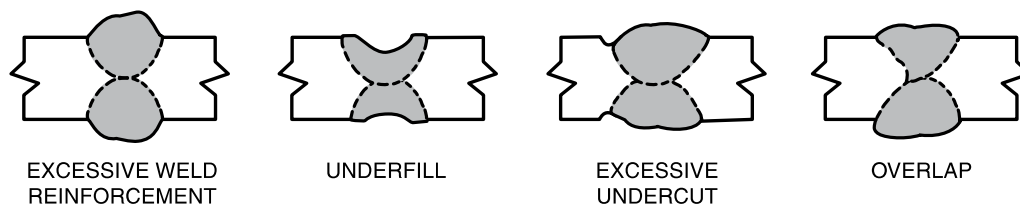
**(A) DESIRABLE FILLET WELD PROFILES****(B) ACCEPTABLE FILLET WELD PROFILES**

^aConvexity, C, of a weld or individual surface bead with dimension W shall not exceed the value of the following table:

WIDTH OF WELD FACE OR INDIVIDUAL SURFACE BEAD, W	MAX CONVEXITY, C
$W \leq 5/16$ in [8 mm]	1/16 in [2 mm]
$W > 5/16$ in [8 mm] TO $W < 1$ in [25 mm]	1/8 in [3 mm]
$W \geq 1$ in [25 mm]	3/16 in [5 mm]

**(C) UNACCEPTABLE FILLET WELD PROFILES**

^bReinforcement R shall not exceed 1/8 in [3 mm] (see 5.24.4).

(D) ACCEPTABLE GROOVE WELD PROFILE IN BUTT JOINT**(E) UNACCEPTABLE GROOVE WELD PROFILES IN BUTT JOINTS****Figure 4.1—Acceptable and Unacceptable Weld Profiles (see 4.20)**

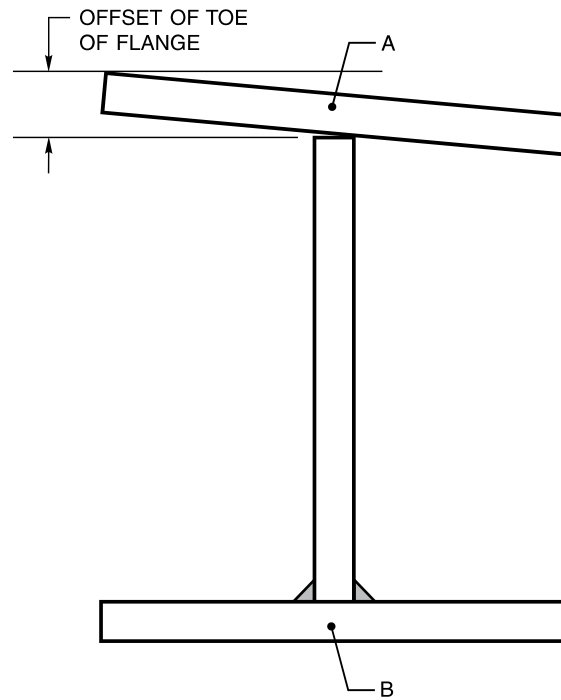


Figure 4.2—Warping of Flanges: Measurement of the Flange Toe Offset for an "I" or "H" Configuration Section (see 4.15.5)

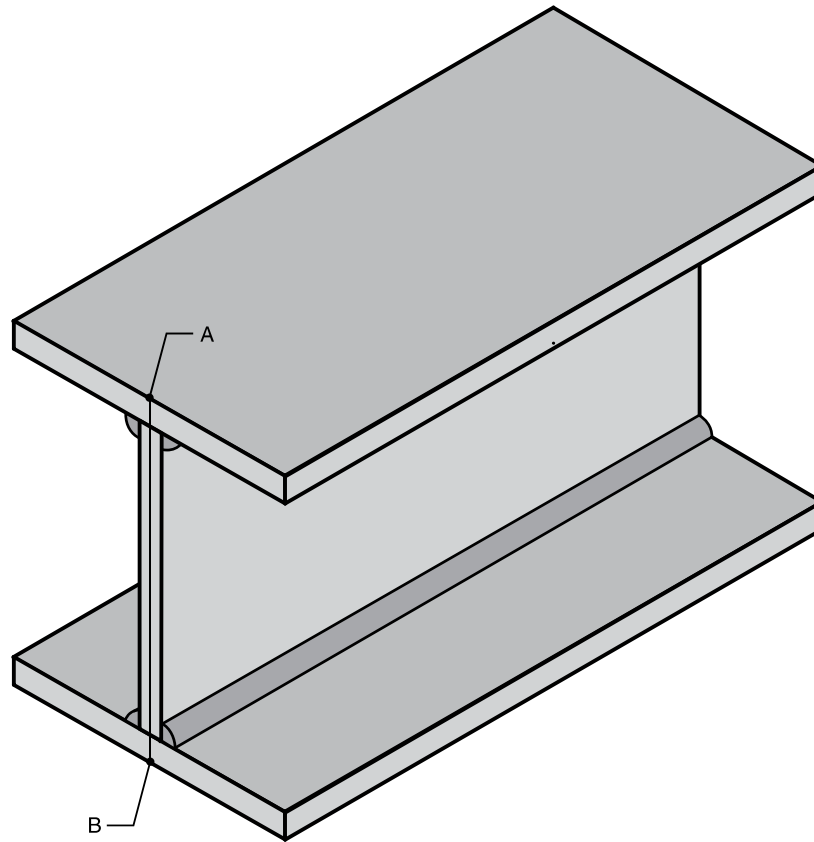


Figure 4.3—Depth Variation: Relative Location at Which the Beam Depth A-B is Measured for an “I” or “H” Configuration Section (see 4.15.6)

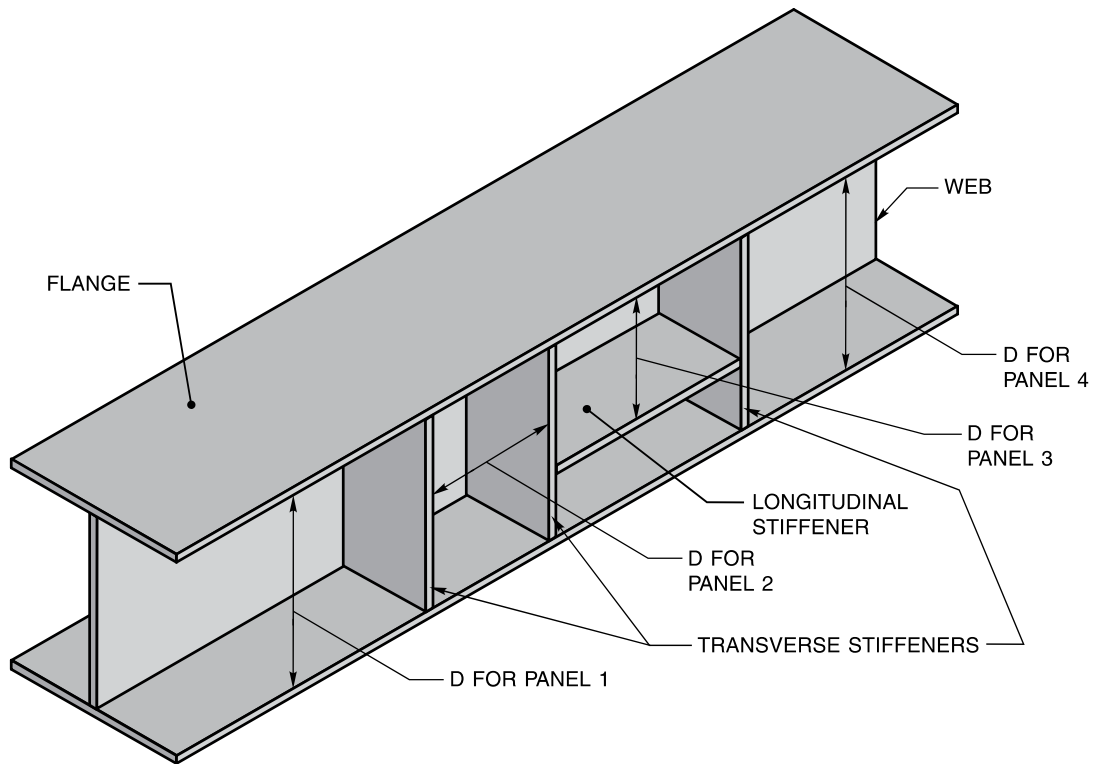


Figure 4.4—Least Panel Dimension “d” (see 4.15.7)

5. Inspection

Part A *General Requirements*

This clause specifies or references the inspection requirements, qualifications, and responsibilities for individuals evaluating welds, acceptance criteria for evaluation of discontinuities, and procedure requirements for nondestructive testing (NDT).

5.1 General

5.1.1 For the purpose of this code, quality control and quality assurance are separate inspection functions. Quality control entails those inspections and testing performed as part of the fabrication process. This inspection shall be performed as necessary prior to assembly, during welding, and after welding, to ensure that materials and workmanship meet the requirements of the contract documents.

5.1.2 Quality Assurance involves verification that an acceptable product is being furnished in accordance with the contract. Verification, when performed, shall be conducted by the Owner. It should be done in a timely manner to avoid work delays, and scheduled so that interference with production is minimal.

5.1.3 Fabrication inspection, as specified in 5.1.1, is the responsibility of the Contractor, while verification is performed at the discretion of the Owner. When the term inspector is used without further qualification, it applies equally to fabrication inspection and verification within the limits of responsibility designated in 5.1.1 and 5.1.2.

5.1.4 Inspector Qualification Requirements

5.1.4.1 Documented qualification is required for those individuals responsible for acceptance or rejection of

material and workmanship. The following are an acceptable basis for this qualification:

(1) Qualification as an AWS Certified Welding Inspector (CWI) or AWS Senior Certified Welding Inspector (SCWI) in accordance with the provisions of AWS QC1, *Standard and Guide for Qualification and Certification of Welding Inspectors*; or

(2) Qualification by the Canadian Welding Bureau (CWB) to the requirements of the Canadian Standard Association (CSA) Standard W178.2, *Certification of Welding Inspectors*; or

(3) An individual who, by training or experience, or both, in metals fabrication, inspection, and testing, is competent to perform inspection of the work.

5.1.4.2 The qualification specified in 5.1.4.1 shall remain in effect indefinitely, provided the individual remains active in inspection of welded fabrication, unless there is specific reason to question the Inspector's ability.

5.1.4.3 Personnel performing nondestructive testing other than visual shall be qualified in accordance with the current edition of the American Society for Nondestructive Testing (ASNT) Recommended Practice No. SNT-TC-1A. Only individuals qualified for NDT Level I and working under the NDT Level II, or individuals qualified for NDT Level II may perform nondestructive testing. NDT Level III individuals with previous Level II certification may act in all capacities of a NDT Level II.

5.1.4.4 Certification of Level I and Level II individuals shall be performed by a Level III individual who (1) has been certified by The American Society for Nondestructive Testing, or (2) has the requisite education, training, experience, and has successfully passed the examinations prescribed in SNT-TC-1A.

5.1.4.5 Personnel performing nondestructive tests other than visual need not be qualified or certified under

the provisions of AWS QC1, nor meet the requirements of 5.1.4.1. Instead they shall meet the vision requirements specified in 5.1.4.6 and the training, experience, and testing requirements referenced in 5.1.4.3 and 5.1.4.4.

5.1.4.6 Individuals qualified under this code to perform visual or other nondestructive test shall pass an eye examination with or without corrective lenses to prove (1) near vision acuity of Snellen English, or equivalent, at 12 in [300 mm], (2) far vision acuity of 20/40, or better. In addition these individuals shall pass an examination distinguishing and differentiating between colors and shades of gray used in the testing methods, as determined by their employer. Acuity test for individuals performing nondestructive testing shall be administered annually. Acuity tests for individuals performing visual examination only, and all color differentiation test shall be administered every three years. These tests may be administered more frequently if necessary to demonstrate adequacy, or to comply with additional requirements.

5.1.4.7 The Engineer shall have authority to verify the qualification of Inspectors.

5.1.4.8 The Inspector shall have the ability to ascertain that all fabrication and welding is performed in accordance with the requirements of the contract documents and this code. Inspectors not familiar with titanium welding should review this code, the contract documents, and any special instructions, as applicable.

5.2 Inspection of Materials

5.2.1 The Contractor shall make certain that only materials conforming to the requirements of the contract are used.

5.3 Inspection of Welding Procedure Specifications and Equipment

5.3.1 The Contractor shall ensure that all welding is performed in accordance with welding procedure specifications (WPSs) that have been qualified in accordance with Clause 3, and Annex A of this code when ballistic armor qualification is specified by contract documents.

5.3.2 The Contractor shall assure that the welding equipment to be used is capable of supporting the welding of titanium and titanium alloys in accordance with the requirements of this code.

5.4 Verification of Welder, Welding Operator, and Tack Welder Qualifications

5.4.1 The Contractor shall permit welding to be performed only by welders, welding operators, and tack welders who are qualified in accordance with the requirements of Clause 3 and Annex A as required.

5.4.2 When the quality of work produced by a welder, welding operator, or tack welder appears to be below the requirements of this code, the Contractor shall determine the root cause. If the welder, welding operator, or tack welder's capability is found to be questionable, the Contractor shall require that individual to demonstrate competency by a means mutually agreeable with the Contractor and the Engineer. This may be accomplished through requalification in accordance with Clause 3, Annex A, or some other means dependent on the severity of the concern.

5.4.3 The Contractor shall require requalification of any welder, welding operator, or tack welder who has not used a welding process (for which they are qualified) for a period exceeding six months.

5.5 Inspection of Work and Records

5.5.1 The Inspector shall examine the work to make certain that it meets the requirements of this clause, and Annex A when applicable. The Inspector shall make certain that the size, length, and location of all welds conform to the requirements of this code and the detail drawings. The size and contour of welds shall be measured with suitable gages.

5.5.2 The Inspector shall also periodically verify that the correct filler metal is used, and that when electrodes are used, they are for the polarity, current, and positions as stated in the WPS.

5.5.3 The Inspector is responsible for ascertaining correct examination procedures are used when nondestructive testing is required.

5.5.4 The Inspector shall identify through some method of recording, all parts and joints which have been inspected and accepted. Any method mutually agreeable is acceptable. Impression stamping of cyclically loaded member without the approval of the Engineer shall be prohibited.

5.6 Obligations of the Contractor

5.6.1 The Contractor shall be responsible for visual inspection and necessary correction of all deficiencies in materials and workmanship in accordance with the requirements of contract documents, this clause, or Annex A as applicable.

5.6.2 The Contractor shall make certain that only welding procedures are used that meet the provisions of Clause 3, and Annex A.

5.6.3 If faulty welding or its removal for rewelding damages the base metal so that its retention is not in accordance with the contract documents, the Contractor shall remove and replace the damaged base metal.

5.6.4 When nondestructive testing other than visual inspection is specified in the information furnished to bidders, it shall be the Contractor's responsibility to ensure that all specified welds meet the quality requirements of this clause, and Annex A when applicable.

5.6.5 The Contractor shall keep a record of qualification of all welders, welding operators, and tack welders, all procedure qualifications requirements, and other information as may be pertinent.

5.6.6 The Contractor shall be responsible for the retention of all inspection records including radiographs for one full year after the completion of the Contractor's work unless directed otherwise. Radiographs of welds may be retained by the Contractor or provided to the Customer, at the Customer's discretion. When requested by the Customer, the Contractor will provide a full set of radiographs of those welds tested including the film of the original defect and any subsequent repair film, including the final acceptance film. The Contractor's requirement to retain custody of the inspection records including radiographs will cease upon one of the following conditions: (1) delivery of the radiographs to the Owner, or (2) one full year after completion of the Contractor's work, or (3) as specifically stipulated in the Contract documents.

5.7 Nondestructive Testing

5.7.1 Visual Examination. When visual inspection is performed as required by this code, the examination method, procedure, and technique shall be in accordance with Clause 5, Part B.

5.7.2 Penetrant Testing. When penetrant testing is performed in accordance with this code, the examination method, procedure, and technique shall be in accordance with Clause 5, Part C.

5.7.3 Radiographic Testing. When radiographic testing is performed, the examination method, procedure, and technique shall be in accordance with ASTM E 1742 and Clause 5, Part D.

5.7.4 Ultrasonic Testing. When ultrasonic testing is performed, the method, procedure, and technique shall be as specified in Clause 5, Part E.

Part B *Visual Examination*

5.8 General

5.8.1 The procedures and standards detailed in Clause 5, Part B govern visual examination of welds required by this code. The requirements specified in this Clause 5, Part B are for visually examining welds in plates, shapes, and bars; and may be accomplished through the use of unaided and optically aided methods within the restrictions specified below. AWS B1.11, *Guide for the Visual Inspection of Welds*, provides guidelines for performance of visual examination of welds and may be used as a reference when establishing welding quality control procedures and practices. Visual inspection may be performed with the use of aids such as lighting equipment or magnifiers to improve the Inspector's detection capability contingent on the inspection environment and criticality of inspection. These aids may be used upon agreement between the Contractor and the Engineer.

5.8.2 Variations in testing procedures, equipment, and acceptance standards may be used upon agreement between the Contractor and the Engineer.

5.8.3 The weld quality acceptance criteria are applicable to all titanium alloys detailed within this code. The three classes of inspection are "A," "B," and "C." These classes are defined in Clause 2, subsection 2.2.4. The acceptance class for examination of production weldments shall be as defined in Clause 5, Part G acceptance criteria or the contract documents. In the event that the contract documents do not specify the weld class, Class B shall be applied.

5.8.4 One hundred percent visual examination shall be performed on all classes of weld, unless otherwise specified in the contract documents.

5.8.5 All welds shall be visually inspected in accordance with the criteria specified in Part G, and when applicable, the discoloration limits in Table 5.3 for the class of weld specified. As part of the visual inspection, the Inspector shall verify that nonspecified welds have not been added

without approval (with the exception of tack welds). When the contract documents, drawings, or specific visual inspection procedures require the removal of backing material, weld reinforcement, or surface roughness, in preparation for examination either to meet specific design criteria or sensitivity levels, the welds shall be prepared by a suitable mechanical means such as grinding or machining.

Part C

Penetrant Testing

5.9 General

The procedures and standards detailed in this Clause 5, Part C govern penetrant examination of welds required by the contract documents. The requirements detailed in this Clause 5, Part C are specifically for testing welds in plates, shapes, and bars with penetrant examination methods.

5.9.1 The methodology shall conform to ASTM E 165, *Standard Test Method for Liquid Penetrant Examination*, and ASTM E 1417, *Standard Practice for Liquid Penetrant Examination*.

5.9.2 Variations in testing procedures, equipment, and acceptance standards may be used upon agreement between the Contractor and the Engineer.

5.9.3 For detecting discontinuities that are open to the surface, liquid penetrant testing may be used. The standards of acceptance shall be in accordance with 5.21 unless otherwise noted. Flaw size shall be determined by discontinuity sizing in accordance with ASTM E 1417, unless specified otherwise by the Owner.

5.9.4 The degree of penetrant examination shall be as required by the contract documents. Visual examination at 10X may be used in lieu of penetrant testing when approved by the Engineer.

5.9.5 When penetrant inspection procedures require the removal of backing material, weld reinforcement, or surface roughness in preparation for examination, then the welds shall be prepared by suitable mechanical means such as grinding or machining.

5.9.6 Weld tabs shall be removed prior to penetrant testing, unless otherwise approved by the Engineer.

Part D

Radiographic Inspection

5.10 General

The procedures and standards detailed in this Clause 5, Part D govern radiographic testing of welds when such inspection is required by the contract documents. The requirements detailed in this Clause 5, Part D are specifically for testing welds in plates, shapes, and bars by X-ray or gamma ray sources.

5.10.1 The methodology shall conform to ASTM E 94, *Standard Guide for Radiographic Testing*, and ASTM E 1742, *Standard Practice for Radiographic Examination*, except as provided herein.

5.10.2 Variations in testing procedures, equipment, and acceptance standards shall be used upon agreement between the Contractor and the Owner. Such variations include, but are not limited to the unusual application of film; unusual Image Quality Indicators (IQI) applications including film side IQIs and wire IQIs; and radiographic testing of thicknesses greater than 6 in [150 mm].

5.11 Radiographic Procedures

5.11.1 Radiographs shall be made using a single source of either X-ray or gamma radiation. The radiographic sensitivity shall be judged on the basis of the IQI images. The radiographic technique and equipment shall provide sufficient sensitivity to clearly delineate the required IQIs and the essential holes or wires as described in 5.11.7, Table 5.4, Table 5.5, and Figure 5.1 or Figure 5.2, respectively. Identifying letters and numbers shall show clearly in the radiograph.

5.11.2 Radiography shall be performed in accordance with all applicable safety requirements.

5.11.3 When the contract documents, drawings or radiographic procedures require the removal of backing material, weld reinforcement or surface roughness in preparation for radiography the welds shall be prepared by grinding, machining, or some other suitable method.

5.11.3.1 When weld reinforcement or backing, or both, are not removed, then shims which extend at least 1/8 in [3 mm] beyond the sides of the required IQI shall be placed under the IQI so that the total thickness of material between the IQI and the film is approximately equal to the average thickness of the weld measured through its reinforcement and backing. Shims must be of radiographically similar alloy.

5.11.4 Lead foil screens and radiographic film shall be used as described in ASTM E 94. Radiographic film shall be Type 1 or Type 2. Fluorescent screens may be used when approved by the Engineer.

5.11.5 The source of radiation shall be centered as near as practicable with respect to the length and width of that portion of the weld being examined, and shall conform to the locations specified on the appropriate radiographic inspection drawing of the contract documents.

5.11.5.1 Gamma ray sources, regardless of size, shall be capable of meeting the geometric unsharpness requirement of Section V, Article 2 of ASME *Boiler and Pressure Vessel Code*.

5.11.5.2 The source-to subject distance shall not be less than the total length of film being exposed in a single plane. This provision does not apply to panoramic exposures made under the provisions of 5.10.2.

5.11.5.3 The source-to-subject distance shall not be less than seven times the thickness of the weld plus reinforcement and backing.

5.11.6 X-ray units up to 600 kVp, and Iridium 192 may be used as a source for all radiographic inspection, provided they have adequate penetrating ability. Co 60 may be used for welds that exceed 2-1/2 in [65 mm] in thickness. Other sources may be used if the inspection procedure is qualified.

5.11.7 IQIs shall be selected and placed on the weldment in the area of interest being radiographed as referenced in Table 5.6.

5.11.8 The thickness of the IQI and the essential hole/wire diameter shall be as specified in Table 5.4 or Table 5.5 as applicable, except that an IQI with a higher sensitivity level may be selected, provided all other provisions for radiography are met.

5.11.8.1 The thickness of the weldment shall be measured as T1 or T2, or both, at the locations shown in Figure 5.3, Figure 5.4, Figure 5.5, or Figure 5.6. T1 and T2 may be increased to provide for the thickness of allowable weld reinforcement, provided shims are used as specified in 5.11.3.1. Backing shall not be considered part of the weld or reinforcement in the IQI selection. For hole-type IQIs, the IQI representative of the maximum weld thickness may be placed on either the sloping surface adjacent to the fusion line, or on a shim of suitable thickness on the thinner side. Weld joints with complex geometries such as certain partial penetration welds should have the IQI placed so that its image on the radiograph appears 1/8 in to 1/4 in [3 mm to 6 mm] from the edge of the weld. Because of angles required to radio-

graph these joints the actual placement from the weld's edge may be greater.

5.11.8.2 IQI Selection and Placement. IQIs for titanium shall be manufactured from a radiographically similar alloy. Hole-type IQIs shall conform to dimensions shown in Figure 5.1. For more detailed information, ASTM E 1742 should be consulted. Each hole type IQI shall be manufactured with three holes, one of which shall be of a diameter equal to twice the IQI thickness (2T). The diameter of the two remaining holes shall be selected by the manufacturer. IQI designations 10 through 25 shall contain a 4T hole. Wire type IQIs shall conform to dimensions shown in Figure 5.2 and to the requirements of ASTM E 747.

5.11.9 Technique welded joints shall be radiographed and the film indexed by methods that will provide complete and continuous inspection of the joint within the limits specified to be examined. Joint limits shall show clearly in the radiographs. Short film, short screens (except when required by the radiographic procedure), excessive undercut by scattered radiation, or any other process that obscures portions of the total weld length shall render the radiograph unacceptable.

5.11.9.1 Film shall have sufficient length and shall be placed to produce at least 1/2 in [12 mm] of film beyond the defined area of interest on each side.

5.11.9.2 To check for backscattered radiation, a lead symbol "B," 1/2 in [12 mm] high, 1/16 in [1.5 mm] thick shall be attached to the back of each film cassette. If the "B" image appears on the radiograph, the radiograph shall be unacceptable.

5.11.9.3 Film widths shall be sufficient to depict all portions of the welded joint, including the heat-affected zones, and shall provide sufficient additional space for the required IQIs and film identification. The IQI shall be placed so that its image appears on the radiograph at least 1/8 in [3 mm], but not more than 1/4 in [6 mm] from the weld edge, whenever possible. Typically this corresponds directly to the IQI placement with certain exceptions for partial penetration and other geometrically complex weld configurations (see 5.11.8.2).

5.11.10 **Quality of Radiographs.** All radiographs shall be free from mechanical, chemical, or other blemishes to the extent that they might mask or be confused with the image of any discontinuity in the area of interest in the radiograph. Such blemishes include, but are not limited to the following:

- (1) Fogging
- (2) Processing defects such as streaks, watermarks, or chemical stains

(3) Scratches, finger marks, crimps, dirt, static marks, smudges, or tears

(4) Loss of detail due to poor screen-to-film contact

(5) False indications due to defective screens or internal faults.

5.11.11 Density Limitations. The transmitted film density through the radiographic image of the body of the required IQI(s) and the area of interest shall be 1.8 minimum (preferably in the range from 2.5 to 3.5) for single film viewing for radiographs made with an X-ray source and 2.0 minimum for radiographs made with a gamma-ray source. For composite viewing of multiple film exposures, the minimum density shall be 2.0. The maximum density shall be 4.0 for either single or composite viewing. The film shall be processed to develop a film blackening measured by the H&D radiographic density expressed as:

$$D = \text{H\&D (radiographic) density} = \log_{10} (I_0/I)$$

where:

I_0 = light intensity on the film, and

I = light transmitted through the film

5.11.12 Identification Marks Radiograph identification and location identification marks shall be placed on the weldment at each radiograph location, all of which shall show in the radiograph. The radiographic images shall be produced by placing lead numbers or letters, or any combination thereof, over each of the identical identification and location marks made on the weldment. The images provide the means for matching the developed radiograph with the weld. Additional identification information may be preprinted no less than 3/4 in [19 mm] from the edge of the weld or produced on the radiograph by placing lead figures on the weldment. Information required to show on the radiograph shall include the contract identification, initial of the radiographic inspection company, initials of the fabricator, the fabricator shop order number, the radiographic identification mark, the date, and the weld repair number, if applicable.

5.12 Coverage and Acceptability of Welds

5.12.1 Welds shown by radiographic testing to have discontinuities prohibited by the acceptance criteria specified in 5.22 shall be corrected in accordance with 4.21.

5.12.2 CJP Welds that are designated class A and class C are subject to radiographic testing. In some instances CJP class B welds may also require radiographic testing

if directed by the Engineer or contract documents. Class A welds shall require 100% radiographic testing unless a sampling plan is specified. Class C welds shall be radiographed in accordance with Annex A.

5.13 Examination, Report, and Disposition of Radiographs

5.13.1 Film shall be evaluated with a variable intensity illuminator (viewer) with spot-review or masked spot-review capability. The viewer shall incorporate a means for adjusting the size of the spot under examination. The viewer shall have sufficient capacity to properly illuminate radiographs with an H&D density of 4.0. Film review shall be done in an area of subdued light.

5.13.2 Before a weld subject to radiographic testing is accepted, all of its radiographs, including any that show unacceptable quality prior to repair, and a report evaluating them, shall be submitted to the Owner upon request.

5.13.3 Radiographs of welds may be retained by the Contractor or provided to the Owner, at the Owner's discretion. When requested by the Owner, the Contractor will provide a full set of radiographs of those welds tested including the film of the original defect and any subsequent repair film, including the final acceptance film. The Contractor's requirement to retain radiographs shall cease: (1) upon delivery of the radiographs to the Owner, or (2) one full year after completion of the Contractor's work unless otherwise specified in the contract documents.

Part E Ultrasonic Testing of Groove Welds

5.14 General

5.14.1 When ultrasonic testing is required or permitted by the contract documents, the extent of testing, the procedure, and the acceptance criteria should be specified therein.

5.14.2 The Inspector shall maintain a record of the welds or portions of welds subjected to ultrasonic testing. The Contractor's obligation to retain these records will cease: (1) upon delivery of the records to the Owner, or (2) one full year after completion of the Contractor's work, unless otherwise specified in the contract documents.

5.15 Operator Requirements

5.15.1 UT personnel shall be qualified in accordance with SNT-TC-1A. Qualification of the UT operator may include a specific and practical examination based on the requirements of this code. The examination shall require the operator to demonstrate the ability to apply the rules of this code in the detection, interpretation, and evaluation of defects.

5.15.2 The UT operator shall have made available to him all pertinent information required to make accurate assessments. These include but are not limited to base metal type, weld joint geometry, material thickness, welding process, and repair status.

5.16 Procedure

5.16.1 Ultrasonic examination, when required, shall be performed in accordance with ASTM E 114, *Standard Practice for Ultrasonic Pulse-Echo Straight Beam Examination by the Contact Method*, or ASTM E 587, *Standard Practice for Ultrasonic Angle Beam Examination by the Contact Method*.

5.16.2 The UT equipment shall be the pulse echo type suitable for use with transducers that oscillate at frequencies between 1 MHz and 6 MHz. The display shall be an “A” scan rectified video trace or other display acceptable to the Engineer.

5.16.3 Acceptability and Coverage. Welds tested by Ultrasonic Examination shall conform to the requirements specified by the contract documents.

time imaging when approved by the Engineer. When these alternative methods are used for acceptance purposes, the image on the monitor must be equivalent in sensitivity to that required for traditional radiography.

5.18.2 Procedure Qualification. The procedure shall be approved by an individual qualified as an ASNT SNT-TC-1A NDT Level III. In addition to the certification requirements of SNT-TC-1A, the following requirements shall apply:

(1) Level III personnel shall have six months experience using the same or similar equipment and procedures.

(2) Level II personnel shall be certified by a Level III and shall have three months experience using the same or similar equipment and procedures.

5.18.3 Image Quality Indicators. Wire type IQIs shall be used. IQI placement shall be as described in Part B for static examination. For in-motion examination one IQI shall be placed at the beginning and end of each run with no more than 10 ft [3.0 m] between intervening IQIs.

5.18.4 Image Enhancements. Computer enhancement is acceptable. The use of enhancements shall be clearly noted in the report.

5.18.5 Records. Records shall be maintained as required in 5.6.6 and include the following as a minimum:

- (1) Identification of the weld
- (2) Procedure(s)
- (3) Equipment
- (4) Location of welds
- (5) Results.

Part F *Other Examination Methods*

5.17 General

This part contains NDT methods not contained in Parts B, C, D, and E of Clause 5 of this code. These NDT methods, and others not necessarily specified in this Clause 5, Part F require written procedures and operator qualification.

5.18 Radiation Imaging Systems

5.18.1 General. Examination of welds using ionizing radiation may be accomplished using electronic or real-

Part G *Acceptance Criteria*

5.19 General

5.19.1 The weld quality acceptance/rejection criteria of this Clause 5, Part G are applicable to all titanium alloys specified within this code. The three classes of welds are “A,” “B,” and “C.” The application and criticality of welds in these three classes are defined in 2.2.4.

5.19.2 For welds subject to nondestructive testing, the testing may begin immediately after the completed welds have cooled to ambient temperature. In the case of welds

where coloration is part of the acceptance criteria, each weld pass shall be examined for color, luster, or both as specified in the acceptance requirements, prior to any further work which may alter the surface appearance.

5.20 Visual Examination

5.20.1 All welds shall meet the acceptance criteria in Table 5.1. When the contract document requires coloration to be a factor in the evaluation of weld quality, the welds shall meet the acceptance criteria in Table 5.3.

5.20.2 Welds subject to further nondestructive testing shall first have been found acceptable by visual inspection in accordance with Table 5.1.

5.21 Penetrant Testing

Welds that are subject to penetrant testing shall be evaluated to the applicable acceptance requirements for inspection specified in Table 5.1

5.22 Radiographic Testing

Welds that are subject to radiographic testing shall be evaluated to the applicable acceptance requirements in Table 5.2.

5.23 Ultrasonic Testing

5.23.1 Welds that are subject to ultrasonic testing shall be evaluated to the contract document requirements.

Table 5.1
Visual and Penetrant Acceptance Criteria (see 5.20.1, 5.20.2, 5.21, A4.3.2, and A4.5.3)

Discontinuity	Class A	Class B	Class C
Cracks	None Allowed	None Allowed	None Allowed
Overlap	None Allowed	None Allowed	None Allowed
Incomplete Fusion	None Allowed	None Allowed	None Allowed
Incomplete Joint Penetration	None Allowed	None Allowed	None Allowed
Porosity			
Individual size	0.25T or 3/64 in [1.2 mm], whichever is less	0.33T or 1/16 in [1.5 mm], whichever is less	0.25T or 3/64 in [1.2 mm], whichever is less
Spacing	2 times the size of the larger adjacent discontinuity	N/A	2 times the size of the larger adjacent discontinuity
Accumulated diameters in any 1 in [25 mm] of weld	1/8 in [3 mm]	3/16 in [5 mm]	1/8 in [3 mm]
Accumulated diameters in any 12 in [300 mm] of weld	3/8 in [10 mm]	3/4 in [19 mm]	3/8 in [10 mm]
Weld Profiles	See Figure 4.1	See Figure 4.1	See Figure 4.1
Fillet weld concavity	Acceptable—throat size must meet specified requirement	Acceptable—throat size must meet specified requirement	Acceptable—throat size must meet specified requirement
Fillet weld convexity	Welds $\leq 1/4$ in [6 mm] max. convexity 1/16 in [1.5 mm] Welds $> 1/4$ in [6 mm] $< 3/4$ in [19 mm] max. convexity 1/8 in [3 mm] Welds $\geq 3/4$ in [19 mm] max. convexity 3/16 in [5 mm]	Convexity must not cause interference	Welds $\leq 1/4$ in [6 mm] max. convexity 1/16 in [1.5 mm] Welds $> 1/4$ in [6 mm] $< 3/4$ in [19 mm] max. convexity 1/8 in [3 mm] Welds $\leq 3/4$ in [19 mm] max. convexity 3/16 in [5 mm]
Weld reinforcement	Meet minimum size, reinforcement shall not exceed 5/32 in [4 mm]. Flush finish requirement shall not reduce thinner member more than 1/32 in [0.8 mm]	Meet minimum size, reinforcement shall not exceed 5/32 in [4 mm]. Flush finish requirement shall not reduce thinner member more than 1/32 in [0.8 mm]	Meet minimum size, reinforcement shall not exceed 5/32 in [4 mm]. Flush finish requirement shall not reduce thinner member more than 1/32 in [0.8 mm]
Craters			
Maximum Depth	0.20 T or 1/32 in [0.8 mm], whichever is less	0.30 T or 3/64 in [1.2 mm], whichever is less	0.20 T or 1/32 in [0.8 mm], whichever is less
Maximum Length	1T	1.5T	1T
Maximum Occurrence	two in 12 in [300 mm]	two in 12 in [300 mm]	two in 12 in [300 mm]
Fillet Weld Undersize Tolerance			
Accumulated length not to exceed 10% of weld length	10%E or 1/16 in [1.5 mm], whichever is less	15%E or 3/32 in [2.5 mm], whichever is less	10%E or 1/16 in [1.5 mm], whichever is less

(Continued)

Table 5.1 (Continued)
Visual and Penetrant Acceptance Criteria (see 5.20.1, 5.20.2, 5.21, A4.3.2, and A4.5.3)

Discontinuity	Class A	Class B	Class C
Undercut			
Depth/width ratio	Depth not to exceed 1/2 times width	Depth not to exceed 1/2 times width	Depth not to exceed 1/2 times width
Maximum depth for material $\geq 1/8$ in [3 mm] <1.0 in [25 mm]	1/32 in [0.8 mm] full length, 1/16 in [1.5 mm] not to exceed 1 in [25 mm] in 12 in [300 mm]	1/32 in [0.8 mm] full length, 1/16 in [1.5 mm] not to exceed 2 in [50 mm] in 12 in [300 mm]	1/32 in [0.8 mm] full length, 1/16 in [1.5 mm] not to exceed 1 in [25 mm] in 12 in [300 mm]
Maximum depth for material ≥ 1.0 in [25 mm]	3/64 in [1.2 mm] full length 1/16 in [1.5 mm] not to exceed 2 in [50 mm] in 12 in [300 mm]	1/16 in [1.5 mm] full length	3/64 in [1.2 mm] full length 1/16 in [1.5 mm] not to exceed 2 in [50 mm] in 12 in [300 mm]
Arc Strikes	None Allowed	None Allowed	None Allowed

Notes:

1. Penetrant inspection of welds may begin immediately after the completed welds have cooled to ambient temperature. Visual inspection may begin immediately after completion.
2. Surface porosity measuring less than 1/32 in [0.8 mm] diameter shall not be considered with the exception of aligned porosity.
3. E is the nominal fillet weld throat thickness design size.

Table 5.2
Radiographic Allowance for CJP and PJP Welds (see 3.8.2, 5.22, and A4.3.2)

Discontinuity Types	Base Material Thickness Range, in [mm]	Radiograph Category, in [mm]	Acceptance Level (Reference ASTM E 390 Radiographs)
Cracks	All	N/A	None allowed
Fine Scattered Porosity	$\geq 1/8$ [3] and $\leq 1/2$ [12]	Up to 3/8 [10], incl.	1
	$> 1/2$ [12] and $\leq 1-1/2$ [38]	Up to 3/4 [19], incl.	1
	$> 1-1/2$ [38] and ≤ 3 [76]	Up to 2 [50], incl.	2
Coarse Scattered Porosity	$\geq 1/8$ [3] and $\leq 1/2$ [12]	Up to 3/8 [10], incl.	1
	$> 1/2$ [12] and $\leq 1-1/2$ [12]	Up to 3/4 [19], incl.	1
	$> 1-1/2$ [38] and ≤ 3 [76]	Up to 2 [50], incl.	2
Linear Porosity or Rounded Indications	$\geq 1/8$ [3] and $\leq 1/2$ [12]	Up to 3/8 [10], incl.	1
	$> 1/2$ [12] and $\leq 1-1/2$ [38]	Up to 3/4 [19], incl.	1
	$> 1-1/2$ [38] and ≤ 3 [76]	Up to 2 [50], incl.	2
Nonmetallic Inclusions	$\geq 1/8$ [3] and $\leq 1/2$ [12]	Up to 3/8 [10], incl.	2
	$> 1/2$ [12] and $\leq 1-1/2$ [38]	Up to 3/4 [19], incl.	2
	$> 1-1/2$ [38] and ≤ 3 [76]	Up to 2 [50], incl.	3
Tungsten Inclusions	$\geq 1/8$ [3] and $\leq 1/2$ [12]	Up to 3/8 [10], incl.	2
	$> 1/2$ [12] and ≤ 3 [76]	Up to 3/4 [19], incl.	2
Incomplete Joint Penetration CJP only	$\geq 1/8$ [3] and $\leq 1/2$ [12]	Up to 3/8 [10], incl.	2
	$> 1/2$ [12] and $\leq 1-1/2$ [38]	Up to 3/4 [19], incl.	2
	$> 1-1/2$ [38] and ≤ 3 [76]	Up to 2 [50], incl.	3
Incomplete Fusion CJP only	$\geq 1/8$ [3] and $\leq 1/2$ [12]	Up to 3/8 [10], incl.	2
	$> 1/2$ [12] and $\leq 1-1/2$ [38]	Up to 3/4 [19], incl.	2
	$> 1-1/2$ [38] and ≤ 3 [76]	Up to 2 [50], incl.	3
Incomplete Joint Penetration—Partial joint penetration welds only	All	N/A	1/32 [0.8] width full weld length 1/16 [1.5] width 4T in 8T weld length
Incomplete Fusion—Partial joint penetration welds only	All	N/A	1/32 [0.8] width full weld length 1/16 [1.5] width 4T in 8T weld length

Notes:

1. Porosity or inclusions allowed by this table shall be cause for rejection when closer than twice their maximum dimension to an edge or extremity of a weldment in a highly stressed or critical area, as determined by design engineering personnel.
2. Linear is described as having a length greater than three times the width. Rounded is defined by the converse.

Table 5.3
Coloration Acceptance Criteria (see 3.7.2.2, 3.7.2.3, 5.8.5, and 5.20.1)

Color Discriminator	Class A	Class B	Class C
Bright Silver	Acceptable ^a	Acceptable ^a	Acceptable ^a
Silver	Acceptable ^a	Acceptable ^a	Acceptable ^a
Light Straw	Acceptable ^a	Acceptable ^a	Acceptable ^a
Dark Straw	Acceptable ^a	Acceptable ^a	Acceptable ^a
Bronze	Acceptable ^a	Acceptable ^a	Acceptable ^a
Brown	Acceptable ^a	Acceptable ^a	Acceptable ^a
Violet	Unacceptable ^{b, c}	Acceptable ^a	Unacceptable ^{b, c}
Dark Blue	Unacceptable ^{b, c}	Acceptable ^a	Unacceptable ^{b, c}
Light blue	Unacceptable ^{b, c}	Acceptable ^a	Unacceptable ^{b, c}
Green	Unacceptable ^{b, c}	Acceptable ^a	Unacceptable ^{b, c}
Gray	Unacceptable	Unacceptable	Unacceptable ^{b, c}
White	Unacceptable	Unacceptable	Unacceptable ^{b, c}

^a Discoloration must be removed prior to additional welding.

^b On the weld and in the HAZ up to 0.03 in [0.8 mm] beyond the weld.

^c Violet, blue, and green discoloration is rejectable if additional welding is to be performed. Blue and green discoloration is acceptable on finished welds but must be removed prior to subsequent processing.

Note: Discoloration comes in various shades tones and hues.

Table 5.4
Hole-Type IQI Requirements (see 5.11.1 and 5.11.8)

Nominal Material Thickness Range, in [mm]	IQI Identification	IQI Thickness, in [mm]	Essential Hole
Up to 0.25 [6] incl.	10	0.010 [0.254]	4T
Over 0.25 [6] to 0.375 [10]	12	0.012 [0.305]	4T
Over 0.375 [10] to 0.50 [12]	15	0.015 [0.381]	4T
Over 0.50 [12] to 0.625 [16]	15	0.015 [0.381]	4T
Over 0.625 [16] to 0.75 [19]	17	0.017 [0.432]	4T
Over 0.75 [19] to 0.875 [22]	20	0.020 [0.508]	4T
Over 0.875 [22] to 1.00 [25]	20	0.020 [0.508]	4T
Over 1.00 [25] to 1.25 [31]	25	0.025 [0.635]	4T
Over 1.25 [31] to 1.50 [38]	30	0.030 [0.762]	2T
Over 1.50 [38] to 2.00 [51]	35	0.035 [0.889]	2T
Over 2.00 [51] to 2.50 [63]	40	0.040 [1.016]	2T
Over 2.50 [63] to 3.00 [76]	45	0.045 [1.143]	2T
Over 3.00 [76] to 4.00 [102]	50	0.050 [1.27]	2T
Over 4.00 [102] to 6.00 [152]	60	0.060 [1.524]	2T

Table 5.5
Wire IQI Requirements (see 5.11.1 and 5.11.8)

Nominal Material Thickness ^a Range		Source Side Maximum Wire Diameter		Film Side ^b Maximum Wire Diameter	
in	mm	in	mm	in	mm
Up to 0.25 incl.	Up to 6 incl.	0.010	0.25	0.008	0.20
Over 0.25 to 0.375	Over 6 to 10	0.013	0.33	0.010	0.25
Over 0.375 to 0.625	Over 10 to 16	0.016	0.41	0.013	0.33
Over 0.625 to 0.75	Over 16 to 20	0.020	0.51	0.016	0.41
Over 0.75 to 1.50	Over 20 to 38	0.025	0.63	0.020	0.51
Over 1.50 to 2.00	Over 38 to 50	0.032	0.81	0.025	0.63
Over 2.00 to 2.50	Over 50 to 65	0.040	1.02	0.032	0.81
Over 2.50 to 4.00	Over 65 to 100	0.050	1.27	0.040	1.02
Over 4.00 to 6.00	Over 100 to 150	0.063	1.60	0.050	1.27
Over 6.00 to 8.00	Over 150 to 200	0.100	2.54	0.063	1.60

^a Single-wall radiographic thickness (for tubulars).

^b Applicable to tubular structures only.

Table 5.6
IQI Selection and Placement (see 5.11.7)

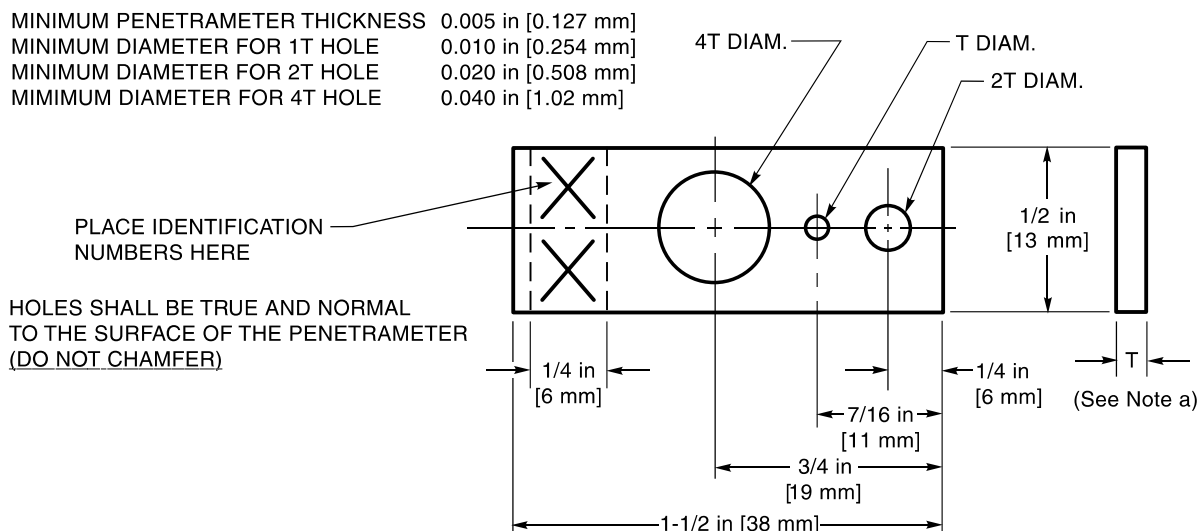
IQI Types	Equal T ≥ 10 in [250 mm] L		Equal T < 10 in [250 mm] L		Unequal T ≥ 10 in [250 mm] L		Equal T < 10 in [250 mm] L	
	Hole	Wire	Hole	Wire	Hole	Wire	Hole	Wire
Number of IQIs:								
Nontubular	2	2	1	1	3	2	2	1
Pipe Girth	3	3	3	3	3	3	3	3
ASTM Standard	E 1025	E 747	E 1025	E 747	E 1025	E 747	E 1025	E 747
Selection:								
Table	5.5	5.6	5.5	5.6	5.5	5.6	5.5	5.6
Figures		5.3		5.4		5.5		5.6

T = Nominal base metal thickness (T1 and T2 of Figures).

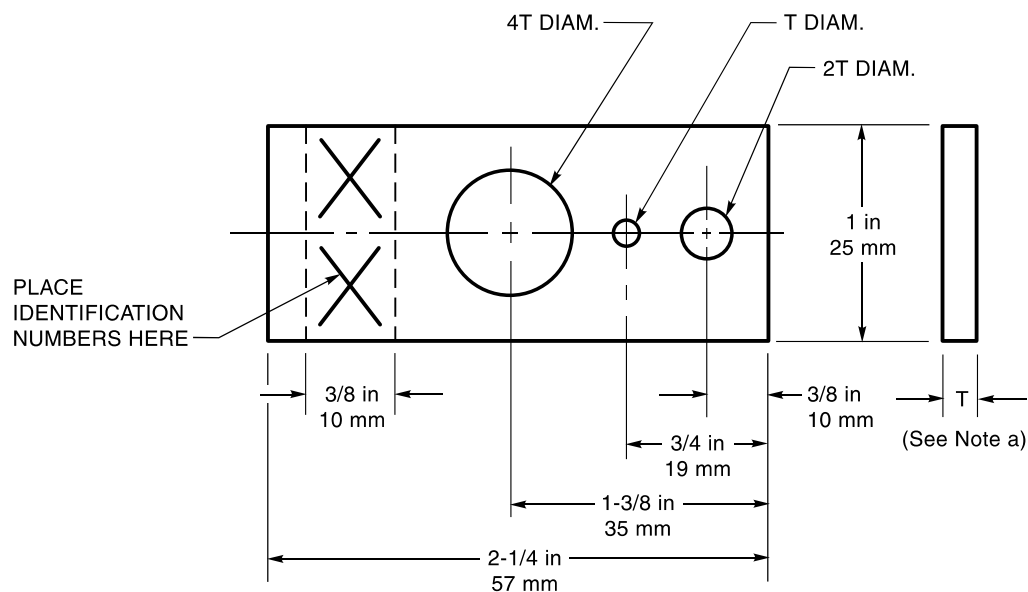
L = Weld Length in area of interest of each radiograph.

Notes:

1. Backing shall not be considered part of the weld or weld reinforcement in IQI selection.
2. T may be increased to provide for the thickness of allowable weld reinforcement provided shims are used under hole IQIs per 5.11.3.1.
3. When a complete circumferential pipe weld is radiographed with a single exposure and the radiation source is placed at the center of the curvature, at least three equally spaced hole type IQIs shall be used.



DESIGN FOR PENETRATOR THICKNESS FROM 0.005 in [0.127 mm] AND INCLUDING 0.050 in [1.27 mm]:
 OVER 0.012 in [0.305 mm] THROUGH 0.020 in [0.508 mm], MADE IN 0.0025 in [0.0638 mm] INCREMENTS
 OVER 0.020 in [0.508 mm] THROUGH 0.050 in [1.27 mm], MADE IN 0.005 in [0.127 mm] INCREMENTS
 PENETRATOR THICKNESSES BETWEEN THE INCREMENTS INDICATED MAY BE USED,
 PROVIDED THEY DO NOT EXCEED THE MAXIMUM THICKNESS REQUIRED.



DESIGN FOR PENETRATOR THICKNESS FROM 0.060 in [1.52 mm] TO 0.160 in [4.06 mm] INCLUSIVE, MADE IN 0.010 in [0.254 mm] INCREMENTS.

^a Tolerances on penetrator thickness and hole diameter shall be $\pm 10\%$ or one half of the thickness increment between parameter sizes, whichever is smaller.

Figure 5.1—Hole Type IQI Design (see 5.11.1 and 5.11.8.2)

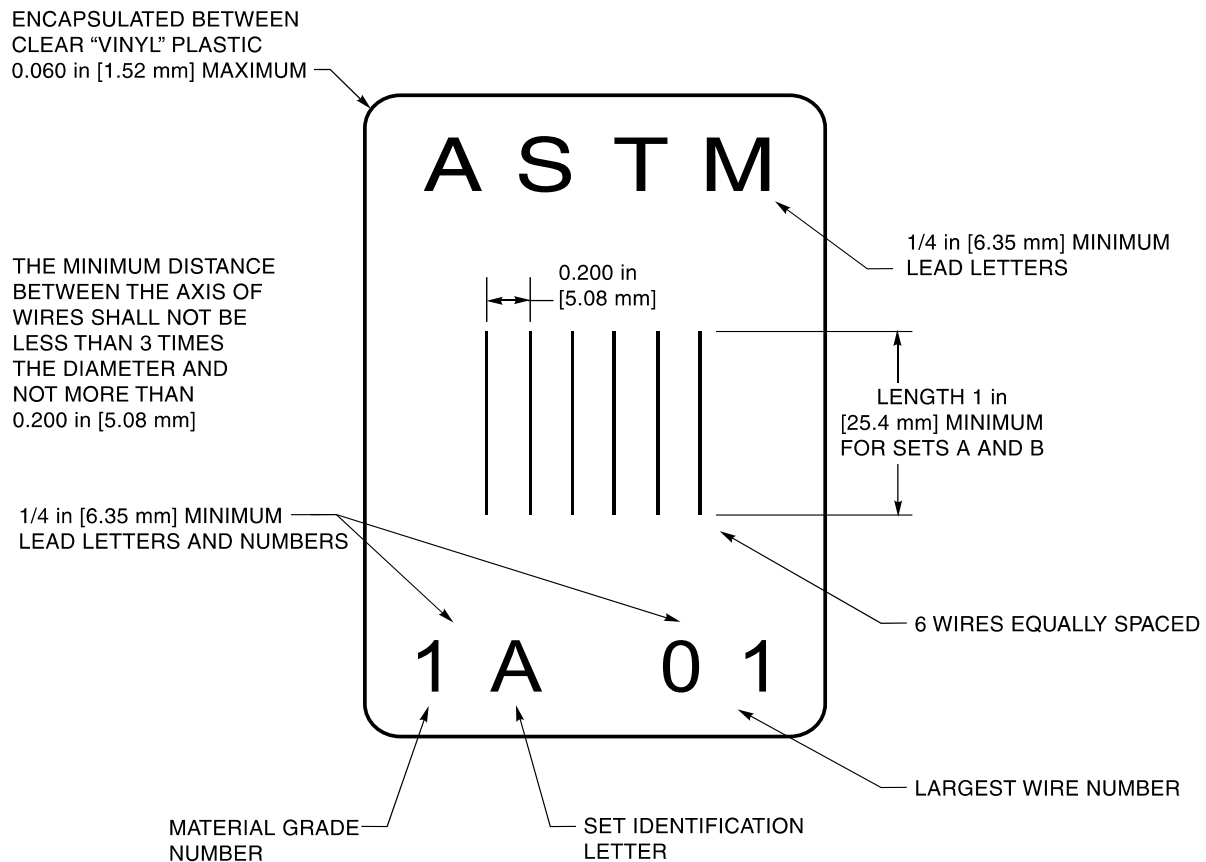
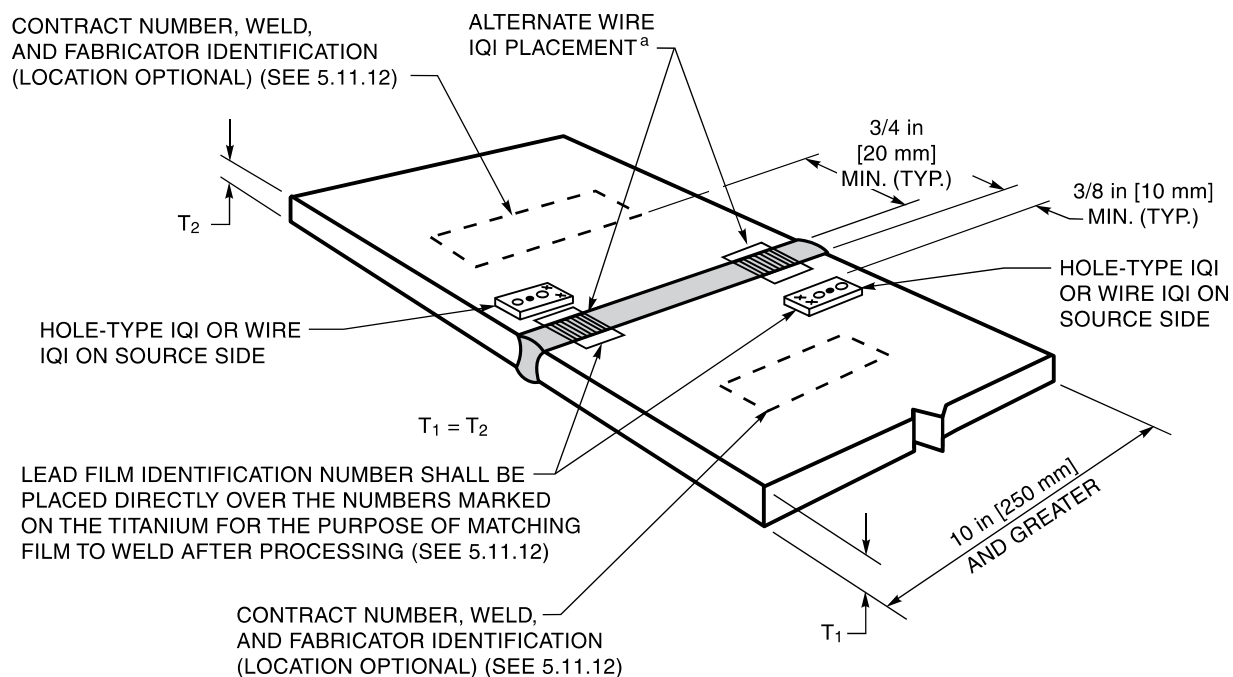


Image Quality Indicator (Wire Penetrameter) Sizes			
Wire Diameter, in [mm]			
Set A	Set B	Set C	Set D
0.0032 [0.08]	0.010 [0.25]	0.032 [0.81]	0.10 [2.5]
0.004 [0.1]	0.013 [0.33]	0.040 [1.02]	0.125 [3.2]
0.005 [0.13]	0.016 [0.4]	0.050 [1.27]	0.160 [4.06]
0.0063 [0.16]	0.020 [0.51]	0.063 [1.6]	0.20 [5.1]
0.008 [0.2]	0.025 [0.64]	0.080 [2.03]	0.25 [6.4]
0.010 [0.25]	0.032 [0.81]	0.100 [2.5]	0.32 [8]

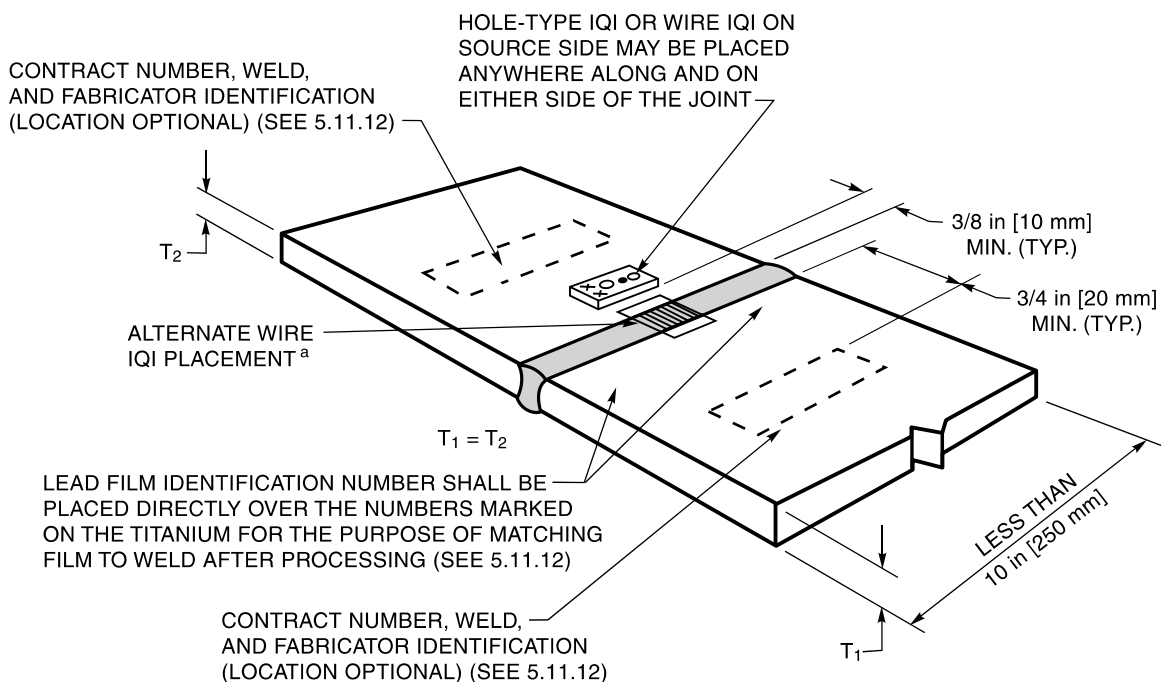
Figure 5.2—Wire IQI Design (see 5.11.1 and 5.11.8.2)

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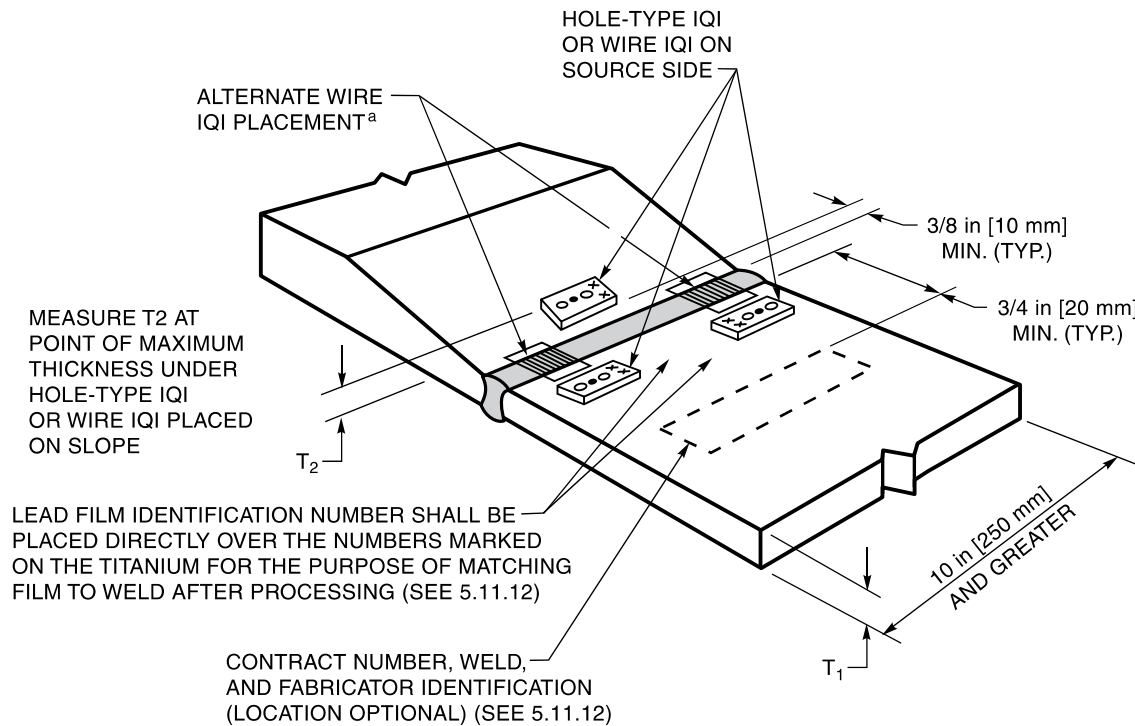
^a Alternate source side IQI placement allowed for tubular applications and other applications when approved by the Engineer.

Figure 5.3—RT Identification and Hole-Type or Wire IQI Locations on Approximately Equal Thickness Joints 10 in [250 mm] and Greater in Length (see 5.11.8.1)



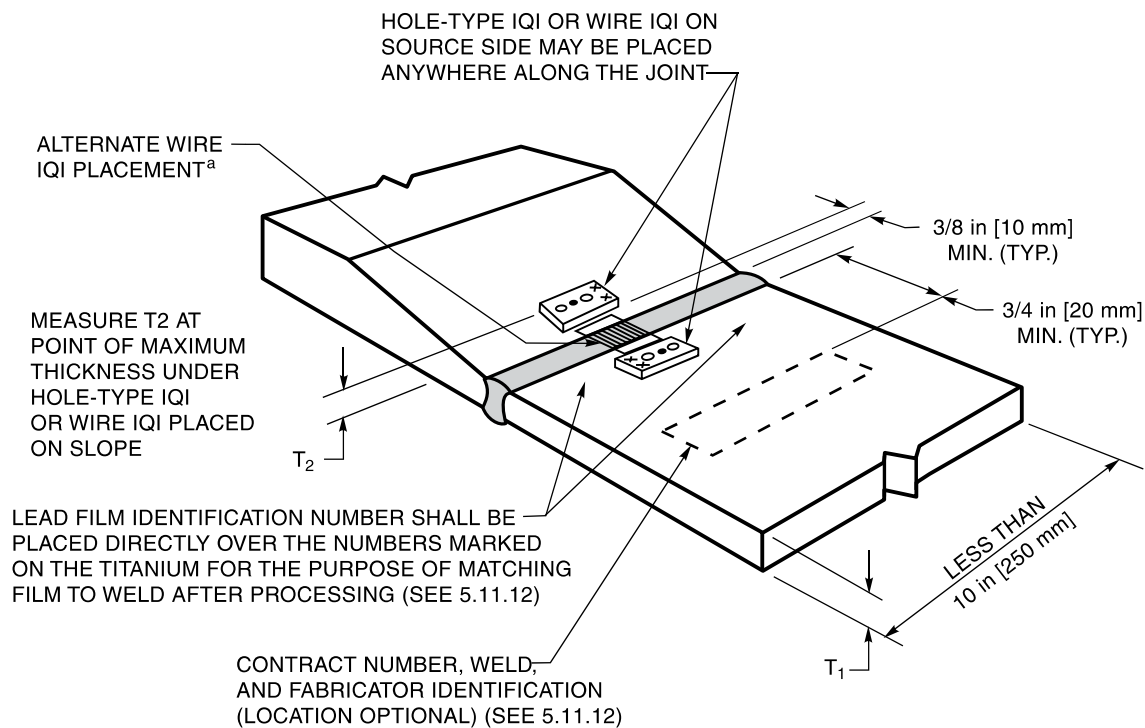
^a Alternate source side IQI placement allowed for tubular applications and other applications when approved by the Engineer.

Figure 5.4—RT Identification and Hole-Type or Wire IQI Locations on Approximately Equal Thickness Joints Less than 10 in [250 mm] in Length (see 5.11.8.1)



^a Alternate source side IQI placement allowed for tubular applications and other applications when approved by the Engineer.

Figure 5.5—RT Identification and Hole-Type or Wire IQI Locations on Transition Joints 10 in [250 mm] and Greater in Length (see 5.11.8.1)



^a Alternate source side IQI placement allowed for tubular applications and other applications when approved by the Engineer.

Figure 5.6—RT Identification and Hole-Type or Wire IQI Locations on Transition Joints Less than 10 in [250 mm] in Length (see 5.11.8.1)

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Annex A (Normative)

Welding of Titanium Armor Structures

This annex is part of AWS D1.9/D1.9M:2007-ADD1, *Structural Welding Code—Titanium*, and includes mandatory elements for use with this standard.

A1. Introduction

This annex contains the supplementary requirements for the ballistic testing and inspection of structural titanium armor.

A2. Application

A2.1 This class of weld is applicable to weld joints that are critical to the ballistic integrity of a structure. Weld joints that are not exposed to direct ballistic attack shall be specified with nonballistic weld classes.

A2.2 When welding titanium armor, the drawing shall contain a note that states: “Welding in accordance with Class C, Spec AWS D1.9/D1.9M, *Structural Weld Code—Titanium*.”

A3. Materials

A3.1 The armor base metal to be welded under this code shall be limited to:

- (1) SAE-AMS-T-9046—Titanium Alloy, Sheet, Strip, and Plate (Grade AB-1, Condition A)
- (2) SAE-AMS-T-9047—Titanium and Titanium Bars (rolled or forged) and Reforging Stock, Aircraft Quality
- (3) MIL-DTL-46077—Armor Plate, Titanium, Weldable

A3.2 Combinations of armor and nonarmor base metals may be welded, provided the welding procedures are qualified in accordance with Clause 3 of this code.

A3.3 Weld tabs shall be of the same material as qualified on the PQR.

A4. Requirements

A4.1 Weldments. The dimensions and locations of welds shall be those shown on the engineering drawings and shall not be changed without the written approval from the Engineer. Alternate weld joint geometries will also be permitted subject to approval by the Engineer and supported by experimental data and or engineering analysis.

A4.2 Preparation of Welding Procedures and Drawings

A4.2.1 Prior to the production fabrication of any weldment, the Contractor shall prepare an image (drawing or electronic) of the structure showing the location of each ballistic joint. The Contractor also shall establish welding procedure specifications (WPSs) to cover all welding (including a general outline for the repair of base metal and welded joints) to be performed under this document.

A4.3 Welders or Welding Operator

A4.3.1 Test Plate Requirements. As a minimum for determining qualification, the welders or welding operators shall weld a double bevel test plate as detailed in the approved WPS in addition to those plates required by Clause 3 for welder qualification. The test plate (A typical example is shown in Figure A.1) must be made from 1.0 in [25 mm] thick material, and must be at least 12 in [300 mm] long, 6.0 in [150 mm] wide. Test plate must be made from material identified on the WPS. For welding positions and welding process, see Clause 3.

A4.3.2 Test Plate Acceptance. All test plates shall be visually inspected per Table 5.1, Class C Ballistic Welds and radiographically evaluated to Table 5.2. The first and last inch of the test plate are excluded from evaluation. Test plate shall be subjected to the same testing as defined in Clause 3 for welder and welding operator qualification.

A4.4 Welding Attachments to Armor

A4.4.1 Armor welding procedures qualified by ballistic testing (Annex A) shall also provide qualification of welding attachments to armor that are integral to structure integrity. Welding of attachments that do not contribute to the structure integrity may be welded using welding procedures qualified in accordance with Clause 3.

A4.5 Welding and Submission of Ballistic Test Plates.

Prior to fabricating a structure with ballistic requirements the Contractor shall fabricate a ballistic test plate that meets the requirements of this annex.

A4.5.1 Data Submission. The forms illustrated in Figures A6 through A8 are required for use to record data for ballistic qualification test plate submission. All of the data required by the forms shall be submitted with the test plates. The completed forms shall be submitted to the contract approved test agency. Additional information provided shall include the contract number, a description of the structure weldments, and the date submitted. The ballistic test plate and the forms listed below shall be forwarded to the contract approved test agency.

- (1) Figure A.6—Welded Armor Data (Sheet 1)
- (2) Figure A.7—Armor Plate Data (Sheet 2)
- (3) Figure A.8—Weld Radiographic Report (Sheet 3)

A4.5.2 Ballistic Testing Requirements

A4.5.2.1 Test Plate Dimensions. The test plate shall be constructed to the form and minimum dimensions shown in Figure A.2. The thickness of the ballistic test plate relative to the joint thickness of the plate shall be as shown in Table A.1.

A4.5.2.2 Number of Test Plates. One test specimen representing each thickness range and WPS to be welded in production as identified in Table A.1 shall be prepared and tested. If Class 4, MIL-DTL-46077 is used, a separate WPS is necessary using that particular declared alloy composition.

A4.5.2.3 Fabrication of Test Plates. The test plate joint configuration shall conform to that detailed in the approved welding procedure specification (WPS) to be used to fabricate the ballistic test plate. Examples of typical weld preparations are given in Figures A.3 and A.4.

(1) *Preparation of the Ballistic Test Plate.* Each ballistic test plate shall be welded in accordance with the Contractor's WPS.

(2) *Identification Marking of Test Plates.* Each ballistic test plate shall be marked clearly for easy identification on the front surface of the plate. Marking shall be in letters not less than 1 in [25 mm] high and shall include the number of the plate, the Contractor's name, and a designation showing the front of the plate. The number of the plate and the Contractor's name shall also be stamped into the metal or painted in the upper right corner. All markings shall be fully legible. Painted markings shall not be obliterated in normal handling. The front of the ballistic plate shall be designated as the exterior surface of the represented structure.

(3) *Marking of Retest Plates.* When two ballistic test plates are submitted for retest (see A4.5.7), both shall be marked with the number of the original rejected plate as well as the new numbers with the suffix "R" indicating retest.

A4.5.2.4 Ballistic Test Acceptance. The ballistic test plates shall meet the weld cracking requirements of Table A.1 and Figure A.5 after being subjected to ballistic shock. In borderline cases, where crack length measured by visual observation is close to the maximum allowable, the area in the vicinity of the crack ends shall be inspected with liquid dye penetrant in accordance with Clause 5 to assure an accurate determination of the crack length.

A4.5.2.5 Test Method. The ballistic test plates shall be supported rigidly along the two vertical sides parallel to the weld, with the weld vertical and subjected to ballistic shock in accordance with Table A.1. The test fixture shall have a horizontal rigid base made of concrete or steel. Two steel uprights spaced 28 in to 32 in [710 mm to 810 mm] apart shall be used to clamp the test plate in position.

A4.5.2.6 Test Decision on Additional Impacts. When a test plate is declared a "no test" [see A4.5.2.8(3)] after first impact, and the condition of the plate will permit additional impacts, the plate shall be evaluated on the results of the first additional impact meeting the requirements for velocity and location in accordance with the following criteria:

(1) When cracking exceeds that allowed by Table A.1 and Figure A.5, the qualification decision shall be considered "failure."

(2) When cracking does not exceed that allowed by the specification, the qualification decision shall be "satisfactory."

A4.5.2.7 Location of Impact

(1) *The Initial Impact of the 57 mm PP M1001 or the 57 mm PP M1001.* A plate proofing projectile must contact the weld to be considered meeting the ballistic test requirements. Contact of the weld by any part of the projectile that spreads after initial impact does not meet the test requirements.

(2) *Unacceptable and Acceptable Impacts.* Impacts less than 6 in [150 mm] from the top or bottom edge of the plate that cause cracking beyond the limits of Table A.1 shall be considered as failing to meet the test requirements and declared a “no test.” If, however, the cracking meets the requirements of Table A.1 and A4.5.2.7(1), the impact shall be considered acceptable.

A4.5.2.8 Evaluation of Test Results. The test plates shall not exceed the limitations for maximum allowable weld cracking as specified in Table A.1 and Figure A.5 and are subject to the interpretations in (1), (2), and (3) below.

(1) *Parallel Cracks.* Cracks in the armor parallel to the weld and within 1/8 in [3 mm] of the weld toe shall be considered as part of the total weld cracking area.

(2) *Cracks Outside the Acceptable Limits for Impacts.* Any length of weld cracking revealed as a result of an impact which does not conform with A4.5.2.6(1); and is not linked to cracking originating in the initial impact; but is otherwise acceptable per A4.5.2.6(2); shall be cause for rejection of the WPS.

(3) *Conditions for a “No Test” Decision.* When test conditions are such that the level of performance of welding procedure represented by the plate cannot be determined, a “no test” decision shall be rendered. The conditions for this decision are as follows:

(a) The point of impact of the projectile is not located within the distance limits specified in A4.5.2.7(1), and cracking does not exceed the limits specified in Table A.1 and Figure A.5.

(b) The striking velocity of the projectile is above the maximum allowed and excessive cracking occurs.

(c) The striking velocity of the projectile is below the minimum allowed and excessive cracking does not occur.

(d) The location of the center of impact of the projectile is less than 6 in [150 mm] from the top or bottom edge of the plate and excessive cracking occurs.

(e) Excessive cracking occurs from an impact subsequent to the first impact when more than one is required.

(f) Cracks in the plate occur which are greater than 6 in [150 mm] and do not pass through the center of impact.

(g) Cracking of the plate occurs outside a circle of 6 in [150 mm] radius, the center of which is the center of impact, and excessive weld cracking has not occurred. In this event, the cracked plate shall be subjected to a ballistic limit test in accordance with the applicable material specification. If the plate passes the ballistic limit requirements, the WPS is acceptable; otherwise (ballistic limit failure) a “no test” decision shall be rendered.

A4.5.3 Visual Examination of Test Plates. The ballistic test plate weld shall be visually inspected in accordance with Table 5.1 before shipment to the designated test agency.

A4.5.4 Radiographic Inspection of the Test Plate. Prior to the ballistic shock test, the Contractor shall radiographically inspect the test plate weld. Welds shall be inspected for conformance to Class C, Clause 5. Initially, with the direction of radiation parallel to the weld interface, then normal to the weld face, and finally parallel to the opposite weld interface. Radiographs may be subject to review by the test agency that may perform additional radiographic inspections. Should the test plate fail radiographic inspection, the ballistic shock test shall not be performed until after the defective weld area(s) has (have) been repaired and inspected by the Contractor.

A4.5.5 Repair of Test Plate. Weld repair on a test plate shall not exceed a total length of 8 in. The same area shall not be repaired more than twice. The cause(s) for, extent of, and location of repairs and subsequent inspection shall be reported to the Engineer in writing.

A4.5.6 Rejection of Ballistic Test Plate. Failure of any ballistic test plate to pass the visual inspection, the radiographic inspection (subsequent to repair attempts), or the ballistic test at the test agency shall be cause for rejection of the WPS.

A4.5.7 Retests. Retests may be made. Two additional test plates shall be made using the initial WPS and marked in accordance with A4.5.2.3(3), “Marking of Retest Plates,” and submitted to the test agency for retest. Failure of either of these plates shall be cause for denial of ballistic approval.

A4.6 Inspection of Production Weldments. Inspection of production armor weldments shall be in accordance with 5.8.4, 5.9.4, 5.12.2, and 5.14.1. Any deviations from this that are applicable to a specific weapon system shall be agreed with the Engineer.

A4.6.1 Visual Examination. Visual examination of production ballistic weldments shall be in accordance with Clause 5, Class C.

A4.6.2 Radiographic Examination

A4.6.2.1 First Production Weldment. The first weldment in production shall be radiographed attaining 100% coverage of all welds indicated on the radiographic inspection procedure. If rejectable indications are found, then these areas shall be radiographed on subsequent production weld joints until no rejectable indications are found.

A4.6.2.2 Production Sampling. The second and subsequent production weldments shall be sample inspected by radiography in accordance with the following subclauses:

(1) *Selection of Joints for Radiography.* Radiography shall be performed on specific joints, for the complete or partial length, and with a frequency and extent to be indicated by the drawings or contract documents. Thus production sampling will not require radiography of all joints in a single weldment.

(2) *Rejectable Joints.* When radiographic sampling of a weldment indicates a defect, the remainder of the weld shall be radiographed. All defects found shall be repaired and those repaired areas subsequently radiographed. The repaired areas shall conform to the radiographic standard established for the weld.

(3) *Corresponding Welds.* On the next weldment designated for production sampling, the position(s) found rejectable in A4.6.2.2(2), will require radiographic inspection in addition to the other position(s) selected for radiography. Should a defect be found, the remainder of the weld shall be radiographed. All defects then found in the weld shall be repaired, and the repaired areas subsequently radiographed. The repaired areas shall conform to the radiographic standard established for the particular weld.

(4) *Checking of Consecutive Weldments.* When the radiographs required by A4.6.2.2(3) indicate a defect, then the corresponding weld on the next weldment (in production) shall be completely radiographed. If no defects are found, then production sampling shall be resumed. If defects are found, then complete radiography of the corresponding weld shall be continued with each consecutive weldment produced until a weld with no defects is obtained. All defects in all rejectable welds shall be repaired. Radiographs of the repaired areas shall conform to the radiographic standard established for the particular weld.

A4.6.2.3 Alternative Sampling Plan. In lieu of the examination requirements specified in A4.6.2.2, the Contractor may utilize an alternative sampling method that is process focused. This sampling plan can only be utilized when adequate process controls are in place. If this alternate method is invoked, then it cannot be withdrawn.

(1) Selection of Production Sampling

(a) The sampling coverage required shall be determined by the pool of titanium weldments scheduled for production at a facility on a monthly basis.

(b) Sampling shall be performed on a rotational basis, so that all weld joint types are examined before repeating examination of a weld joint type.

(c) Areas to be sampled shall be selected by the Contractor and approved by the Engineer.

(2) Radiographic Testing Frequency (see Table A.2)

(a) *Low Production.* When production levels are less than 15 structures or assemblies per month, a minimum of 5 positions will be radiographed per month.

(b) *Medium Production.* When production levels range between 15 and 20 structures or assemblies per month, a minimum of 10 positions will be radiographed per month.

(c) *High Production.* When production levels exceed 20 structures or assemblies per month, a minimum of 15 positions will be radiographed per month.

(d) *Alternate Testing Frequency.* An alternative testing frequency, using other statistical methods of selection may be used if agreed between the Contractor and the Engineer. This sampling may increase or decrease the frequency of radiographic testing, depending on type, number and severity of discontinuities disclosed; or alternately, reduced frequency based on reduction in discontinuities.

A4.6.3 Alternative Testing Methods. An alternative testing method may be used for ballistic welds when agreed by the Engineer and the Contractor. When ultrasonic testing is used, reference shall be made to the contract documents for acceptance criteria. If penetrant testing is used, the acceptance criteria shall be determined by agreement between the Contractor and the Engineer.

A4.6.4 Marking of Repairs to Weldments. All repairs to weldments shall be indicated on the weldments by suitable markings, easily legible and of such nature that the marking shall not be obliterated in handling.

Table A.1
Thickness of Test Plates and Requirements for Ballistic Tests
(see A4.5.2.1, A4.5.2.2, A4.5.2.4, A4.5.2.5, A4.5.2.6, A4.5.2.7, and A4.5.2.8)

Maximum or Minimum "T" Thickness of Plate in Joint, in [mm]	Thickness of Test Plate, in [mm] ^{a, b}	Test Plate Ballistic Joint Type	Projectile	Striking Velocity, ^c f/s + 25 f/s [m/s + 7.6 m/s]	Maximum Allowable Weld Cracking, ^d in [mm]
$1/4 \leq T \leq 1/2$ [6 ≤ T ≤ 12]	3/8 [10]	Figure A.3	57 Aluminum	840 [256]	12 [300]
$1/2 < T$ [12 < T]	1 [25]	Figure A.4	57 Steel	870 [265]	12 [300]

^a For forged and rolled armor, the material thickness specification shall be applied.

^b Before welding, forged or rolled plates 18 in × 48 in [450 mm × 1220 mm] shall have a maximum out-of-flatness tolerance of 1/16 in [1.6 mm] in any direction. Completed test plates shall have a maximum out-of-flatness tolerance of 1/4 in [6 mm] in any direction.

^c If the actual plate thickness is more than the nominal thickness, the test striking velocity shall be increased. If the actual plate thickness is less than the nominal thickness, the test striking velocity shall be decreased. The correction factor shall be 25 f/s velocity for each 0.01 in deviation in plate thickness.

^d Typical crack situations are illustrated in Figure A.5.

Table A.2
Radiographic Sampling Requirements [see A4.6.2.3(2)]

Acceptance Rate	Radiographic Testing Requirement
When the acceptance rate of a structure radiographed equals or exceeds 98%.	Radiography is conducted on 1 structure per month
When the acceptance rate of a structure radiographed equals or exceeds 95% but is less than 98%.	(1) Radiography is conducted on 1 structure per month. (2) Corrective action is required. Production work on the next structure available is reviewed in each area defective. A corrective action shall be developed which will include determination of assignable cause and may include welding of validation plates as necessary.
When the acceptance rate of a structure radiographed is less than 95%.	(1) Corrective action is required. Production work on the next structure available is reviewed in each area defective. The contractor will develop corrective action which will include determination of assignable cause, and may include welding of validation plates as necessary. (2) The following month: (a) Sampling radiography is performed on the structure scheduled for testing that month. (b) Radiography is performed on the structure type which had 95% or less acceptance rate (full sample).

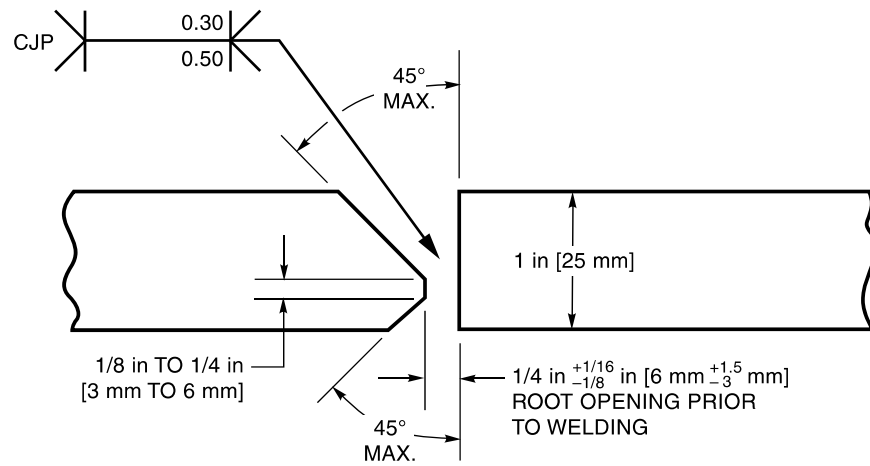
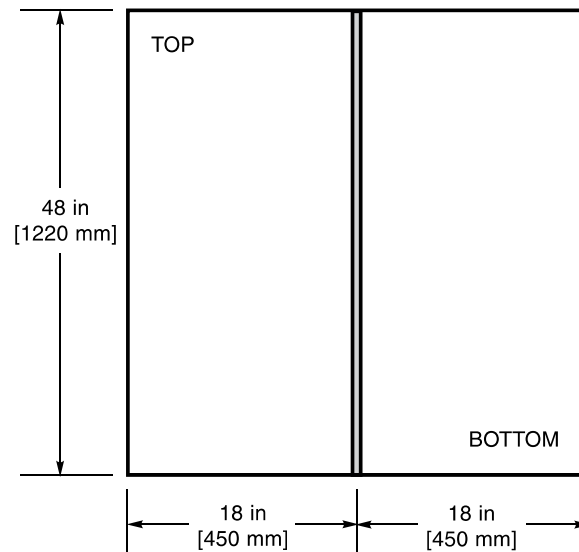


Figure A.1—Specimen for Armor Welder Qualification (see A4.3.1)



NOTE: Dimensions are in inches and test plate is of minimum size. Top and bottom of the front surface shall be identified for testing purposes. The marking shall be clearly identified and legible for photographic purposes

Figure A.2—Ballistic Test Plate (see A4.5.2.1)

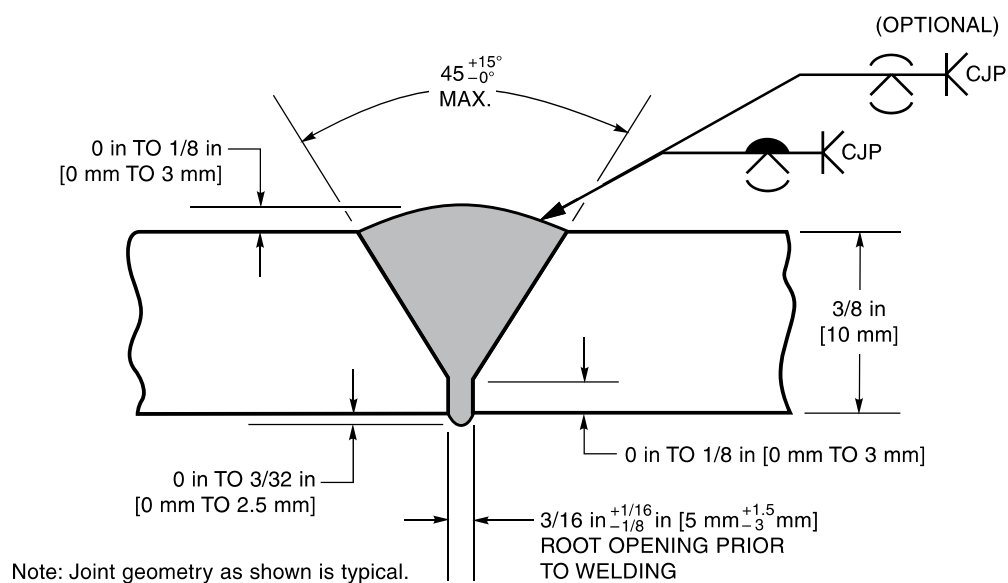


Figure A.3—Single Groove Welds (see A4.5.2.3 and Table A.1)

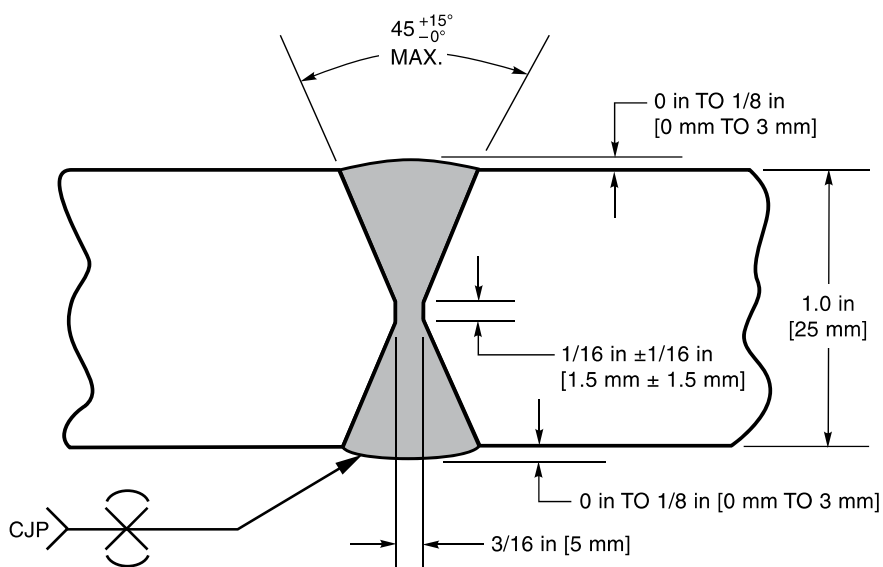
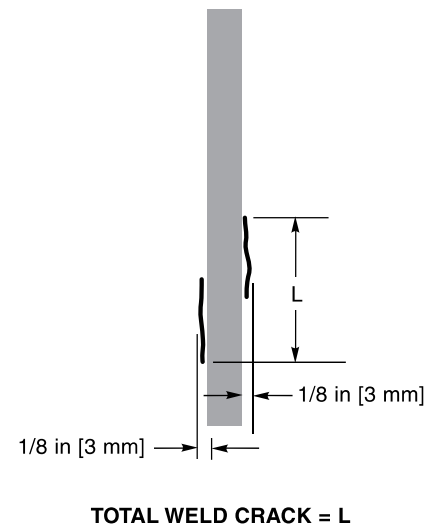
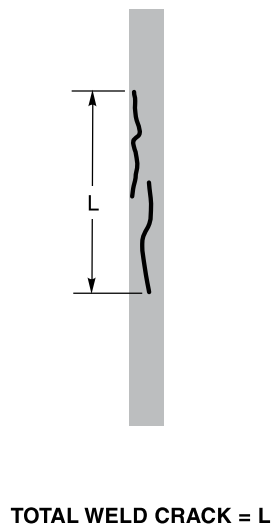
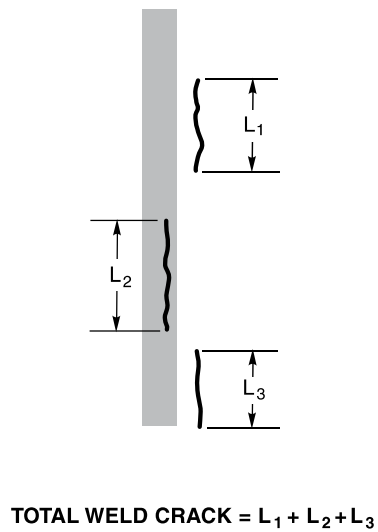
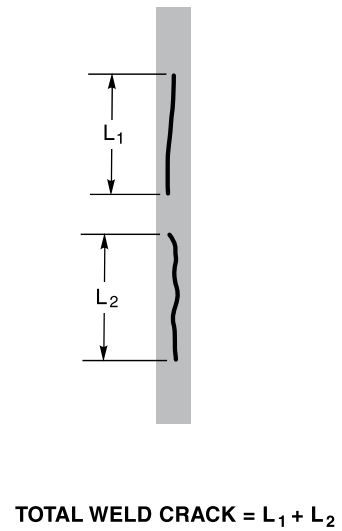
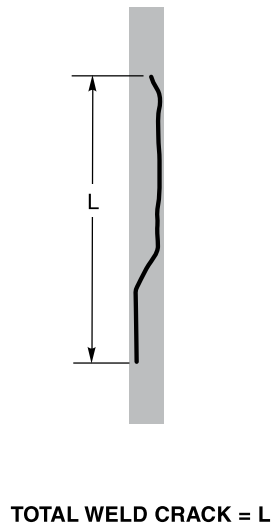
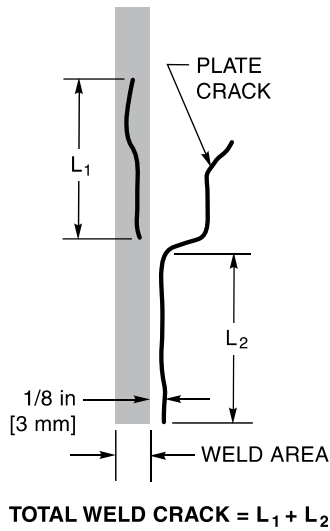


Figure A.4—Double Groove Weld (see A4.5.2.3 and Table A.1)



Note: All dimensions are typical.

Figure A.5—Examples of Weld Cracks That Can Occur from Projectile Impact and Indication of Measurement of Total Weld Crack for Acceptance Purposes (see A4.5.2.4, A4.5.2.6, A4.5.2.8, and Table A.1)

TITANIUM ARMOR WELDING DATA SHEET #1						Report Number				
WELDED ARMOR DATA						Sheet Number of				
SUBMITTED BY										
PLATE NUMBER										
DATE										
WPS NUMBER										
PLATE THICKNESS										
SPECIFICATION						AWS D1.9				
WELDED BY										
CONTRACT NUMBER										
On a dimension sketch of the groove and weldment, indicate (1) the included angle; (2) the root opening; (3) the root face; (4) the bead sequence; (5) additional sketch of spacer strip or back-up, if any; (6) width of masking, if any on edges of cast plate; and (7) average height of weld reinforcement.										
Weld reinforcement has ☐ has not ☐ been removed.										
WELDING DATA										
PLATE PREPARATION										
POSITION OF WELDING: FLAT – HORIZONTAL – VERTICAL – OVERHEAD										
WELDING PROCESS						POLARITY: DCEN – DCEP – PULSE				
PREHEAT (°F)						POSTHEAT (°F)				
PEENING						AUTOMATIC SEMIAUTOMATIC MANUAL				
PASS NO.	PROCESS	ELECTRODE		PASS TYPE ¹	AVG AMPS	AVG. VOLTS	TRAVEL SPEED	WFS IPM	TEMPERATURE	
		SIZE	TYPE						PRE	INT
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
1. S = STRINGER PASS W = WEAVE PASS										

Figure A.6—Welded Armor Data (Sheet 1) (see A4.5.1)

TITANIUM ARMOR WELDING DATA SHEET #2										Report Number	
ARMOR PLATE DATA										Sheet Number of	
TEST PLATE NUMBER											
				PLATE "A"				PLATE "B"			
MANUFACTURER											
TYPE											
THICKNESS											
HEAT											
LOT											
MELT PROCESS				PAM EBM VAM VAR				PAM EBM VAM VAR			
CHEMICAL COMPOSITION											
		Al	V	C	O	N	H	Fe	Ti		
PLATE "A"											
PLATE "B"											
HEAT TREATMENT DATA											
HEAT TREATED BY											
ELECTRODE OR FILLER METAL DATA											
TABLE 1											
SIZE	MANUFACTURER			TRADE NAME			TYPE			CLASS	
TABLE 2											
MANUFACTURER TRADE NAME AND SIZE		CHEMICAL ANALYSIS									
			Al	V	C	O	N	H	Fe	Ti	Coating
		WELD METAL									
		WELD METAL									
		WELD METAL									
		WELD METAL									
REMARKS											
FABRICATOR REPRESENTATIVE						RESIDENCE INSPECTOR OF ORDNANCE					

Figure A.7—Armor Plate Data (Sheet 2) (see A4.5.1)

TITANIUM ARMOR WELDING DATA SHEET #3				Report Number	
WELD RADIOGRAPHIC REPORT				Sheet Number of	
X-RAY SERIAL NUMBER					
PLATE SUBMITTED BY			PLATE NUMBER		SPECIFICATION
RADIOGRAPHED BY					DATE
PLATE THICKNESS	KV	MA			TIME
FOCAL DISTANCE		TYPE OF FILM		SCREEN OR FILTERS	
SHOCK TEST PLATE					
Show Locations of Radiographs and Results of Tests					
<input style="width: 50px; height: 20px;" type="checkbox"/> CRACK		<input style="width: 50px; height: 20px;" type="checkbox"/> INCOMPLETE FUSION		<input style="width: 50px; height: 20px;" type="checkbox"/> INCOMPLETE PENETRATION	
<input style="width: 50px; height: 20px;" type="checkbox"/> POROSITY AND SLAG INCLUSIONS		<input style="width: 30px; height: 20px;" type="checkbox"/> UNDERCUTTING			
RESULTS					
REVIEWED BY					

Figure A.8—Weld Radiographic Report (Sheet 3) (see A4.5.1)

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Annex B (Normative)

Reference Documents

This annex is part of AWS D1.9/D1.9M:2007-ADD1, *Structural Welding Code—Titanium*, and includes mandatory elements for use with this standard.

AWS Standards¹

1. ANSI Z49.1:2005, *Safety in Welding, Cutting, and Allied Processes*
2. AWS A2.4-98, *Standard Symbols For Welding, Brazing, and Nondestructive Examination*
3. AWS A3.0:2001, *Standard Welding Terms and Definitions*
4. AWS A5.12/A5.12M-98, *Specification for Tungsten and Tungsten Alloy Electrodes for Arc Welding and Cutting*
5. AWS A5.16/A5.16M:2004, *Specification for Titanium and Titanium Alloy Welding Electrodes and Rods*
6. AWS A5.32/A5.32M-97, *Specification for Welding Shielding Gases*
7. AWS B1.11:2000, *Guide for the Visual Inspection of Welds*
8. AWS B2.1:2005, *Specification for Welding Procedure and Performance Qualification*
9. AWS B4.0-98, *Standard Methods for Mechanical Testing of Welds, U.S. Customary Only*
10. AWS B4.0M:2000, *Standard Methods for Mechanical Testing of Welds, Metric Only*

¹ANSI Z49.1 and AWS standards are published by the American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

11. AWS QC1:2006, *Standard for AWS Certification of Welding Inspectors*

ASTM Standards²

1. ASTM E 8-04, *Standard Test Methods for Tension Testing of Metallic Materials*
2. ASTM E 94-04, *Standard Guide for Radiographic Examination*
3. ASTM E 114-95(2005), *Standard Practice for Ultrasonic Pulse-Echo Straight-Beam Examination by the Contact Method*
4. ASTM E 165-02, *Standard Test Method for Liquid Penetrant Examination*
5. ASTM E 390-01(2006), *Standard Reference Radiographs for Steel Fusion Welds*
6. ASTM E 587-00(2005), *Standard Practice for Ultrasonic Angle-Beam Examination by the Contact Method*
7. ASTM E 747-04, *Standard Practice for Design, Manufacture and Material Grouping Classification of Wire Image Quality Indicators (IQI) Used for Radiology*
8. ASTM E 1025-05, *Standard Practice for Design, Manufacture, and Material Grouping Classification*

²ASTM standards are published by the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

of Hole-Type Image Quality Indicators (IQI) Used for Radiology

9. ASTM E 1409-05, *Standard Test Method for Determination of Oxygen and Nitrogen in Titanium and Titanium Alloys by the Inert Gas Fusion Technique*
10. ASTM E 1417-05, *Standard Practice for Liquid Penetrant Testing*
11. ASTM E 1447-05, *Standard Test Method for Determination of Hydrogen in Titanium and Titanium Alloys by the Inert Gas Fusion Thermal Conductivity/Infrared Detection Method*
12. ASTM E 1742-05, *Standard Practice for Radiographic Examination*

CSA Standards³

1. Canadian Standard Association (CSA) Standard W178.2-01, *Certification of Welding Inspectors*

³CSA standards are published by the Canadian Standards Association, 178 Rexdale Boulevard, Toronto, Ontario, Canada, M9W 1R3.

MIL Standards⁴

1. MIL-DTL-46077, Rev. F, *Armor Plate, Titanium, Weldable*

SAE Standards⁵

1. SAE AMS 4954, Rev. G, *Titanium Alloy, Welding Wire, 6Al-4V*
2. SAE AMS 4956, Rev. D, *Titanium Alloy Welding Wire, 6Al-4V, Extra Low Interstitial Environment Controlled Packaging*
3. SAE AMS-T-9046, Rev. B, *Titanium Alloy, Sheet, Strip and Plate (Grade AB-1 Condition A)*
4. SAE AMS-9047, Rev. A, *Titanium and Titanium Bars (rolled or forged) and Reforging Stock, Aircraft Quality*

⁴MIL standards are published by the U.S. Department of Defense.

⁵SAE standards are published by SAE World Headquarters 400 Commonwealth Drive, Warrendale, PA 15096-0001.

Annex C

There is no Annex C. Annex C has been omitted in order to avoid potential confusion with references to Commentary clauses.

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Annex D (Informative)

Safe Practices

This annex is not part of AWS D1.9/D1.9M:2007-ADD1, *Structural Welding Code—Titanium*, but is included for informational purposes only.

D1. Electrical Hazards

Electric shock can kill. However, it can be avoided. Live electrical parts should not be touched. Read and understand the manufacturer's instructions and recommended safe practices. Faulty installation, improper grounding, and incorrect operation and maintenance of electrical equipment are all sources of danger. All electrical equipment and the workpiece should be grounded. A separate connection is required to ground the workpiece. The work lead should not be mistaken for ground connection. To prevent shock, the work area, equipment, and clothing should be kept dry at all times. Dry gloves and rubber soled footwear should be worn. The welder should stand on a dry board or insulated platform. Cables and connectors should be kept in good condition. Worn, damaged, or bare cables should not be used. In case of electric shock, the power should be turned off immediately. If the rescuer must resort to pulling the victim from the live contact, nonconducting materials should be used. A physician should be called and CPR continued until breathing has been restored, or until a physician has arrived (see References 8, 7, and 10).

D2. Fumes and Gases

Many welding, cutting, and allied processes produce fumes and gases which may be harmful to one's health. Fumes and solid particles originate from welding consumables, the base metal, and any coatings present on the base metal. Gases are produced during the welding process or may be produced by the effects of process radia-

tion on the surrounding environment. Everyone associated with the welding operation should acquaint themselves with the effects of these fumes and gases. The possible effects of overexposure to fumes and gases range from irritation of eyes, skin, and respiratory system to more severe complications. Effects may occur immediately or at some later time. Fumes can cause symptoms such as nausea, headaches, dizziness, and metal fume fever. Sufficient ventilation, exhaust at the arc, or both, should be used to keep fumes and gases from breathing zones and the general work area. For more detailed information on fumes and gases produced by the various welding processes, see References 1, 4, and 11.

D3. Noise

Excessive noise is a known health hazard. Exposure to excessive noise can cause a loss of hearing. This loss of hearing can be either full or partial, and temporary or permanent. Excessive noise adversely affects hearing capability. In addition, there is evidence that excessive noise affects other bodily functions and behavior. Personal protective devices such as ear muffs or ear plugs may be employed. Generally, these devices are only accepted when engineering controls are not fully effective (see References 5 and 11).

D4. Burn Protection

Molten metal, sparks, slag, and hot work surfaces are produced by welding, cutting, and allied processes.

These can cause burns if precautionary measures are not used. Workers should wear protective clothing made of fire-resistant material. Pant cuffs or clothing with open pockets or other places on clothing that can catch and retain molten metal or sparks should not be worn. High-top shoes or leather leggings and fire-resistant gloves should be worn. Pant legs should be worn over the outside of high-top boots. Helmets or hand shields that provide protection for the face, neck, and ears, should be worn, as well as a head covering to protect the head. Clothing should be kept free of grease and oil. Combustible materials should not be carried in pockets. If any combustible substance is spilled on clothing, it should be replaced with clean fire resistant clothing before working with open arcs or flame. Appropriate eye protection should be used at all times. Goggles or equivalent also should be worn to give added eye protection. Insulated gloves should be worn at all times when in contact with hot items or handling electrical equipment. For more detailed information on personal protection References 2, 3, 8, and 11 should be consulted.

D5. Fire Prevention

Molten metal, sparks, slag, and hot work surfaces are produced by welding, cutting, and allied processes. These can cause fire or explosion if precautionary measures are not used. Titanium can spontaneously combust when finely divided. Titanium fires require special fire fighting controls and powders in extinguishers. Explosions have occurred where welding or cutting has been performed in spaces containing flammable gases, vapors, liquid, or dust. All combustible material should be removed from the work area. Where possible, move the work to a location well away from combustible materials. If neither action is possible, combustibles should be protected with a cover of fire resistant material. All combustible materials should be removed or safely protected within a radius of 35 ft [11 m] around the work area. Welding or cutting should not be done in atmospheres containing dangerously reactive or flammable gases, vapors, liquid, or dust. Heat should not be applied to a container that has held an unknown substance or a combustible material whose contents when heated can produce flammable or explosive vapors. Adequate ventilation should be provided in work areas to prevent accumulation of flammable gases, vapors or dusts. Containers should be cleaned and purged before applying heat. For more detailed information on fire hazards from welding and cutting operations, see References 6, 8, 9, and 11.

D6. Radiation

Welding, cutting, and allied operations may produce radiant energy (radiation) harmful to health. Everyone should acquaint themselves with the effects of this radiant energy. Radiant energy may be ionizing (such as X-rays) or nonionizing (such as ultraviolet, visible light, or infrared). Radiation can produce a variety of effects such as skin burns and eye damage, if excessive exposure occurs. Some processes such as resistance welding and cold pressure welding ordinarily produce negligible quantities of radiant energy. However, most arc welding and cutting processes (except submerged arc when used properly), laser welding and torch welding, cutting, brazing, or soldering can produce quantities of nonionizing radiation such that precautionary measures are necessary. Protection from possible harmful radiation effects include the following:

(1) Welding arcs should not be viewed except through welding filter plates (see Reference 2). Transparent welding curtains are not intended as welding filter plates, but rather, are intended to protect passersby from incidental exposure.

(2) Exposed skin should be protected with adequate gloves and clothing as specified (see Reference 8).

(3) The casual passerby to welding operations should be protected by the use of screens, curtains, or adequate distance from aisles, walkways, etc.

(4) Safety glasses with ultraviolet protective side shields have been shown to provide some beneficial protection from ultraviolet radiation produced by welding arcs.

D7. References Cited

1. American Conference of Governmental Industry Hygienists (ACGIH). Threshold limit values for chemical substances and physical agents in the workroom environment. Cincinnati, Ohio: American Conference of Governmental Industry Hygienists (ACGIH).
2. American National Standards Institute. Practice for occupational and educational eye and face protection, ANSI Z87.1. New York: American National Standards Institute.
3. American National Standards Institute. Personal Protection—Protective Footwear, ANSI Z41.1. New York: American National Standards Institute.

4. American Welding Society. Fumes and gases in the welding environment, AWS report. Miami, Florida: American Welding Society.
5. American Welding Society. Method for sound level measurement of manual arc welding and cutting processes, AWS F6.1. Miami, Florida: American Welding Society.
6. American Welding Society. Recommended safe practices for the preparation for welding and cutting containers and piping, AWS F4.1. Miami, Florida: American Welding Society.
7. American Welding Society. Safe Practices. (Reprint from Welding Handbook, Volume 1, Eighth Edition) Miami, Florida: American Welding Society.
8. American Welding Society. Safety in welding, cutting, and allied processes. ANSI Z49.1. Miami, Florida: American Welding Society.
9. National Fire Protection Association. Fire prevention in use of cutting and welding processes, NFPA Standard 51B. Quincy, Massachusetts: National Fire Protection Association.
10. National electrical code. NFPA No. 70. Quincy, Massachusetts: National Fire Protection Association.
11. Occupational Safety and Health Administration. Code of Federal Regulations, Title 29 Subtitle B, Chapter XVII, Part 1910; Occupational Safety and Health Standards. Washington, DC: U.S. Government Printing.

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Annex E (Informative)

Sample Welding Forms

This annex is not part of AWS D1.9/D1.9M:2007-ADD1, *Structural Welding Code—Titanium*, but is included for informational purposes only.

E1. General

This annex contains five forms that the Structural Welding Committee has approved for the recording of data required by this code. These are WPS qualification (Form E-1), procedure qualification record (PQR) (Form E-2), welder qualification, welding operator qualification, and tack welder qualification (Form E-3), report of radiographic examination of welds (Form E-4), and report of penetrant examination of welds (Form E-5).

It is recommended that the qualification and NDT information required by this code be recorded on these forms or similar forms which have been prepared by the user. Variations of these forms to suit the user's needs are allowable.

E2. Use of WPS Forms E-1

The Form E-1 may be used to record information for either a WPS or a PQR. The user should indicate their selected application in the appropriate boxes or the user may choose to blank out the inappropriate headings.

The WPSs and PQRs are to be signed by the authorized representative of the Fabricator or Contractor.

For joint details on the WPS, a sketch or a reference to the applicable joint detail may be used. A Form E-1 has been completed and included as an example for guidance purposes only.

E3. Qualified by Testing

The WPS may be qualified by testing in conformance with the provisions of Clause 3. In this case, a supporting PQR is required in addition to the WPS. For the PQR, Form E-1 can again be used with an appropriate heading change. Also, the Form E-2, may be used to record the test results and the certifying statement.

For the WPS, state the allowed ranges qualified by testing or state the appropriate tolerances on essential variable (e.g., 250 amps $\pm 10\%$).

For the PQR, the actual joint details and the values of essential variables used in the testing should be recorded. A copy of the Mill Test Report for the material tested should be attached. Also, Testing Laboratory Data Reports may also be included as backup information.

The inclusion of items not required by the code is optional; however, they may be of use in setting up equipment, or understanding test results.

WELDING PROCEDURE SPECIFICATION (WPS) Yes ☐
QUALIFIED BY TESTING _____
or PROCEDURE QUALIFICATION RECORDS (PQR) Yes ☐

Company Name _____
 Welding Processes _____
 Supporting PQR No.(s) _____

TYPE OF WELDING

Manual ☐ Machine ☐
 Semiautomatic ☐ Automatic ☐

JOINT DESIGN USED

Type _____

Single ☐ Double Weld ☐Backing Yes ☐ No ☐

Type _____

Root Opening _____ Root Face Dimensions _____

Groove Angle _____ Radius (J or U) _____

Back Grinding Yes ☐ No ☐ Method _____

Dimensioned Test Assembly Sketch (see attached sketch)

BASE METALS

Material Specification _____

Base Material Identity _____

Type or Grade _____

Thickness _____ Groove _____ Fillet _____

Diameter (Pipe) _____

FILLER METALS

AWS Specification _____

AWS Classification _____

Heat and Lot Number _____

Wire Diameter _____

SHIELDING

Primary Torch Gas _____

Composition _____ Flow Rate _____

Cup Size (Orifice Size Plasma) _____

Secondary Torch Gas (Plasma) _____

Composition _____ Flow Rate _____ Cup Size _____

Trailing Gas _____

Composition _____ Flow Rate _____

Trail Shield Size _____

Back Purge Gas _____

Composition _____ Flow Rate _____

WPS/PQR Identification No. _____

Revision _____ Date _____ By _____

Authorized by _____ Date _____

Welding Code _____ Revision _____

Welder's Name _____

Welder Identification No. _____

PREHEAT

Preheat Temp. _____

Interpass Temp., Min. _____

Interpass Temp., Max. _____

POSITION

Position of Groove _____

Position of Fillet _____

Other _____

Vertical Progression Up ☐ Down ☐ N/A ☐**ELECTRICAL CHARACTERISTICS**

Transfer Mode (GMAW) _____

Short-Circuiting ☐ Globular ☐ Spray ☐ Pulse ☐Current AC ☐ DCEP ☐ DCEN ☐ Pulsed ☐

Other _____

Tungsten Electrode (GTAW)

Size _____

Type _____

TECHNIQUE

Stringer or Weave Bead _____

Electrode/Torch Angle _____

Multipass or Single Pass (per side) _____

Number of Electrodes _____

Electrode Spacing _____

Longitudinal _____

Lateral _____

Transverse _____

Contact Tube to Work Distance (GMAW) _____

Interpass Cleaning _____

Postweld Heat Treatment

Temp. _____

Time _____

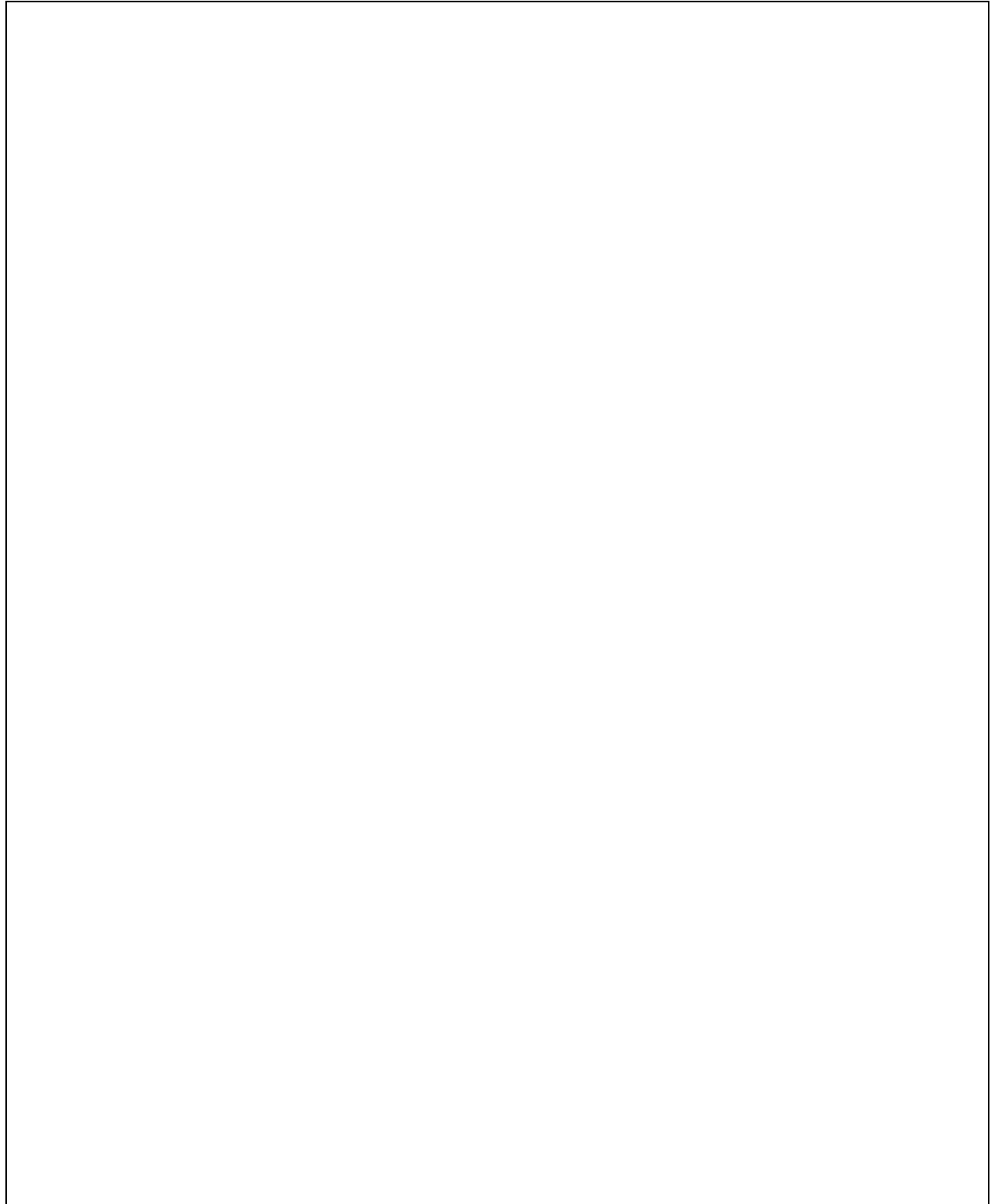
WELDING VARIABLES

Pass or Weld Layer(s)	Process	Filler Metals		Current		Volts	Travel Speed
		Class	Diameter	Type and Polarity	Amps or Wire Feed Speed		

Other information _____

WELDING PROCEDURE SPECIFICATION (WPS) Yes ☐
QUALIFIED BY TESTING _____
or PROCEDURE QUALIFICATION RECORDS (PQR) Yes ☐

DIMENSIONED TEST ASSEMBLY SKETCH



Form E-1 (Continued)

WELDING PROCEDURE SPECIFICATION (WPS) Yes ☒
QUALIFIED BY TESTING _____
or PROCEDURE QUALIFICATION RECORDS (PQR) Yes ☒

Company Name Weld it Well
 Welding Processes Gas Metal Arc Welding
 Supporting PQR No.(s) _____

TYPE OF WELDING

Manual ☐ Machine ☒
 Semiautomatic ☐ Automatic ☐

JOINT DESIGN USED

Type _____
 Single ☒ Double Weld ☐
 Backing Yes ☒ No ☐

Type _____
 Root Opening 0 in Root Face Dimensions 0 in
 Groove Angle 75° incl. Radius (J or U) N/A
 Back Grinding Yes ☐ No ☒ Method _____
 Dimensioned Test Assembly Sketch (see attached sketch)

BASE METALS

Material Specification ASTM B 265
 Base Material Identity Never lost 12
 Type or Grade Grade 5 titanium alloy (Ti6Al4V)
 Thickness Groove 3/8 in Fillet _____
 Diameter (Pipe) _____

FILLER METALS

AWS Specification AWS A5.16 grade 5
 AWS Classification ER Ti-5
 Heat and Lot Number HT98765
 Wire Diameter 0.035 in

SHIELDING

Primary Torch Gas
 Composition 100% Argon Flow Rate 20 cfh
 Cup Size (Orifice Size Plasma) 5/8 in
 Secondary Torch Gas (Plasma)
 Composition N/A Flow Rate _____ Cup Size _____
 Trailing Gas
 Composition 100% Argon Flow Rate 40 cfh
 Trail Shield Size 6 in long x 2 in wide x 1 in
 Back Purge Gas
 Composition 100% Argon Flow Rate 4 cfh

WPS/PQR Identification No. HWE 001

Revision 0 Date 7/5/05 By Argun Jones

Authorized by D Manager Date _____

Welding Code AWS D1.9 Revision 0

Welder's Name Peter McToon

Welder Identification No. 123456

PREHEAT

Preheat Temp. Ambient 70°F

Interpass Temp., Min. 180°F

Interpass Temp., Max. 300°F

POSITION

Position of Groove Flat (1G)

Position of Fillet _____

Other _____

Vertical Progression Up ☐ Down ☐ N/A ☒

ELECTRICAL CHARACTERISTICS

Transfer Mode (GMAW)

Short-Circuiting ☐ Globular ☐ Spray ☐ Pulse ☒

Current AC ☐ DCEP ☒ DCEN ☐ Pulsed ☐

Other _____

Tungsten Electrode (GTAW)

Size _____

Type _____

TECHNIQUE

Stringer or Weave Bead Stringer

Electrode/Torch Angle Vertical with 10° trail

Multipass or Single Pass (per side) Multiple

Number of Electrodes _____

Electrode Spacing _____

Longitudinal _____

Lateral _____

Transverse _____

Contact Tube to Work Distance (GMAW) 5/8 in

Interpass Cleaning None

Postweld Heat Treatment

Temp. N/A

Time _____

WELDING VARIABLES

Pass or Weld Layer(s)	Process	Filler Metals		Current		Volts	Travel Speed
		Class	Diameter	Type and Polarity	Amps or Wire Feed Speed		
1 to 5	GMAW-P	ER Ti-5	0.035 in	DC Electrode +ve	350 ipm	32	10 ipm

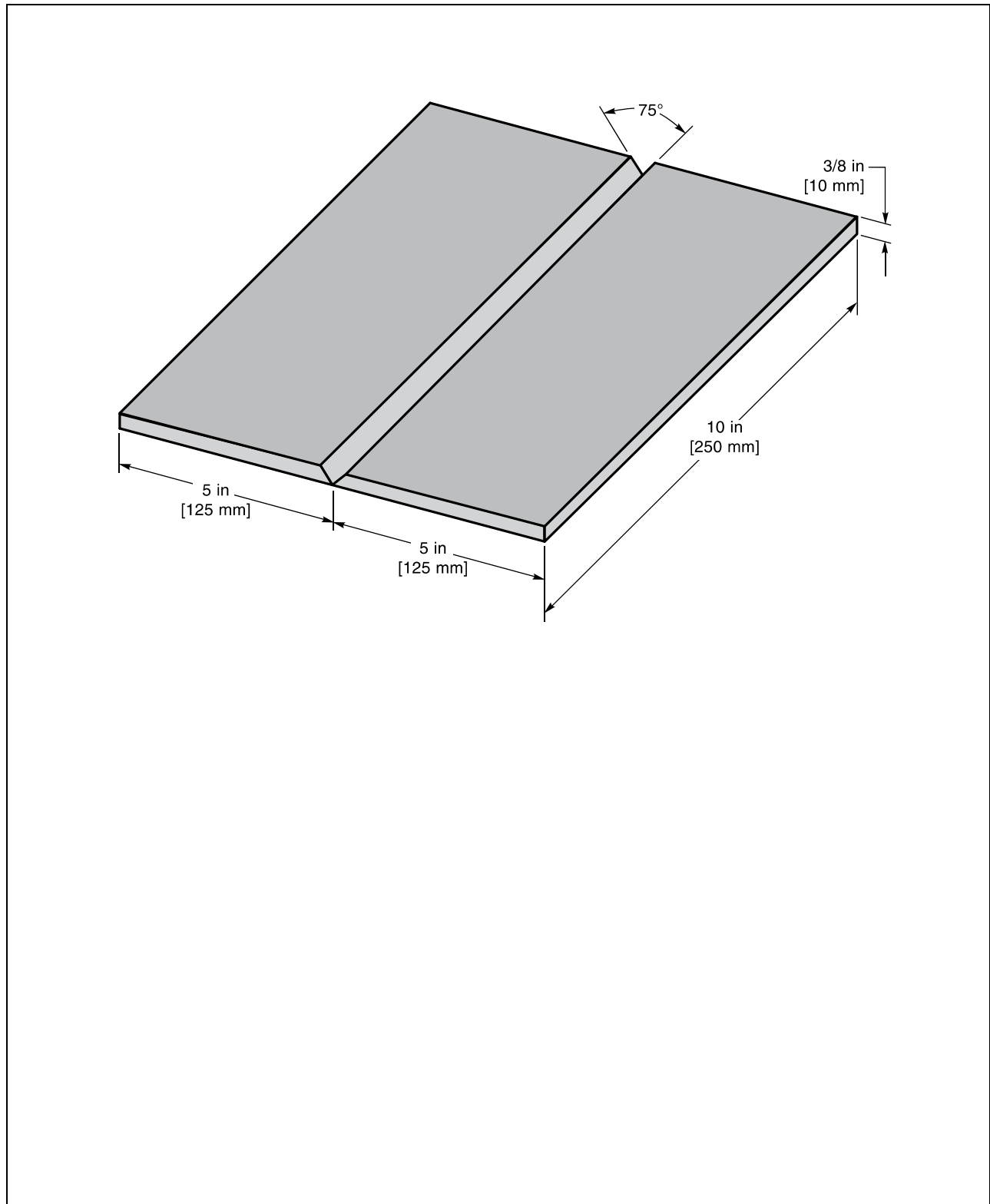
Other information Power supply: Ancient and old-fabricator unknown

Torch ACME Co Robo 2345 with 2 ft harness

Wire feeder ACME Co power feeder

WELDING PROCEDURE SPECIFICATION (WPS) Yes ☒
QUALIFIED BY TESTING _____
or PROCEDURE QUALIFICATION RECORDS (PQR) Yes ☒

DIMENSIONED TEST ASSEMBLY SKETCH



Form E-1 (Continued)

Procedure Qualification Record (PQR) # _____
Test Results

TENSILE TEST

Specimen No.	Width	Thickness	Area	Ultimate Tensile Load, lb [kg]	Ultimate Unit Stress, psi [N/mm ²]	Character of Failure and Location

BEND TEST

Specimen No.	Type of Bend	Result	Remarks

VISUAL INSPECTION

Appearance _____
 Undercut _____
 Piping Porosity _____
 Convexity _____
 Test Date _____
 Witnessed by _____

Radiographic-Ultrasonic Examination

RT Report No. _____ Result _____
 UT Report No. _____ Result _____

FILLET WELD TEST RESULTS

Minimum Size	Maximum Size
Macroetch	Macroetch
1. _____ 3. _____	1. _____ 3. _____
2. _____	2. _____

All-Weld-Metal Tension Test

Tensile Strength, psi [N/mm²] _____
 Yield Point/Strength, psi [N/mm²] _____
 Elongation in 2 in [50 mm] % _____
 Laboratory Test No. _____

Welder's Name _____

Clock No. _____ Stamp No. _____

Tests Conducted by _____ Laboratory _____

Test Number _____

Per _____

We, the undersigned, certify that the statements in this record are correct and that the test welds were produced, welded, and tested in accordance with the requirements of Clause 3 of AWS D1.9/D1.1M, (_____) *Structural Welding Code—Titanium*.
 (year)

Fabricator or Contractor _____

Authorized By _____

Date _____

Signed _____

Title _____

Form E-2

WELDER, WELDING OPERATOR, OR TACK WELDER QUALIFICATION TEST RECORD

Type of Welder _____

Name _____ Identification No. _____

Welding Procedure Specification No. _____ Rev _____ Date _____

	Record Actual Values Used in Qualification	Qualification Range
Variables		
Process Type		
Electrode Type		
Electrode (Single or Multiple)		
Current/Polarity		
Position		
Weld Progression		
Backing Yes ☐ No ☐		
Material Specification		
Base Metal		
Thickness		
Groove		
Fillet		
Thickness		
Groove		
Fillet		
Diameter (Pipe)		
Groove		
Fillet		
Filler Metal		
Specification No.		
Class		
F-No.		
Gas Type		
Other		

VISUAL INSPECTION)			
Acceptable Yes ☐ No ☐			
Bend Test Results			
Type	Result	Type	Result
Fillet Test Results			
Appearance _____		Fillet Size _____	
_____		Macroetch _____	
(Describe the location, nature, and size of any crack or tearing of the specimen.)			

 Inspected by _____ Test Number _____
 Organization _____ Date _____

RADIOGRAPHIC TEST RESULTS					
Film Identification Number	Results	Remarks	Film Identification Number	Results	Remarks

 Interpreted by _____ Test Number _____
 Organization _____ Date _____

 We, the undersigned, certify that the statements in this record are correct and that the test welds were produced, welded, and tested in accordance with the requirements of Clause 3 of AWS D1.9/D1.1M, (_____) *Structural Welding Code—Titanium*.
 (year)

Fabricator or Contractor _____ Authorized By _____

Date _____ Signed _____ Title _____

Form E-3

Project _____
 Quality Requirements—Section No. _____
 Reported to _____

Technique

Source _____
Film to Source _____
Exposure Time _____
Screens _____
Film Type _____

[illegible]

We, the undersigned, certify that the statements in this record are correct and that the test welds were produced, welded, and tested in accordance with the requirements of Clause 3 of AWS D1.9/D1.1M, () *Structural Welding Code—Titanium*.
(year)

Fabricator or Contractor _____

Authorized by _____

Title _____

Signed _____

118

REPORT OF PENETRANT EXAMINATION OF WELDS**Project** _____

Quality requirements—Section No. _____

Reported to _____

WELD LOCATION AND IDENTIFICATION SKETCH

Quantity _____ Total Accepted _____ Total Rejected _____

Date	Weld Identification	Area Examined		Interpretation		Repairs		Remarks
		Entire	Specific	Accept	Reject	Accept	Reject	

PRE-EXAMINATION

Surface Preparation _____

METHOD OF INSPECTION

- ☐ Magnifying Lens
☐ Fluorescent Penetrant
☐ Visible Dye

POST EXAMINATION

Cleaning Technique (if required) _____

We, the undersigned, certify that the statements in this record are correct and that the test welds were produced, welded, and tested in accordance with the requirements of Clause 3 of AWS D1.9/D1.1M, (_____) *Structural Welding Code—Titanium*.
(year)

Inspector _____

Fabricator or Contractor _____

Level _____

Authorized By _____

Test Date _____

Title _____

Date _____

Signed _____

Form E-5

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Annex F (Informative)

Guidelines for the Preparation of Technical Inquiries

This annex is not part of AWS D1.9/D1.9M:2007-ADD1, *Structural Welding Code—Titanium*, but is included for informational purposes only.

F1. Introduction

The American Welding Society (AWS) Board of Directors has adopted a policy whereby all official interpretations of AWS standards are handled in a formal manner. Under this policy, all interpretations are made by the committee that is responsible for the standard. Official communication concerning an interpretation is directed through the AWS staff member who works with that committee. The policy requires that all requests for an interpretation be submitted in writing. Such requests will be handled as expeditiously as possible, but due to the complexity of the work and the procedures that must be followed, some interpretations may require considerable time.

F2. Procedure

All inquiries shall be directed to:

Managing Director
Technical Services Division
American Welding Society
550 N.W. LeJeune Road
Miami, FL 33126

All inquiries shall contain the name, address, and affiliation of the inquirer, and they shall provide enough information for the committee to understand the point of concern in the inquiry. When the point is not clearly defined, the inquiry will be returned for clarification. For efficient handling, all inquiries should be typewritten and in the format specified below.

F2.1 Scope. Each inquiry shall address one single provision of the standard unless the point of the inquiry involves two or more interrelated provisions. The provision(s) shall be identified in the scope of the inquiry along with the edition of the standard that contains the provision(s) the inquirer is addressing.

F2.2 Purpose of the Inquiry. The purpose of the inquiry shall be stated in this portion of the inquiry. The purpose can be to obtain an interpretation of a standard's requirement or to request the revision of a particular provision in the standard.

F2.3 Content of the Inquiry. The inquiry should be concise, yet complete, to enable the committee to understand the point of the inquiry. Sketches should be used whenever appropriate, and all paragraphs, figures, and tables (or annex) that bear on the inquiry shall be cited. If the point of the inquiry is to obtain a revision of the standard, the inquiry shall provide technical justification for that revision.

F2.4 Proposed Reply. The inquirer should, as a proposed reply, state an interpretation of the provision that is the point of the inquiry or provide the wording for a proposed revision, if this is what the inquirer seeks.

F3. Interpretation of Provisions of the Standard

Interpretations of provisions of the standard are made by the relevant AWS technical committee. The secretary of the committee refers all inquiries to the chair of the particular subcommittee that has jurisdiction over the por-

tion of the standard addressed by the inquiry. The subcommittee reviews the inquiry and the proposed reply to determine what the response to the inquiry should be. Following the subcommittee's development of the response, the inquiry and the response are presented to the entire committee for review and approval. Upon approval by the committee, the interpretation is an official interpretation of the Society, and the secretary transmits the response to the inquirer and to the *Welding Journal* for publication.

F4. Publication of Interpretations

All official interpretations will appear in the *Welding Journal* and will be posted on the AWS web site.

F5. Telephone Inquiries

Telephone inquiries to AWS Headquarters concerning AWS standards should be limited to questions of a general nature or to matters directly related to the use of the standard. The *AWS Board Policy Manual* requires that

all AWS staff members respond to a telephone request for an official interpretation of any AWS standard with the information that such an interpretation can be obtained only through a written request. Headquarters staff cannot provide consulting services. However, the staff can refer a caller to any of those consultants whose names are on file at AWS Headquarters.

F6. AWS Technical Committees

The activities of AWS technical committees regarding interpretations are limited strictly to the interpretation of provisions of standards prepared by the committees or to consideration of revisions to existing provisions on the basis of new data or technology. Neither AWS staff nor the committees are in a position to offer interpretive or consulting services on (1) specific engineering problems, (2) requirements of standards applied to fabrications outside the scope of the document, or (3) points not specifically covered by the standard. In such cases, the inquirer should seek assistance from a competent engineer experienced in the particular field of interest.

Annex G (Informative)

Metallurgical Sample Preparation

This annex is not part of AWS D1.9/D1.9M:2007-ADD1, *Structural Welding Code—Titanium*, but is included for informational purposes only.

G1. Introduction

Figure G.1 and Figure G.2 contrast the benefits of good and bad metallographic weld sample preparation techniques. A literature review and discussions with other laboratories have shown a range of techniques in use which are summarized below for commercially pure (CP) titanium and its alloys.

For this review, techniques involving mechanical and chemical methods (as opposed to electrolytic) will be considered. Different procedures are evident between CP titanium and its alloys such as Ti-6Al-4V. CP tends to be softer and subject to the formation of deformation layers that can be difficult to remove and, if not removed, may conceal metallographic features.

G2. Sample Cutting

For cutting down to metallographic preparation size it is recommended by all sources to avoid high heat and high distortion methods such as saw blades, which will increase the sample preparation time significantly. Abrasive cutting wheels with adequate coolant are recommended, or the use of a low speed diamond saw to minimize surface deformation (see Reference 2).

G3. Mounting

It is safest to use castable (“cold”) mounting resins for pure titanium (see Reference 1) rather than hot compression mounting to avoid changing the hydride content and morphology.

G4. Cutting Procedures

Fine cutting procedures, such as the use of a low speed diamond saw, can minimize deformation layers and reduce time on silicon carbide papers. If fine cutting cannot be employed, the grinding stage can be very time consuming and laborious.

G5. Wet Grinding

The initial function and difficulty in mechanical polishing is the elimination of the deformation layer and the nonuniform etching of the polished face (see Reference 3).

All references use wet grinding on rough silicon carbide papers to start and work to a finer grit. The literature varies on what grit to work to. One recommendation is 240 grit to 320 grit then go to 9 μm Metadi Diamond Paste (see Reference 2). Other sources recommend moving to finer grits such as 1200 (see Reference 4) or even up to 4000 (see Reference 4). There is further variation in the procedure. One source recommends low pressure long times on finer grit papers (see Reference 4). Another source recommends average pressure for very short times, such as 5 s max. (see Reference 4). All techniques aim to achieve a flat surface and the removal of the cutting deformation layer.

G6. Polishing

Once “flat” is achieved and the deformation layer removed, a polishing procedure can be implemented. The polishing procedures differ greatly throughout the

literature. A number of the sources do recommend the use of some form of etchant in the polishing phase such as aqueous (cold) oxalic acid solution (see Reference 4), or various solutions of acids containing HF and HNO₃ (see Reference 3).

Each method contains two main phases of polishing a rough polish and then final.

G6.1 Rough Polish. The rough polish usually involves either felt cloth, short-nap, or a perforated napless nonwoven cloth pad with either Alumina No. 1 (see Reference 3) or 9 µm diamond paste (see Reference 2). Times vary from 30 min with the alumina to 10 min to 15 min with the diamond paste.

G6.2 Final Polish. Final stages involve a medium nap synthetic cloth using a Colloidal Polishing Suspension for 10 min to 15 min (see Reference 2), or soft synthetic velvet cloth with low nap and Alumina No. 3 with a series of intermediate etchings using a solution of 60 ml H₂O₂, 10 ml of HF, and 30 ml of H₂O (see Reference 3).

Alternate procedures that are highly commended (see Reference 1), especially for alpha alloys use an attack polishing solution (comprising 10 ml H₂O₂ (30%) and 5 ml Kroll's reagent) with the colloidal silica abrasive.

One procedure recommends working with diamond pastes down to 3 µm and then final with shock polishing using TiEP1 (see Reference 4).

G7. First Optical Examination

Once polishing is completed it should be possible to examine the unetched polished surface in plain polarized light. If the grain structure is unclear, the surface is not free of deformation (see Reference 2). The specimen should be repolished with the desired process until the grain structure becomes visible.

G8. Alternates for TiAlV Alloys

For TiAlV alloys a different procedure can be used since the material possesses some different characteristics from CP. Minimizing deformation by using low speed cutting wheels with plenty of coolant is still recommended. One procedure utilized a polishing machine, which could be programmed through weight and time to remove exact amounts of material (see Reference 5).

The process breaks down to:

- (1) Coarse grinding at 250 µm using a stone lap.

- (2) Fine grinding was performed on a diamond grinding and lapping disc using 9 µm diamond abrasive with ethanol.

- (3) Polishing is a two-step procedure.

- (4) Initial polish with a 6 µm diamond paste followed by a 3 µm paste, both on nonwoven fabric laps.

- (5) Final polish on nonwoven fabric laps was with a 0.04 µm colloidal silica abrasive for 3 min at 90 N force followed by 90 s at 65 N (see Reference 5).

G9. Etching

Etching of the specimen can be done a number of ways depending on what the examiner is interested in. First and foremost, since alpha titanium has a hexagonal crystal structure and is anisotropic, the microstructure can be examined with just polarized light, this is known as physical etching (see Reference 4).

The literature suggests a number of etchants for macro and micro purposes as detailed below:

- (1) Keller's reagent can be used for both macroetching and microetching

- (2) Kroll's (1 ml–3 ml HF, 2 ml–6 ml HNO₃ and 100 ml water) and Weck's reagents are used for microetching (see Reference 4).

Etching is most effective (see Reference 1) if done immediately after preparation by swabbing rather than immersion.

For TiAl alloys, the etchant most helpful in revealing microstructure of the two-phase alloy is Weck's, which tints the anisotropic alpha-phase, but leaves the isotropic beta-phase white (see Reference 6). Other sources provide detailed tables with other etchants and what they should achieve (see References 2, 3, 5, 6, and 7).

With respect to weldments and trying to reveal the grain structure, the inherent high corrosion resistance of titanium renders it necessary to use aggressive etchants. When joints in CP titanium are etched, there is little evidence of weld metal coring, to the extent that location of the fusion boundary between weld metal and high temperature heat-affected zone (HAZ) is difficult (see Reference 7).

G10. References

1. Vander Voort, G. Metallographic preparation of titanium and its alloys. Buehler Tech Note.

2. Springer, C. and Ahmed, W., "Metallographic Preparation of Titanium." Practical Metallography, Vol. 21, pp. 200–203, 1984.
3. Simmen, B. and Schmalfuss, D., "Comments on the Preparation of Metallographic Specimens of Titanium with Particular Reference to Chemical Polishing." Practical Metallography, Vol. 15, pp. 78–85, 1978.
4. Petzow, G., Metallographic Etching, 2nd Edition, Materials Park, OH: ASM International, 1999.
5. Barbuto, A. T., "An Automatic Polishing Procedure to Metallographically Prepare High Temperature TiAl Base Alloys." Proceedings of the Twenty-Second Annual Technical meeting of the International Metallographic Society, Microstructural Science, Vol. 18, ASM International, pp. 125–131, 1990.
6. Radzikowska, J., "Color Etching in Foundry Metallography." Advanced Materials and Processes, pp. 31–34, July 2000.
7. Gooch, T. G. Metallography and Examination of Welds. Welding and Metal Fabrication, pp. 157–164, April 1990.

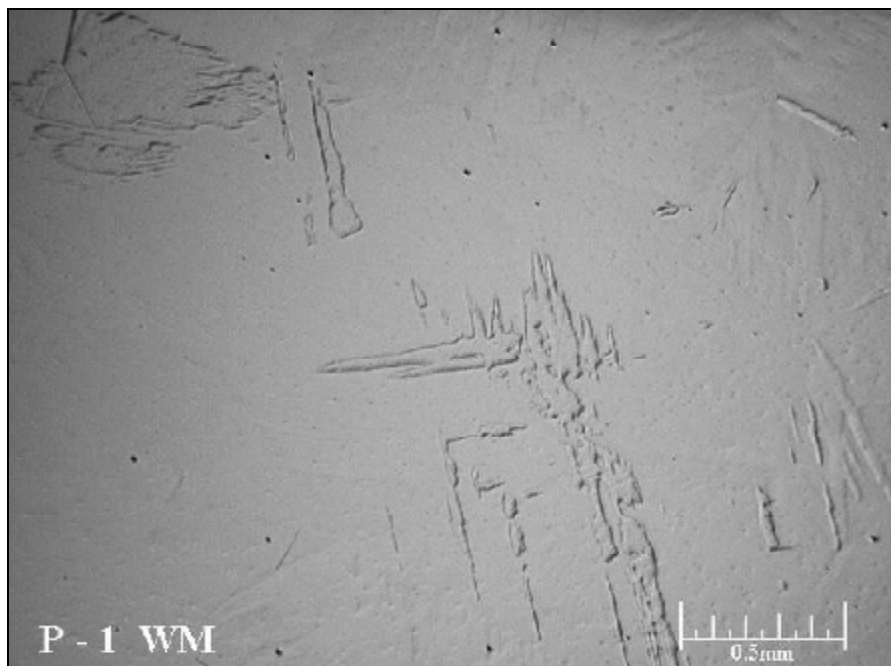


Figure G.1—Well Prepared Grade 2 Titanium Metallographic Specimen

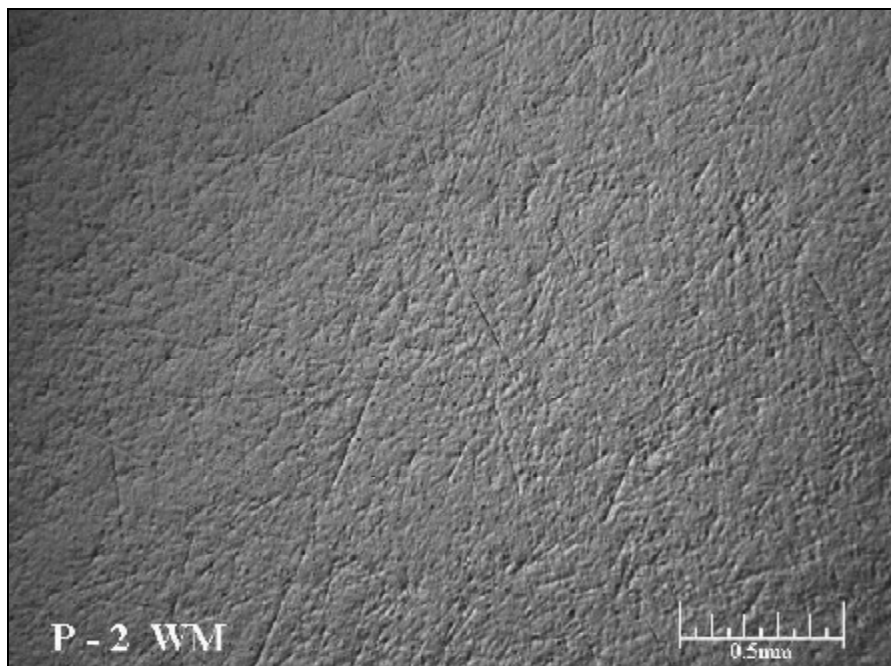


Figure G.2—Poorly Prepared Grade 2 Titanium Metallographic Specimen

Commentary on Structural Welding Code—Titanium

1st Edition

Prepared by the
AWS D1 Committee on Structural Welding

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

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Foreword

This foreword is not part of AWS D1.9/D1.9M:2007-ADD1, *Structural Welding Code—Titanium*, but is included for informational purposes only.

This commentary on AWS D1.9/D1.9M:2007 has been prepared to generate better understanding in the application of the code to titanium construction welding. Since the code is written in the form of a specification, it cannot present background material or discuss the Structural Welding Committee's intent; it is the function of this commentary to fill this need.

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Commentary on Structural Welding Code—Titanium

C-1. General Requirements

The code provides welding requirements for the fabrication of titanium structures. It is intended to be complementary with any general code or specification for design and fabrication of titanium structures. Although the provisions of the code are generally applicable to any titanium structure, the Owner, architects, and Engineers using the code for structures should recognize that not all of its provisions may be applicable or suitable to their particular structures. Recommended provisions are given in Clause 2—Design; Clause 3—Qualification; Clause 4—Fabrication; and Clause 5—Inspection. However, any modifications of the code deemed necessary by these authorities should be clearly referenced in the contractual

agreement between the Owner and the Contractor. The Engineer may accept qualifications to other standards. However, such acceptance should be based upon properly qualified performance and procedure tests, as well as service conditions.

Note: All references to numbered subclauses, tables, and figures, unless otherwise indicated, refer to subclauses, tables, or figures in AWS D1.9:2007—Structural Welding Code—Titanium. References to subclauses, tables, or figures in this commentary are prefixed with a “C-.” For example, 3.2 is in AWS D1.9, while C-3.2 is in this commentary.

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C-2. Design of Welded Connections

C-2.1 General

Designers should be aware that titanium alloys are susceptible to degradation of their mechanical properties as a result of atmospheric contamination while hot, an increasingly likely consequence as welding operations move from controlled workshop conditions to “exposed” outdoor locations. Designers should take into account the need for supplemental shielding methods to be employed during welding. This usually means providing sufficient access around the weld surfaces to introduce inert gas shielding.

C-2.2.4 Inspection. Inspection classes are defined based upon the severity of the effect of a failure of the welded joint. It is recognized that other means of classification may be more appropriate for a given structure, such as the risk of a severe loading event occurring for a particular weldment. If no designations are provided for inspection on the drawing or specification Class B shall apply (see 5.8.3).

C-2.3 Allowable Stresses

The allowable static design strength of welded joints for the full range of loading cases has usually been set based upon a combination of the yield strength of the base metal and the ultimate strength of the weld metal. Titanium base metals are commonly supplied with the minimum yield strength specified. However, titanium weld filler metals are not usually supplied with a required minimum ultimate strength. They are supplied to chemical composition requirements, which are slightly different from the chemical composition requirements of the associated base materials, as shown in AWS A5.16/A5.16M.

Since titanium filler metals are designed to provide a similar chemical composition to the base metal, their minimum strength may be estimated based upon the strength of the adjacent base metal. Titanium alloy sys-

tems have very few cases where such small differences in chemical composition, even with the differing heat treatment history between welds and base metal, will cause the weld metal to be of significantly lower yield strength than the base metal. In commercially pure grades (M51 and M52), this could occur if the level of such elements as O, N, or C were lower in the finished weld metal than the base metal. Although filler metals are often specified with slightly lower levels of these elements than the base metal, these elements will be picked up from the melted base metal or from the welding environment. In alpha-beta grades (M54), this may occur if solution-treated and aged metal is used. Thus, there is no ready reference for determining the weld metal ultimate strength, or, for that matter, its yield strength.

Several cases in Table 2.1 use 0.9 times the base metal standard minimum yield strength. The 0.9 factor is designed to allow for differences between the weld and the base metal. The 0.9 factor is also embedded in the factors used for shear strength of weld metal. If different values of ultimate tensile and yield strength are obtained during procedure qualification, then those values may be used.

One example of a dissimilar weld and base metal combinations that may need to be assessed before acceptance of the design is joining of alpha-beta alloys, such as Grade 5, with commercially pure weld metal (similar to Grades 1 and 2), where hydrogen concentrated near the weld boundary may reduce the load-carrying capacity.

C-2.6 Plug and Slot Welds

The plug hole size or slot size should be specified with caution since incomplete root fusion can reduce the joint area at the faying surface. The Engineer may recommend additional qualification of these joint types to demonstrate compliance with the design intent.

C-2.13 Skewed T-Joints

Skewed T-joints may be designed using Z-loss values, which give the additional throat needed for a given effective throat based on welding process and the dihedral angle of the joint. Z-loss values for titanium alloys have not been determined.

C-2.14 General

The requirements of Clause 2, Part D apply to members and connections subject to cyclic load of frequency and magnitude sufficient to:

- (1) Indicate the possibility of fatigue failure
- (2) Initiate cracks that progress to failure.

The provisions of Clause 2, Part D are applied to minimize the possibility of this failure mechanism.

C-2.15 Region of Applicability

These limits are designed to avoid assessing welds for fatigue resistance where fatigue would not be the primary cause of failure. The values for cycles are defined using the methods in 2.18 one of the lowest Fat 3.5 classes and a stress range of twice the allowable stress in 2.3 based on the yield strength maximums allowed for the materials in the M51, M52, and higher M classes.

C-2.18 Cyclic Load Stress Range

The fatigue performance of titanium alloy base materials has been widely tested, with many parameters found to have important effects, such as alloy grade, strength, oxygen content, size of microstructural features, and the ratio of minimum to maximum stress in the cycles.

The fatigue performance of titanium alloy welded joints has not been widely tested and only a limited number of joint shapes have available test results. Some general conclusions can be made from these data, particularly in comparison with data for other metal alloys, such as steel and aluminum.

Many parameters which have strong effects on the performance of base metal have much weaker effects on the performance of welded joints where the weld has added a stress concentrating feature. Tests on Ti-6Al-4V and commercially pure titanium have given similar results when welds, such as fillets and butt joints with caps and roots retained, have been included. This was true even though there were great differences between these alloys in strength, oxygen content, and microstructural features.

This is similar to the experience for both steels and aluminum alloys.

The stress concentrating features of a welded joint may come from the shape of the weld or from the shape of the parts being joined, or both. Table 2.3 is organized based upon the type of stress concentrating feature in the shape of the welded joint.

The fatigue allowable stresses in Figure 2.9 and the fatigue categories in Table 2.3 have been derived from requirements for steel and aluminum alloys in *Fatigue Design of Welded Joints and Components*, the recommendations of the International Institute of Welding (IIW) Joint Working Group XIII-XVI from 1996.¹¹

Four changes have been made to the steel requirements to make them appropriate to structural titanium, fitting the available test data for titanium.

First, many geometry cases have been removed, since they have not yet been tested in fatigue in titanium alloys.

Second, some geometry cases for base metal, cut edges and ground welds have been removed because the stress concentration effect does not dominate these cases. Cases where the weld cap and root are removed become sensitive to many variables including those mentioned above and the distribution of internal imperfections such as weld pores. Some investigators have demonstrated effects of weld pores below the sizes that can be detected and sized by current technology. That said, these geometry cases can have fatigue performance that is much better than those of welds where stress concentrating surface features have been retained.

Third, the design curves in Figure 2.9 have been modified from those used for steel to change the slope exponent from $-1/3$ to $-1/3.5$. This is based on crack growth rate data collected by M. Salama¹² and fatigue S/N data reported by W. C. Mohr¹³ and T. Iwata.¹⁴

¹¹ Hobbacher, A. *Fatigue Design of Welded Joints and Components, Recommendations of IIW Joint Working Group XIII-XV*, Abington Publishing, Cambridge, UK.

¹² Salama, M. "Fatigue Crack Growth Behavior of Titanium Alloy Ti-6Al-4V and Weldment." *Offshore Mechanics and Arctic Engineering Conference*, New Orleans, LA, Paper OMAE2000-2001, 2000.

¹³ Mohr, W. C. "Publication of Fatigue Classifications for the Performance of Grade 5 Titanium." *International Titanium Association Conference and Exposition*, Las Vegas, NV, 2001.

¹⁴ Iwata, T. "Effect of Thickness on Fatigue Strength of Titanium Fillet Welded Joint." *International Titanium Association Conference and Exposition*, Las Vegas, NV, 2001.

Fourth, configurations where a fatigue crack would begin at a stress concentration at the weld, but then progress across unwelded material, have been reduced by two category levels. This reduction is based on the observation of T. Iwata that longitudinal attachments in commercially pure titanium perform more poorly than expected for steel in high cycle fatigue.

In addition to the data from Mohr and Iwata, data on butt joints from R. Witt¹⁵ and S. Ohta¹⁶ are useful supporting information, including information on sensitivity to welding imperfections.

The listing of configurations in Table 2.3 is not designed to limit weld configurations for cyclic loading to only those within the table. Fatigue testing and engineering analysis may be used either to determine an absolute level of fatigue performance or to demonstrate a level of performance matching one of those within the table. Preliminary predictions could be made by choosing a category to compare into Figure 2.3. A first approximation could be obtained by taking the category for steel in the IIW recommendations.

¹⁵ Witt, R. et al. "Exploratory Development of Weld Quality Definition and Correlation with Fatigue Properties, Air Force Materials Laboratory Report AFML-TR-75-7, 1975.

¹⁶ Ohta, S. et al. "The Effect of Weld Defects on the Fatigue Strength of Thin Welded Titanium Tubes under Cyclic Internal Pressure." Titanium Science and Technology '80, Fourth International Conference on Titanium, Kyoto, Japan, 1980, pp. 1815–1824.

Variable amplitude loading may be assessed using a linear summation of the damage from the different stress ranges, that is, by using a Miner's sum.

One of the effects of postweld heat treatment is the reduction of residual stress magnitudes. Welded joints with low residual stress magnitudes may be designed for a slightly higher stress range when some or all of the applied stress cycle is compressive. During the most compressive part of the cycle, the load can be carried from one crack face to the other in bearing, thus, relieving stress around the crack tip.

An example can be given of the design process for cyclic load as follows. A designer of a structure with a requirement for 100 000 cycles wishes to choose a joint design where either a transverse butt joint from both sides or a gusseted joint that includes a longitudinal attachment plate can be made in the field. Both of these welds can be found in Table 2.3. The butt joint has a fatigue category of 80 while the splice has a fatigue category of 56, once the fillet welds have been chosen to have sufficient size. The designer can then check the design stress range on Figure 2.9. Starting with 100 000 cycles on the x-axis, the designer goes up to the appropriate fatigue category and then across to the stress range value on the y-axis. The stress range value for the butt joints is 27.3 ksi [188 MPa] while the value for the splice fillet welds is 21.5 ksi [148 MPa].

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C-3. Qualification

Part A *General Requirements*

C-3.2 General

All contractors are responsible for the quality of their final product. Therefore, it is their responsibility to comply with the qualification requirements of the code relative to WPSs, welders, welding operators, and tack welders. Properly documented WPSs and personnel qualification tests conducted by the Contractor in accordance with this code are generally acceptable to the Engineer for the contract.

C-3.3 Qualification of WPSs

C-3.3.1 Many titanium alloys are heat treatable. During welding, certain areas of the heat-affected zone are subjected to temperatures that cause a partial annealing of the base metal.

The extent of this partial annealing is dependent upon the welding conditions affecting the heat input. Thus, these variations in heat input can drastically alter the load carrying capacity of the welded structures. Therefore, all WPSs approved for use under this code shall be qualified by test. The Engineer is encouraged to accept properly documented evidence of previously qualified WPSs.

C-3.4 Qualification of Welding Personnel

C-3.4.1 Welders, welding operators, and tack welders should have a minimum of three months of successful experience welding on titanium alloys. In lieu of such experience, they should be instructed in the welding of titanium and its alloys with special reference to the con-

sequence of failing to apply appropriate and necessary process controls.

Since tack welds become a part of the final weld, and can affect the base material in the same manner as a butt or fillet weld, tack welders are required to complete a full qualification test for the type of joint to be welded.

C-3.4.1 Visual evidence of welding quality is expected to include reference to the color of the deposited weld metal. An acceptable color, as determined by the approved contractual documents, provides a degree of assurance that the welder and inspection authority fully understands the implications of effective shielding and its relationship to weld quality

The term volumetric evidence refers to weld quality as determined by radiographic examination.

C-3.5.2.5 Experience has shown that the quality of deposited, welds either where the joint configuration or access conditions are unique, improves if the production conditions are replicated during the approval process.

Part B *Types of Tests, Test Methods, and* *Acceptance Criteria*

The types of tests, test methods, and acceptance criteria for each specific requirement are found in this part of the code. It alerts the user to the types of tests required for WPS and performance qualification and to see the types and limits of discontinuities that each type of test is designed to detect.

C-3.6 Types of Tests, Test Methods, and Acceptance Criteria

This subsection describes tests, the WPSs for conducting them, and the basis for acceptance. Table 3.5 describes

the number, type, and range of thicknesses for groove, fillet, and plug and slot welds. Since AWS A5.16/A5.16M does not define weld metal tensile properties, an indication of the weld metal tensile strength may be determined by conducting an all weld metal tensile test during the weld procedure qualification process.

C-3.7 Visual Examination

Visual examination is commonly undertaken for nonferrous alloys with the aid of penetrant fluid and developer. When incompletely removed, these penetrants have the potential to adversely affect both the mechanical properties and quality of welds made onto/over the residue. This code accordingly promotes the use of visual examination with the aid of magnifying lenses.

Implicit within this approach are:

- (1) Penetrant fluids have a magnifying effect when applied and assessed
- (2) Due diligence will be applied during the visual examination.

Note: A penetrant fluid “bleed out” of 1/16 in [1.5 mm] would be expected to be associated with a surface-breaking defect substantially smaller.

Color is a criteria that can be applied during the visual inspection of titanium welds, its presence is indicative of the formation of a surface oxide layer whose color changes with oxide thickness. The absence of color is an indicator of good quality but does not positively confirm the absence of a surface oxide and it can never be used to determine quality of the “bulk weld.”

It is noteworthy that contaminants, such as Nitrogen can be introduced, from the gas supply, via the welding torch directly into the weld metal with no effect on color. Examination of the tungsten welding electrode or tip of the GMAW filler wire can provide valuable evidence regarding the efficiency of the gas shield.

Titanium is unique material and can be subject to contamination that adversely affects the mechanical properties and the use of surface color as acceptance criteria is an important tool that should be considered as a means of driving high standards.

C-3.9.2 When examining macro specimens it is frequently found easier to observe incomplete fusion and other crack like defects by first examining the specimens in the polished and unetched condition.

When examining micro specimens deleterious phases and constituents shall be absent in the weld and heat-affected zone when examined at 100X magnification minimum. These include alpha case, titanium hydrides, and segregation including alpha and beta defects which could affect weld properties.

C-3.10.1.4 Reduced Section All Weld Test Specimen—Plate. When specifying an all weld test specimen, consideration should be given to the choice of the U.S. Customary or metric dimensions as the gauge length to diameter ratio is different and will, as a consequence, give different values of elongation.

C-3.11 Bend Tests—Groove Welds—Plate and Pipe

Experience has shown that without the use of a wrap-around bend test jig as shown in Figure 3.19, the results will be varied. When reviewing any bend test failures it may be appropriate to test the base material as once its thickness exceeds 3/16 in [5 mm] bend testing is not mandatory.

C-3.12 Chemical Analysis

When the Engineer establishes chemical requirements for the analysis of deposited weld metal (perhaps as a quality control measure to help ensure that atmospheric contamination has been minimized during the welding process) reference may be made to any of the following:

- (1) The limits set forth in AWS A5.16/A5.16M welding filler material specification
- (2) Limits set with reference to the actual base and filler material chemical compositions
- (3) Alternate and product/application specific requirements.

Part C WPS Qualification

C-3.13 General WPS Qualification

This Part sets forth the requirements for qualifying a WPS. The code recognizes that the approved titanium

alloys are weldable with attention to detail and good process control, many of the conditions being generic for all of the titanium alloys. The mechanical tests are used to determine freedom from embrittlement and the achievement of the required ductility.

C-3.14 Limits of Qualified Positions for WPSs

Table 3.1 summarizes the requirements for the positions that are qualified by each qualification test. The test positions qualified are based on the experience, technique, and skill required to make a welded joint.

C-3.15 Limitation of Essential Variables—WPS Qualification

Some degree of deviation from the variables stated in the PQR is recognized in the WPS as permissible without requiring verification. Deviations from a WPS that do affect predictable results are referred to as essential variables and are considered to be items that will affect the mechanical or chemical properties, or both, of the weldment. The limits set forth in Table 3.3 are based on the combined experience of the members of the subcommittee on welded titanium structures.

C-3.18 General Performance Qualification

The welder, welding operator, or tack welder qualification test is specifically designed to determine the ability to produce sound welds in any given test weld. After successfully completing the performance qualification tests, the welder, welding operator, or tack welder should be considered to have minimum acceptable competence.

Knowledge of the base metal is beneficial to welders, welding operators, or tack welders in producing a sound weldment; therefore, it is recommended that before welding titanium and its alloys, welders, welding operators, or tack welders be given instructions as to the properties of these base metals to advise them of the special care required and the consequences of poor practices.

C-3.20.3 Tack Weld Qualification. The code requires tack welders to be qualified to the same standard as fillet and complete joint penetration groove welders in recognition of the significant effect on joint integrity of a tack weld made outside the requirements of a qualified WPS.

C-3.23 Retests

If a specimen from the test weld fails a specific test, an immediate testing of two additional specimens from the same test weld or an additional test weld is allowed under the code. If it is apparent that additional training is necessary, a complete retest at such time as this training has been accomplished is allowed by the code.

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C-4. Fabrication

C-4.1 Scope

When selecting the GMAW process, it is recommended that the fabricator pay particular attention to (a) the selection and maintenance during development, approval, and production of welding parameters, welding equipment, and support activities that will maintain the required level of process stability and joint integrity; (b) the consequences of “spatter” which becomes oxidized, thus, forming a high temperature refractory “ball” that may become included within the weld as an “invisible” defect.

C-4.2 Processes

Certain gas metal arc and gas tungsten arc WPSs in conjunction with certain related types of joints have a long record of proven satisfaction performance.

The processes covered by the code are limited to the following processes:

- (1) gas metal arc welding (GMAW),
- (2) gas tungsten arc welding (GTAW),
- (3) plasma arc welding (PAW),
- (4) electron beam welding (EBW), and
- (5) laser beam welding (LBW).

C-4.3 Base Metal

Recommended combinations of base metals and filler metals are shown in Table 4.2.

C-4.3.3 When an alloy not listed is considered for use, a special welding investigation is required to confirm the

weldability of a specific composition and heat-treated or work-hardened condition.

C-4.4 Filler Metal

C-4.4.1 These group designations do not imply that filler metals may be interchanged without consideration of compatibility from the standpoints of metallurgical and mechanical properties, design, and service requirements.

C-4.6 Shielding Gases

C-4.6.1 Gas Hose Selection. Experience has shown that many of the compounds used to manufacture flexible gas delivery hoses are prone to moisture permeation. Fabricators are therefore urged to:

- (1) Minimize the length of flexible hose between the pure gas supply and point of welding.
- (2) Select a hose material with a low moisture permeability.
- (3) Purge the flexible hoses for as long as possible before welding to promote drying.

C-4.6.2 Measurement of Contaminants within the Welding Gases. Before commencing to fabricate titanium alloys fabricators are urged to obtain and use analytical equipment capable of measuring oxygen levels to better than 10 ppm and dew points to better than -76°F [-60°C].

C-4.6.3 Contamination. In addition to the direct readings obtained from oxygen and dew point meters fabricators attention is also drawn to the following “tell tale” signs that may be used to gauge the quality of the welding gas:

- (1) Discolored tungsten electrode or filler material
- (2) Discoloration of the weld crater (perhaps a result of inadequate post welding gas flow times).

C-4.12 Preparation of Base Metal

C-4.12.1 Edge Condition. When the material has been allowed to stand in conditions that promote oxidation or contamination of the weld surface after initial weld joint preparation it is recommended that additional mechanical preparation and cleaning practices using solvents appropriate for the removal of the contaminant be included in the fabrication process.

C-4.12.2 Grinding. Grinding of titanium for edge preparation is generally not recommended; however, the code recognizes that it is necessary in some instances. In these instances, care must be taken not to contaminate the base metal by embedding abrasive particles in the titanium surface. It is recommended that one additional “die grinding operation” be introduced using a “metal” cutting tool.

C-4.12.3 Re-Entrant Corners. In buildings and tubular structures, the code permits a smaller re-entrant corner radius than is permitted for bridges. The smaller radius is necessary for some standard bolted or riveted connections.

C-4.13 Assembly

C-4.13.1 Localized heating to correct dimensional discrepancies by heat-shrinking is not recommended for titanium structures.

C-4.13.3 Partial Joint Penetration Groove Welds. A partial joint penetration groove weld has an unwelded portion at the root of the weld. This condition may also exist with a groove weld in a single-welded joint without backing and with a groove weld in a double-welded joint without back-machining. Therefore, the code places the same application limits on these welds as for partial joint penetration groove welds.

The unwelded portions are no more harmful than those in fillet welded joints. These unwelded portions constitute a significant stress concentration when fatigue loading is applied transversely to the joint.

However, when the load is applied longitudinally, there is no appreciable reduction in fatigue strength. Irrespective of the rules governing the service application of these particular groove welds, the eccentricity of shrinkage forces in relation to the center of rotation of the joint members will result in angular distortion on cooling after welding. This angular distortion can also result in secondary bending due to axial load acting through the shrinkage-induced eccentricity. Therefore, means shall be applied to restrain or preclude such rotation, both during fabrication and in service.

Statically loaded partial joint penetration groove welds, made from one side only, should be restrained to prevent localized rotation.

C-4.13.5 Fillet and Lap Welds. Except for the root opening in lap joints and the separation between a backing and base metal, a root opening of 1/16 in [1.5 mm] maximum is permitted for fillet welding base metal not exceeding 3 in [76 mm] in thickness. For base metal over 3 in [76 mm], the maximum permissible root opening is 5/16 in [8 mm]. These root openings are necessitated by the allowable mill tolerances and inability to bring thick parts into closer alignment. The code presupposes straightening of members prior to assembly or an application of an external load mechanism to force and keep the members in alignment during assembly.

The root openings may require backing, either as a backing weld or other types of backing capable of supporting molten weld metal. It should be realized that upon release of any external jacking loads, additional stresses may act upon the welds. Any root opening 1/16 in [1.5 mm] or greater requires an increase in size of the fillet weld leg size by the size of the root opening.

C-4.14 Tack Welds and Temporary Welds

Because of the effects of heat on the titanium structural alloys, it is essential that temporary welds, not incorporated in the final welds, be identified and approved by the Engineer.

C-4.19 Control of Distortion and Shrinkage

C-4.19.1 Sequence. In assembling and joining parts of a structure or of built-up members, and in welding reinforcing parts to members, the WPS and sequence should be such as will minimize distortion and shrinkage. Joints expected to have significant shrinkage should usually be welded before joints expected to have lesser shrinkage. When possible, all welds shall be deposited in a sequence that will balance the applied heat of welding while the welding progresses.

C-4.21 Repairs

C-4.21.1 Consideration should be given to the process involved in making repair. It is not the intent of the code to specify the mode of correction. Details of allowable steps in the process should be identified and agreed between both the Engineer and the Fabricator prior to commencement of initial fabrication.

C-5. Inspection

C-5.2 Inspection of Materials

This code provision is all encompassing. The inspection of materials may include the review of both destructive and nondestructive test reports, as well as other contractually required reports, and visual inspection, to verify that the products meet the requirements of both the material specification and any additional requirements specified by the Engineer. It is important that this work be done in a timely manner so that unacceptable material is not incorporated in the work.

C-5.7 Nondestructive Testing

C-5.7.2 Penetrant Testing

(1) Under certain conditions titanium can react adversely with contaminants leading to premature failure. Caution must be exercised when performing penetrant testing. Caution must be exercised when performing penetrant testing to assure the testing materials are compatible with titanium and titanium alloys.

(2) Care should be exercised when using a penetrant to search for discontinuities open to the surface that may have “through thickness” depth, causing the penetrant to bleed into an area such as an internal cavity or unfused space between the abutting members of a T-joint configuration. Similarly ballistic and other rabbeted weld joints may have unfused root face areas that provide a source of penetrant capture and slow diffusion, resulting in extreme detriment in weld quality.

(3) Penetrant inspection in this code should be considered as an enhanced visual inspection for purposes of discontinuity detection. As such, extreme care should be exercised to determine the true size and character of any flaws discovered, discounting the exaggeration created by penetrant bleedout.

C-5.8 General

C-5.8.5 Visual Inspection for Coloration. Visual inspection utilizing color, luster, or both as a discriminator shall be determined by the contract drawings. Industry experts are sharply divided regarding the validity of using these criteria. While the current body of knowledge acknowledges that color or luster is not necessarily true indicators of quality, there is at present no demonstrated substitute. The philosophy was that color and luster were indicators of contamination or lack of, and as such were determinators of weld integrity, i.e., mechanical strength. This may be consistent with certain applications especially in the aerospace and navy nuclear industry but may not be a valid criterion for less critical applications.

It is at the prerogative of the Owner to invoke these requirements. When color is required by the contract documents it should be noted that natural light is preferred when examining weldments for coloration as artificial light can alter the visual appearance of welds and surfaces that have been exposed to air. This code provides tables for discerning acceptable welds when this requirement is mandated by the customer. Luster is not addressed in this code. If luster is a requirement, the acceptance requirements shall be determined between the Owner and the Contractor.

GMAW welds can appear black and sooty due to the spontaneous combustion of finely divided metal vapor that has deposited during the weld process on the weld/parent material surface. This spontaneous combustion typically occurs once the deposited vapor leaves the protective inert gas environment of the welding system.

C-5.8 Weld Surface Preparation

(1) Extreme caution is advised when performing weld preparation. Titanium welds are very sensitive to

contamination and the lack of proper precautions to ensure contamination-free bevels or faying surfaces will result in a significant deterioration in weld quality. Surfaces may be machined, water jet cut, ground, or otherwise suitably prepared for welding. Machining can include milling and the use of die grinders fitted with rotary cutters. Grinding may be accomplished with disk, “wheels,” or both that have been selected to minimize heat build up and contamination. It should be noted that grinding may adversely affect weld quality if the wheels and discs have not been designed for grinding titanium.

(2) Grinding may include electric die grinders, die grinders with solid carbide burrs, or special grinders with silicon carbide wheels with specific grit sizes. Caution must be utilized when grinding titanium. Some grades are more prone to contamination and should not be ground. The user must be careful to verify that what grinding mechanism if any is appropriate.

C-5.17 Substitution of Nondestructive Methods

Substitution of one nondestructive method over another, such as radiographic testing for ultrasonic testing, or vice versa should not be done lightly. Considerations such as access, environment, and other factors may justifiably favor the use of the alternative method over the specified test method. In the instance of RT and UT, the Engineer should understand that although both methods provide reliable detection of internal flaws, each method does not detect the same flaws equally. Porosity, especially fine porosity is difficult to detect, and more difficult to measure when utilizing ultrasonic testing. Sidewall lack of fusion is more difficult to detect when using radiographic testing. These are only a few examples of the difference in the detection ability of these test methods. Conversely, these methods are often used interchangeably with favorable results. The Engineer should understand the limitations imposed by substitution and determine applicability of these options.

List of AWS Documents on Structural Welding

Designation	Title
D1.1/D1.1M	<i>Structural Welding Code—Steel</i>
D1.2/D1.2M	<i>Structural Welding Code—Aluminum</i>
D1.3/D1.3M	<i>Structural Welding Code—Sheet Steel</i>
D1.4/D1.4M	<i>Structural Welding Code—Reinforcing Steel</i>
D1.5M/D1.5	<i>Bridge Welding Code</i>
D1.6/D1.6M	<i>Structural Welding Code—Stainless Steel</i>
D1.7/D1.7M	<i>Guide for Strengthening and Repairing Existing Structures</i>
D1.8/D1.8M	<i>Structural Welding Code—Seismic Supplement</i>
D1.9/D1.9M	<i>Structural Welding Code—Titanium</i>

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