

Welding Processes, Inspection, and Metallurgy

API RECOMMENDED PRACTICE 577
THIRD EDITION, OCTOBER 2020



Special Notes

API publications necessarily address problems of a general nature. With respect to particular circumstances, local, state, and federal laws and regulations should be reviewed.

Neither API nor any of API's employees, subcontractors, consultants, committees, or other assignees make any warranty or representation, either express or implied, with respect to the accuracy, completeness, or usefulness of the information contained herein, or assume any liability or responsibility for any use, or the results of such use, of any information or process disclosed in this publication. Neither API nor any of API's employees, subcontractors, consultants, or other assignees represent that use of this publication would not infringe upon privately owned rights.

API publications may be used by anyone desiring to do so. Every effort has been made by the Institute to assure the accuracy and reliability of the data contained in them; however, the Institute makes no representation, warranty, or guarantee in connection with this publication and hereby expressly disclaims any liability or responsibility for loss or damage resulting from its use or for the violation of any authorities having jurisdiction with which this publication may conflict.

API publications are published to facilitate the broad availability of proven, sound engineering and operating practices. These publications are not intended to obviate the need for applying sound engineering judgment regarding when and where these publications should be utilized. The formulation and publication of API publications is not intended in any way to inhibit anyone from using any other practices.

Any manufacturer marking equipment or materials in conformance with the marking requirements of an API standard is solely responsible for complying with all the applicable requirements of that standard. API does not represent, warrant, or guarantee that such products do in fact conform to the applicable API standard.

All rights reserved. No part of this work may be reproduced, translated, stored in a retrieval system, or transmitted by any means, electronic, mechanical, photocopying, recording, or otherwise, without prior written permission from the publisher. Contact the Publisher, API Publishing Services, 200 Massachusetts Avenue, NW, Suite 1100, Washington, DC 20001.

Copyright © 2020 American Petroleum Institute

Foreword

Nothing contained in any API publication is to be construed as granting any right, by implication or otherwise, for the manufacture, sale, or use of any method, apparatus, or product covered by letters patent. Neither should anything contained in the publication be construed as insuring anyone against liability for infringement of letters patent.

The verbal forms used to express the provisions in this document are as follows.

Shall: As used in a standard, “shall” denotes a minimum requirement in order to conform to the standard.

Should: As used in a standard, “should” denotes a recommendation or that which is advised but not required in order to conform to the standard.

May: As used in a standard, “may” denotes a course of action permissible within the limits of a standard.

Can: As used in a standard, “can” denotes a statement of possibility or capability.

This document was produced under API standardization procedures that ensure appropriate notification and participation in the developmental process and is designated as an API standard. Questions concerning the interpretation of the content of this publication or comments and questions concerning the procedures under which this publication was developed should be directed in writing to the Director of Standards, American Petroleum Institute, 200 Massachusetts Avenue, Suite 1100, Washington, DC 20001. Requests for permission to reproduce or translate all or any part of the material published herein should also be addressed to the director.

Generally, API standards are reviewed and revised, reaffirmed, or withdrawn at least every five years. A one-time extension of up to two years may be added to this review cycle. Status of the publication can be ascertained from the API Standards Department, telephone (202) 682-8000. A catalog of API publications and materials is published annually by API, 200 Massachusetts Avenue, Suite 1100, Washington, DC 20001.

Suggested revisions are invited and should be submitted to the Standards Department, API, 200 Massachusetts Avenue, Suite 1100, Washington, DC 20001, standards@api.org.

Contents

Page

1	Scope	1
2	Normative References	1
3	Terms, Definitions, and Acronyms	3
3.1	Terms and Definitions	3
3.2	Acronyms	12
4	Welding Processes	12
4.1	General	12
4.2	Shielded Metal Arc Welding (SMAW)	12
4.3	Gas Tungsten Arc Welding (GTAW)	15
4.4	Gas Metal Arc Welding (GMAW)	18
4.5	Flux-Cored Arc Welding (FCAW)	21
4.6	Submerged Arc Welding (SAW)	24
4.7	Stud Arc Welding (SW)	26
4.8	Plasma Arc Welding (PAW)	26
4.9	Electrode Gas Welding (EGW)	28
5	Welding Materials	30
5.1	General	30
5.2	P-Number Assignment to Base Metals	30
5.3	F-Number Assignment to Filler Metals	31
5.4	AWS Classification of Filler Metals	31
5.5	A-Number	31
5.6	Filler Metal Selection	31
5.7	Consumable Storage and Handling	32
6	Welding Procedure	32
6.1	General	32
6.2	Welding Procedure Specification (WPS)	33
6.3	Procedure Qualification Record (PQR)	45
6.4	Reviewing the WPS and PQR	45
6.5	Tube-to-Tubesheet Welding Procedures	45
7	Welder Qualification	47
7.1	General	47
7.2	Welders and Welding Operators	47
7.3	Examination Failure of a Production Weld	47
7.4	Retest for qualification	47
7.5	Expiration, Revocation, and Renewal of Welder or Welding Operator Qualification	47
7.6	Welder Performance Qualification	47
7.7	Reviewing a WPQ	48
7.8	Limitations for Welder Qualifications	49
8	Nondestructive Examination	50
8.1	Discontinuities/imperfections	50
8.2	Materials Identification	54
8.3	Visual Examination (VT)	55
8.4	Magnetic Particle Examination (MT)	62
8.5	Alternating Current Field Measurement	66
8.6	Liquid Penetrant Examination (PT)	67

Contents

	Page
8.7 Eddy Current Examination (ET)	69
8.8 Radiographic Examination (RT)	69
8.9 Ultrasonic Examination (UT)	83
8.10 Hardness Testing	95
8.11 Pressure and Leak Testing/Examination (LT)	96
9 Welding Inspection	97
9.1 General	97
9.2 Tasks Prior to Welding	97
9.3 Tasks During Welding Operations	101
9.4 Tasks Upon Completion of Welding	103
9.5 Nonconformances and Defects	105
9.6 NDE Examiner Certification	105
9.7 Weld Inspection Data Recording	106
10 Metallurgy	109
10.1 General	109
10.2 Structure of Metals and Alloys	109
10.3 Physical Properties	111
10.4 Mechanical Properties	113
10.5 Preheating	116
10.6 Heat Treatment	116
10.7 Material Test Reports	119
10.8 Weldability of Metals	120
10.9 Weldability of High Alloys	122
11 Refinery and Petrochemical Plant Welding Issues	124
11.1 General	124
11.2 Hot Tapping and In-Service Welding	124
11.3 Lack of Fusion With GMAW-S Welding Process	127
11.4 Caustic Service	128
11.5 Controlled Deposition Welding	128
12 Safety Precautions	130
Annex A (normative) Technology and Symbols	131
Annex B (normative) Actions to Address Improperly Made Production Welds	137
Annex C (informative) WPS/PQR Review	139
Annex D (normative) Guide to Common Filler Metal Selection	174
Annex E (informative) Example Report of RT Results	178
Annex F (informative) Inspection Considerations	179
Annex G (informative) Welding Safety	181
Bibliography	182
Figures	
1 SMAW Welding Process	13
2 SMAW Welding Electrode Deposition	14
3 GTAW Welding Equipment	16

Contents

Page

4	GTAW Welding Process	17
5	GMAW Equipment	18
6	GMAW Welding Process	19
7	FCAW Equipment	22
8	FCAW Welding Process	23
9	FCAW Welding Process, Self-shielded	23
10	SAW Welding Process	25
11	Comparison of the Gas Tungsten Arc and Plasma Arc Welding Processes	27
12	Electrode Gas Welding With a Solid Electrode	29
13	Typical Discontinuities Present in a Single Bevel Groove Weld in a Butt Joint	52
14	Direct Visual Examination Requirements	55
15	Inspector's Kit	58
16	Bridge Cam Gauge	58
17	Adjustable Fillet Weld Gauge	59
18	Skew-T Fillet Weld Gauge	59
19	Weld Fillet Gauge	60
20	Weld Fillet Gauge	60
21	Weld Size Gauge	61
22	Hi-Lo Gauge	61
23	Surface-Breaking Discontinuity	62
24	Subsurface Discontinuity	62
25	Weld Discontinuity	64
26	Flux Lines	64
27	Detecting Discontinuities Transverse to Weld	65
28	Detecting Discontinuities Parallel to the Weld	65
29	Pie Gauge	66
30	Fluorescent Penetrant Technique	68
31	IQI Common Hole Diameters	71
32	IQI	72
33	Single-Wall Techniques	74
34	Double-Wall Techniques	74
35	Incomplete or Lack of Penetration (LOP)	77
36	Interpass Slag Inclusions	77
37	Cluster Porosity	78
38	Lack of Side Wall Fusion	78
39	Elongated Slag (Wagon Tracks)	79
40	Burn-Through	79
41	Offset or Mismatch With Lack of Penetration (LOP)	80
42	Excessive Penetration (Icicles, Drop-Through)	80
43	Internal (Root) Undercut	81
44	Transverse Crack	81
45	Tungsten Inclusions	82
46	Root Pass Aligned Porosity	82
47	A-Scan	84
48	B-Scan	84
49	C-Scan	85
50	D-Scan	86
51	S-Scan	87
52	TOFD D-Scan Display	88

Contents

Page

53	TOFD B-Scan	89
54	TOFD Transducer Arrangement and Ultrasonic Energy Beam Propagation	89
55	DAC Curve for a Specified Reference Reflector	92
56	DAC Curve for an Unknown Reflector	92
57	Location of Hardness Measurements	96
A.1	Joint Types and Applicable Welds	132
A.2	Symbols for Various Weld Joints	133
A.3	Supplementary Symbols for Welds	133
A.4	Standard Weld Symbols	134
A.5	Groove Weld Nomenclature	135
A.6	SMAW Welding Electrode Identification System	135
A.7	GMAW/GTAW/PAW Welding Electrode Identification System	135
A.8	FCAW Welding Electrode Identification System	136
A.9	SAW Welding Electrode Identification System	136
A.10	EGW Welding Electrode Identification System	136
B.1	Suggested Actions for Welds Made by an Incorrect Welder	137
B.2	Steps to Address Production Welds Made by an Improper Welding Procedure	138

Tables

1	P-Number Assignments	31
2	Common Types of Discontinuities	51
3	Commonly Used NDE Methods	52
4	Capability of the Applicable Examination Method for Weld-Type Joints	53
5	Capability of the Applicable Method vs. Discontinuity	53
6	Discontinuities Commonly Encountered with Welding Processes	54
7	ASTM E94 IQIs	71
8	Conditions That May Exist in a Material or Product	108
9	Results of Nondestructive Examination	108
10	Results of Application of Acceptance/Rejection Criteria	108
11	Brinell Hardness Limits for Steels in Refining Services	118
12	Weld Crack Tests	122
13	Hot Tapping/In-Service Welding Hazards Associated With Some Particular Substances	126
D.1	Common Welding Consumables for SMAW of Carbon and Low-Alloy Steel	174
D.2	Common Welding Consumables for SMAW of Carbon and Low-Alloy Steel	175
D.3	Copper-Nickel and Nickel-Based Alloys	176
D.4	Classification Changes in Low-Alloy Filler Metal Designations	177

Welding Processes, Inspection, and Metallurgy

1 Scope

This recommended practice (RP) provides guidance to the API authorized inspector on welding inspection as encountered with fabrication and repair of refinery and chemical plant equipment and piping, pipelines, and other related industries. This RP includes descriptions of common welding processes, welding procedures, welder qualifications, metallurgical effects from welding, and inspection techniques to aid the inspector in fulfilling their role implementing API 510, API 570, API 653, and API 582. The level of learning and training obtained from this document is not a replacement for the training and experience required to be a certified welding inspector under one of the established welding certification programs, such as the American Welding Society (AWS) Certified Welding Inspector (CWI), or Canadian and European equivalent schemes such as CWB, CSWIP, PCN, or EFW.

This RP does not require all welds to be inspected, nor does it require welds to be inspected to specific techniques and extent. Welds selected for inspection, and the appropriate inspection techniques, should be determined by the welding inspectors, engineers, or other responsible personnel using the applicable code or standard. The importance, difficulty, and problems that could be encountered during welding should be considered by all involved. A welding engineer should be consulted on any critical, specialized, or complex welding issues.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API 510, *Pressure Vessel Inspection Code: Maintenance, Inspection, Rating, Repair, and Alteration*

API 570, *Piping Inspection Code: Inspection, Repair, Alteration, and Rerating of In-Service Piping Systems*

API Recommended Practice 571, *Damage Mechanisms Affecting Fixed Equipment in the Refining Industry*

API Recommended Practice 574, *Inspection Practices for Piping System Components*

API Recommended Practice 578, *Material Verification Program for New and Existing Alloy Piping Systems*

API Recommended Practice 582, *Recommended Practice and Supplementary Welding Guidelines for the Chemical, Oil, and Gas Industries*

API Recommended Practice 2201, *Procedures for Welding or Hot Tapping on Equipment in Service*

ASME *Boiler and Pressure Vessel Code*¹

Section VIII, *Rules for Construction of Pressure Vessels*

¹ ASME International, 3 Park Avenue, New York, New York 10016-5990, www.asme.org.