Lecture 7

SPECIFICATION FOR COVERED CARBON STEEL ARC WELDING ELECTRODES

SFA-5.1

(Identical with AWS Specification A5.1-81)

Scope

This specification prescribes requirements for the classification of covered carbon steel electrodes for shielded metal arc welding.

Note: The values stated in U.S. customary units are to be regarded as the standard. The SI units are given as equivalent values to the U.S. customary units. The standard sizes and dimensions in the two systems are not identical and, for this reason, conversion from a standard size or dimension in one system will not always coincide with a standard size or dimension in the other. Suitable conversions, encompassing standard sizes of both can be made, however, if appropriate tolerances are applied in each case.

Section A — GENERAL REQUIREMENTS

1.0 Classification

The welding materials covered by this specification are classified according to the following criteria:

(1) Type of current (see Table 1).

(2) Type of covering (see Table 1).

(3) Welding position of the electrode (see Table 1).

(4) Chemical composition of the weld metal (see Table 2).

(5) Mechanical properties of the weld metal in the as-welded condition (see Tables 3 and 4).

Materials classified under one classification shall not be classified under any other classification of this specification.

2.0 Acceptance

Acceptance of the material shall be in accordance with the provisions of Section 3 of AWS A5.01, Filler Metal Procurement Guidelines.

3.0 Certification

For all material furnished under this specification, the manufacturer certifies, by affixing the marking required in 6.0, that the material, or representative material, has passed the tests required for classification by this specification.

4.0 Retests

If any test fails to meet its requirement, that test must be repeated twice. The results of both tests shall meet the requirements. Specimens for retest may be taken from the original test assembly, or from one or two new test assemblies.

5.0 Method of Manufacture

The welding materials classified by this specification may be made by any method yielding product conforming to the requirements of this specification.

6.0 Marking

6.1 The following information shall be legibly marked so as to be visible from the outside of each unit package:

6.1.1 AWS specification and classification numbers.

6.1.2 Supplier's name and trade designation.

6.1.3 Standard size and net weight.

6.1.4 Lot, control, or heat number.

6.2 Marking of any overpacking of unit packages with items listed in 6.1 shall be optional with the manufacturer.

Table 1
Electrode classification

AWS Classification	Type of covering	Capable of producing satisfactory welds in position shown[a]	Type of current[b]
		E60 series electrodes	
E6010	High cellulose sodium	F, V, OH, H	DCEP
E6011	High cellulose potassium	F, V, OH, H	AC or DCEP
E6012	High titania sodium	F, V, OH, H	AC or DCEN
E6013	High titania potassium	F, V, OH, H	AC or DC, either polarity
E6020 }	High iron oxide	H-fillets	AC or DCEN
E6022[c] }	High iron oxide	F	AC or DC, either polarity
E6027	High iron oxide, iron powder	H-fillets, F	AC or DCEN
		E70 series electrodes	
E7014	Iron powder, titania	F, V, OH, H	AC or DC, either polarity
E7015	Low hydrogen sodium	F, V, OH, H	DCEP
E7016	Low hydrogen potassium	F, V, OH, H	AC or DCEP
E7018	Low hydrogen potassium, iron powder	F, V, OH, H	AC or DCEP
E7024	Iron powder, titania	H-fillets, F	AC or DC, either polarity
E7027	High iron oxide; iron powder	H-fillets, F	AC or DCEN
E7028	Low hydrogen potassium, iron powder	H-fillets, F	AC or DCEP
E7048	Low hydrogen potassium, iron powder	F, OH, H, V-down	AC or DCEP

a. The abbreviations, F, V, V-down, OH, H, and H-fillets indicate the welding positions as follows:

F = Flat
H = Horizontal
H-fillets = Horizontal fillets
V-down = Vertical down

V = Vertical
OH = Overhead } For electrodes 3/16 in. (4.8 mm) and under, except 5/32 in. (4.0 mm) and under for classifications E7014, E7015, E7016, and E7018.

b. The term DCEP refers to direct current, electrode positive (DC reverse polarity). The term DCEN refers to direct current, electrode negative (DC straight polarity).

c. Electrodes of the E6022 classification are for single-pass welds.

Table 2
Chemical composition limits for weld metal

AWS Classification	Chemical composition, max percent[a,b,c]					
	Mn	Si	Ni	Cr	Mo	V
E6010, E6011, E6012, E6013, E6020, E6022, E6027	No specific chemical limits					
E7016[d], E7018[d], E7027	1.60**	0.75	0.30**	0.20**	0.30**	0.08**
E7014, E7015, E7024[e], E7028, E7048	1.25*	0.90	0.30*	0.20*	0.30*	0.08*

a. Composition limits are intended to insure a plain carbon steel deposit.
b. For obtaining the chemical composition, DCEN may be used where DC, both polarities is specified.
c. The total of all elements with the asterisk (*) shall not exceed 1.50 percent. The total of all elements with the double asterisk (**) shall not exceed 1.75 percent.
d. Upon agreement between the supplier and the purchaser, electrodes classified as E7016 or E7018 may be supplied to a minimum Charpy V-notch impact requirement of 20 ft · lb at −50° F (27 J at −46° C). Such electrodes shall be identified as E7016-1 or E7018-1, as appropriate.
e. Upon agreement between supplier and purchaser, electrodes classified as E7024 may be supplied to a minimum Charpy V-notch impact requirement of 20 ft · lb at 0° F (27 J at −18° C) and a minimum elongation of 22 percent. Such electrodes shall be identified as E7024-1.

6.3 All packages of welding materials or individually packaged units enclosed within a larger package(s) shall carry the following precautionary labelling as a minimum, prominently displayed in legible type:

WARNING: Protect yourself and others. Read and understand this label.

FUMES AND GASES can be dangerous to your health. ARC RAYS can injure eyes and burn skin. ELECTRIC SHOCK can kill.

- **Read and understand the manufacturer's instructions and your employer's safety practices.**
- **Keep your head out of the fumes.**
- **Use enough ventilation, exhaust at the arc, or both, to keep fumes and gases away from your breathing zone, and the general area.**
- **Wear correct eye, ear, and body protection.**
- **Do not touch live electrical parts.**
- **See American National Standard Z49.1, Safety in Welding and Cutting, published by the American Welding Society, 550 North LeJeune Road, Miami, Florida, 33135; OSHA Safety and Health Standards, 29 CFR 1910, available from the U.S. Government Printing Office, Washington, D.C. 20402.**

DO NOT REMOVE THIS LABEL

7.0 Packaging

7.1 Welding materials shall be suitably packaged to insure against damage during shipment or storage under normal conditions.

7.2 Standard packages shall be as specified in Section C of this specification or as agreed upon by supplier and purchaser.

8.0 Rounding-off Procedures

For purposes of determining conformance with this specification, an observed or calculated value shall be rounded to the nearest 1000 psi for tensile and yield strengths and to the "nearest unit" in the last right-hand place of figures used in expressing the limiting value for other quantities in accordance with the rounding-off method given in ASTM E29, Recommended Practice for Indicating Which Places of Figures are to be Considered Significant in Specified Limiting Values.[1]

1. ASTM Standards can be obtained from the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

Table 3
Tensile strength, yield strength, and elongation requirements for all-weld-metal tension test in the as-welded condition[a]

AWS Classification	Tensile strength, min[b] ksi	Tensile strength, min[b] MPa	Yield strength, at 0.2 percent offset, min[b] ksi	Yield strength, at 0.2 percent offset, min[b] MPa	Elongation min, percent
		E60 series electrodes[c]			
E6010	62	430	50	340	22
E6011	62	430	50	340	22
E6012	67	460	55	380	17
E6013	67	460	55	380	17
E6020	62	430	50	340	22
E6022[d]	67	460	Not required		Not required
E6027	62	430	50	340	22
		E70 series electrodes[e]			
E7014	72	500	60	420	17
E7015	72	500	60	420	22
E7016	72	500	60	420	22
E7018	72	500	60	420	22
E7024[f]	72	500	60	420	17
E7027	72	500	60	420	22
E7028	72	500	60	420	22
E7048	72	500	60	420	22

a. See Table 8 for sizes to be tested.
b. For information on stress relief considerations, see A2.4 through A2.6 of the Appendix.
c. For each increase of one percentage point in elongation over the minimum, the tensile strength or yield strength, or both, may decrease 1000 psi to a minimum of 60 ksi (420 MPa) for the tensile strength and 48 ksi (330 MPa) for the yield strength for all classifications of the E60 electrodes except E6012, E6013, and E6022. For the E6012 and E6013 classifications, the tensile strength and yield strength may decrease to a minimum of 65 ksi (450 MPa) for the tensile strength and 53 ksi (365 MPa) for the yield strength. E6022 electrodes are for single-pass welding, and the yield strength/elongation measurement is not required.
d. A transverse tension test (see 9.1.4, 13.8, 13.9) and a longitudinal guided bend test (see 9.1.5, 13.8, 13.10) are required for classification of 5/32, 3/16, and 7/32 in. (4.0, 4.8, and 5.6 mm) E6022 electrodes. Welding shall be done in the flat position (see footnotes h and k of Table 8).
e. For each increase of one percentage point in elongation over the minimum, the tensile strength or yield strength, or both, may decrease 1000 psi to a minimum of 70 ksi (480 MPa) for the tensile strength and 58 ksi (400 MPa) for the yield strength.
f. Upon agreement between supplier and purchaser, electrodes classified as E7024 may be supplied to a minimum Charpy V-notch impact requirement of 20 ft · lb at 0° F (27 J at –18° C) and a minimum elongation of 22 percent. Such electrodes shall be identified as E7024-1.

Section B — REQUIRED TESTS AND TEST METHODS

9.0 Chemical Composition Limits. The chemical composition of the weld metal deposited by the electrodes shall conform to the limits of Table 2. The details of the test are specified in 13.3.

9.1 Mechanical, Usability, and Soundness Tests and Requirements. When required in Table 8, the following tests are prescribed to demonstrate (1) the usability of electrodes classified herein, and (2) the mechanical properties and soundness of welds deposited with those electrodes. The tests are conducted in the as-welded condition.

9.1.1 All-weld-metal Tension Test. The tension test specimens made from weld metal deposited by the electrodes classified herein shall yield results conforming to the mechanical property requirements prescribed in Table 3. The details of the test are specified in 13.4 and 13.6.

9.1.2 Impact Test. The Charpy V-notch impact test specimens made from weld metal deposited by the electrodes classified herein shall yield results conforming to the impact requirements prescribed in Table 4. The details of the test are specified in 13.4 and 13.7.

Table 4
Impact requirements

AWS Classification	Charpy V-notch	Impact requirement, min
E6010, E6011, E6027, E7015, E7016,[a] E7018,[a] E7027, E7048	20 ft · lb at −20° F	(27 J at −29° C)
E7024,[b] E7028	20 ft · lb at 0° F	(27 J at −18° C)
E6012, E6013, E6020, E6022, E7014, E7024	Not required	

a. Upon agreement between the supplier and the purchaser, electrodes classified as E7016 and E7018 may be supplied to a minimum Charpy V-notch impact requirement of 20 ft · lb at −50° F (27 J at −46° C). Such electrodes shall be identified as E7016-1 and E7018-1, as applicable.

b. Upon agreement between supplier and purchaser, electrodes classified as E7024 may be supplied to a minimum Charpy V-notch impact requirement of 20 ft · lb at 0° F (27 J at −18° C) and a minimum elongation of 22 percent. Such electrodes shall be identified as E7024-1.

Table 5
Radiographic soundness requirements

AWS Classifications	Radiographic standard[a,b]
E6020, E7015, E7016, E7018, E7048	Grade 1
E6010, E6011, E6013, E7014, E7024, E6027, E7027, E7028	Grade 2
E6012, E6022	Not required

a. See Fig. 1.

b. The radiographic soundness obtainable under the actual industrial conditions employed for the various electrode classifications is discussed in A2.10.1 in the Appendix.

9.1.3 Soundness Test. The radiographs of test assemblies shall indicate no cracks or zones of incomplete fusion nor any porosity or slag inclusion in excess of that allowed in Table 5 and Fig. 1. The details of the test are specified in 13.4 and 13.5.

9.1.4 Transverse Tension Test. The transverse tension test specimens shall yield results conforming to the requirements prescribed in Table 3. A specimen that breaks in the base metal shall be considered satisfactory, provided the tensile strength obtained in the test is equal to, or greater than, the tensile strength required in Table 3 for the electrode being tested. The details of the test are specified in 13.8 and 13.9.

9.1.5 Longitudinal Guided Bend Test. The longitudinal guided bend test specimens shall, after bending, show no cracks or other open defect in the weld metal exceeding 1/8 in. (3 mm) measured in any direction. The details of the test are specified in 13.8 and 13.10.

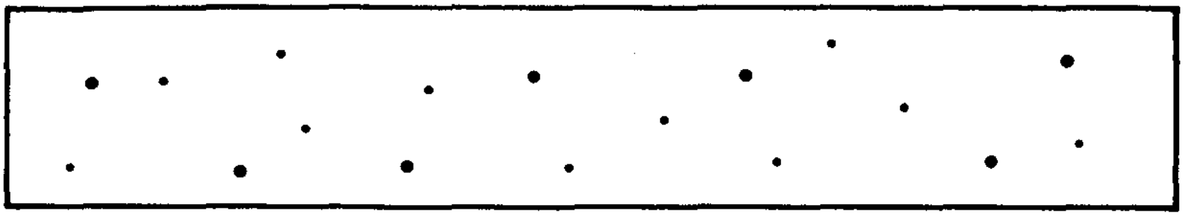
9.1.6 Fillet Weld Test. The fillet weld test specimen shall conform to the following requirements (see 13.11 for details of the test).

9.1.6.1 Examined visually, the test specimen shall be free of cracks, overlap, trapped slag, surface porosity, and substantially free of undercut. An infrequent short undercut up to 1/32 in. (0.8 mm) depth shall be allowed.

9.1.6.2 The convexity (of convex fillet welds) and the difference in length of the two legs of each fillet weld shall be in accordance with the requirements of Table 6.

9.1.6.3 The two fractured surfaces of the fillet weld shall be visually examined with the unaided eye (without magnification) and shall be free of cracks. Incomplete fusion at the root of the weld shall not be greater than 20 percent of the total length of weld. There shall be no continuous area of incomplete fusion greater than 1 in. (25 mm) in length as measured along the longitudinal weld axis except for electrodes of the E6012, E6013, and E7014 classifications. Fillet welds made with electrodes of these electrode classifications may exhibit incomplete fusion throughout the entire length of the weld, provided that at no point this lack of fusion exceeds 25 percent of the smaller leg of the fillet.

Note: The fillet weld test is not intended for the determination of subsurface porosity under the conditions normally encountered because variations in base metals, procedures, welders, etc., will affect the porosity level. Reference should be made to 9.1.3 for the determination of weld metal soundness.



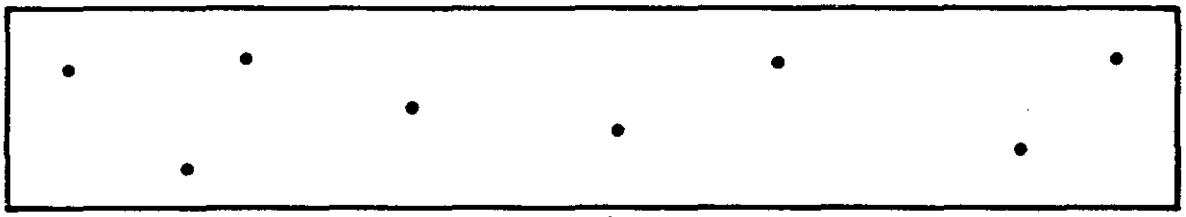
Assorted porosity and/or inclusions

Size 1/64 in. (0.4 mm) to 1/16 in. (1.6 mm) in diameter or in length. Maximum number of indications in any 6 in. (150 mm) of weld = 18, with the following restrictions:

Maximum number of large 3/64 in. (1.2 mm) to 1/16 in. (1.6 mm) diameter and/or length indications = 3.

Maximum number of medium 1/32 in. (0.8 mm) to 3/64 in. (1.2 mm) diameter and/or length indications = 5.

Maximum number of small 1/64 in. (0.4 mm) to 1/32 in. (0.8 mm) diameter and/or length indications = 10.

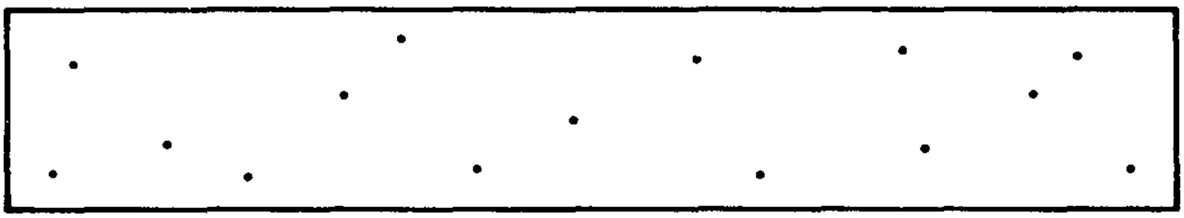


Large porosity and/or inclusions

Size 3/64 in. (1.2 mm) to 1/16 in. (1.6 mm) in diameter and/or length.

Maximum number of indications in any 6 in. (150 mm) of weld = 8.

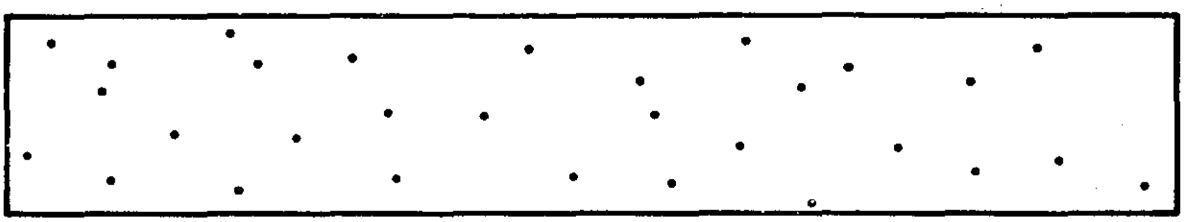
Grade 1



Medium porosity and/or inclusions

Size 1/32 in. (0.8 mm) to 3/64 in. (1.2 mm) in diameter and/or length.

Maximum number of indications in any 6 in. (150 mm) of weld = 15.



Fine porosity and/or inclusions

Size 1/64 in. (0.4 mm) to 1/32 in. (0.8 mm) in diameter and/or length.

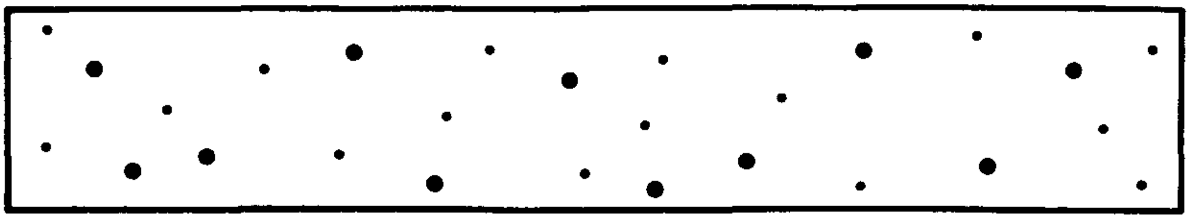
Maximum number of indications in any 6 in. (150 mm) of weld = 30.

Grade 1

Notes:

1. In using these standards, the chart which is most representative of the size of the porosity and/or inclusions present in the test specimen radiograph shall be used for determining conformance to these radiographic standards.
2. Since these are test welds specifically made in the laboratory for classification purposes, the radiographic requirements for these test welds are more rigid than those which may be required for general fabrication.
3. Indications smaller than 1/64 in. (0.4 mm) diameter and/or length shall be disregarded.

Fig. 1 — Porosity and inclusion standards for soundness test



Assorted porosity and/or inclusions

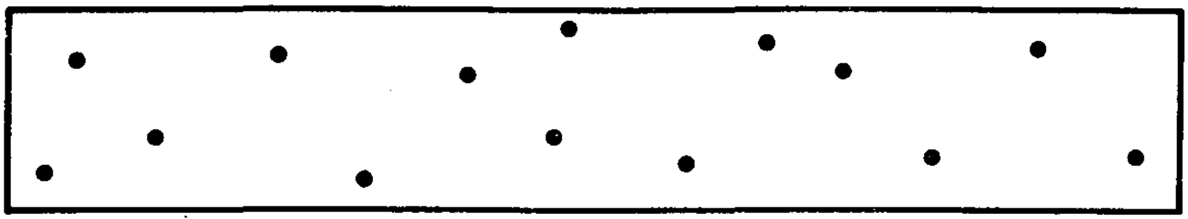
Size 1/64 in. (0.4 mm) to 5/64 in. (2.0 mm) in diameter or in length.

Maximum number of indications in any 6 in. (150 mm) of weld = 27, with the following restrictions:

Maximum number of large 1/16 in. (1.6 mm) to 5/64 in. (2.0 mm) diameter and/or length indications = 3.

Maximum number of medium 3/64 in. (1.2 mm) to 1/16 in. (1.6 mm) diameter and/or length indications = 8.

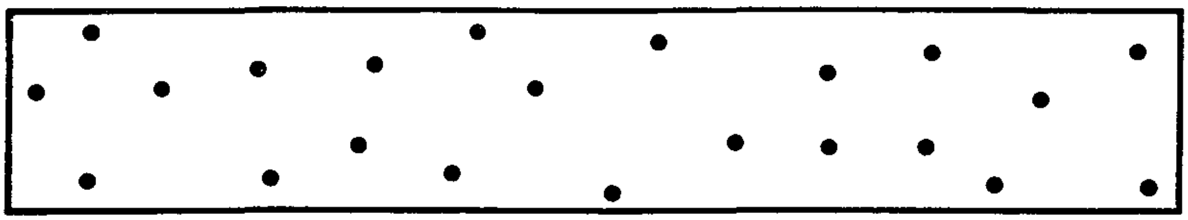
Maximum number of small 1/64 in. (0.4 mm) to 3/64 in. (1.2 mm) diameter and/or length indications = 16.



Large porosity and/or inclusions

Size 1/16 in. (1.6 mm) to 5/64 in. (2.0 mm) in diameter and/or length.

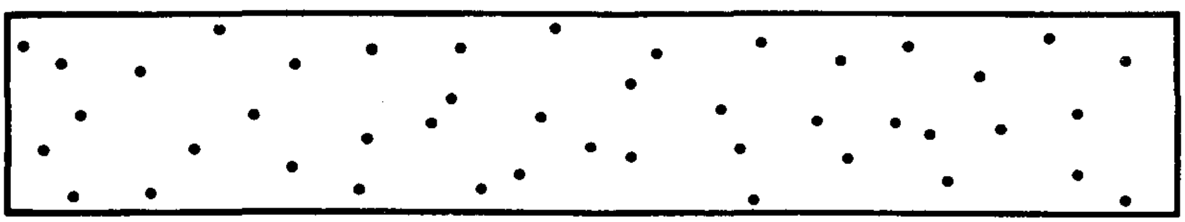
Maximum number of indications in any 6 in. (150 mm) of weld = 14.



Medium porosity and/or inclusions

Size 3/64 in. (1.2 mm) to 1/16 in. (1.6 mm) in diameter and/or length.

Maximum number of indications in any 6 in. (150 mm) of weld = 22.



Fine porosity and/or inclusions

Size 1/64 in. (0.4 mm) to 3/64 in. (1.2 mm) in diameter and/or length.

Maximum number of indications in any 6 in. (150 mm) of weld = 44.

Grade 2

See *Note* on page 1.

Notes:

1. In using these standards, the chart which is most representative of the size of the porosity and/or inclusions present in the test specimen radiograph shall be used for determining conformance to these radiographic standards.
2. Since these are test welds specifically made in the laboratory for classification purposes, the radiographic requirements for these test welds are more rigid than those which may be required for general fabrication.
3. Indications smaller than 1/64 in. (0.4 mm) diameter and/or length shall be disregarded.

Fig. 1 (continued) — Porosity and inclusion standards for soundness test

Table 6
Dimensional requirements for fillet weld usability test specimens

Size of fillet weld		Maximum convexity		Maximum difference between lengths of fillet legs	
in.	mm	in.	mm	in.	mm
1/8	3.2	3/64	1.2	1/32	0.8
5/32	4.0	3/64	1.2	3/64	1.2
3/16	4.8	1/16	1.6	1/16	1.6
7/32	5.6	1/16	1.6	5/64	2.0
1/4	6.4	1/16	1.6	3/32	2.4
9/32	7.1	1/16	1.6	7/64	2.8
5/16	8.0	5/64	2.0	1/8	3.2
11/32	8.7	5/64	2.0	9/64	3.6
3/8	9.5	5/64	2.0	5/32	4.0

Section C — MANUFACTURE, PACKAGING, AND IDENTIFICATION

10.0 Manufacture

10.1 Standard Sizes and Lengths. Standard sizes and lengths of electrodes shall be as shown in Table 7. In all cases, standard size refers to the diameter of the core wire.

10.2 Core Wire and Coverings

10.2.1 The diameter of the core wire shall not vary more than ± 0.002 in. (± 0.05 mm) from the standard size specified. The length shall not vary more than ± 1/4 in. (± 10 mm).

10.2.2 The covering on all sizes of covered electrodes shall be concentric to the extent that the maximum core-plus-one covering dimension shall not exceed the minimum core-plus-one covering dimension by more than 7 percent of the mean dimension in sizes 1/16, 5/64, and 3/32 in. (1.6, 2.0, and 2.4 mm); 5 percent of the mean dimension in sizes 1/8 and 5/32 in. (3.2 and 4.0 mm); and 4 percent of the mean dimension in sizes 3/16 in. (4.8 mm) and larger. The concentricity may be measured by any suitable means.

10.2.3 Core wire and coverings shall be free of defects which would interfere with uniform performance of the electrodes.

10.2.4 The maximum moisture content of the coverings of low hydrogen (E7015, E7016, E7018, E7028, and E7048) classifications, as manufactured, or reconditioned as specified in 13.2, shall be 0.6 percent max. The coating moisture test may be made by any suitable method agreed upon between supplier and purchaser. In case of dispute, the tests will be conducted in accordance with the procedure stipulated in 13.12.

10.3 Exposed Core

10.3.1 The grip portion of the electrode for making contact with the electrode holder shall be as follows:

Electrode size	Bare portion (minimum)	Distance from grip end to full thickness of covering (maximum)
5/32 in. (4.0 mm) and smaller	1/2 in. (13 mm)	1-1/4 in. (30 mm)
3/16 in. (4.8 mm) and larger	3/4 in. (19 mm)	1-1/2 in. (40 mm)

10.3.1.1 Not less than 1 in. (25 mm) shall be bare for electrodes to be used in automatic feeders.

10.3.2 The arc end of each electrode shall be sufficiently bare and the covering sufficiently tapered to permit easy striking of the arc. The covering shall cover the core wire for at least one-half of the circumference of the electrode at the following distances from the arc end:

10.3.2.1 For low hydrogen electrodes (classifications E7015, E7016, E7018, E7028, and E7048), one-half the diameter of the core wire or 1/16 in. (1.6 mm), whichever is smaller.

10.3.2.2 For all other electrodes, two-thirds the diameter of the core wire or 3/32 in. (2.4 mm), whichever is smaller.

11.0 Standard Packages. Electrodes shall be suitably packaged to ensure against damage during shipment and storage under normal conditions. The weight of the package shall be as agreed upon by the supplier and the purchaser.

Table 7
Standard sizes and lengths

Standard sizes, (core wire diameter)[a]		Standard lengths classifications[b,c,d] E6010, E6011, E6012, E6013, E6022, E7014, E7015, E7016, E7018		E6020, E6027, E7024, E7027, E7028, E7048	
in.	mm	in.	mm	in.	mm
1/16[e]	1.6[e]	9	230	–	–
5/64[e]	2.0[e]	9 or 12	230 or 300	–	–
3/32[e]	2.4[e]	12 or 14	300 or 350	12 or 14	300 or 350
1/8	3.2	14	350	14	350
5/32	4.0	14	350	14	350
3/16	4.8	14	350	14 or 18	350 or 450
7/32[e]	5.6[e]	14 or 18	350 or 450	18 or 28	450 or 700
1/4[e]	6.4[e]	18	450	18 or 28	450 or 700
5/16[e]	8.0[e]	18	450	18 or 28	450 or 700

a. Tolerance on the core wire diameter shall be ± 0.002 in. (± 0.05 mm).
b. Tolerance on the length shall be ± 1/4 in. (± 10 mm).
c. Other sizes and lengths may be classified.
d. In all cases, end gripping is standard.
e. These diameters are not manufactured in all electrode classifications (see Table 8).

12.0 Electrode Identification. All electrodes shall be identified in accordance with the following:

12.1 At least one legible imprint of the applicable AWS classification shall be applied to the electrode covering as near as practical to the grip end of the core wire but not more than 2-1/2 in. (65 mm) from that grip end.

12.2 The numbers of the imprinted electrode classification shall be of bold block type and of sufficient size to be legible.

12.3 The ink used for imprinting shall provide sufficient contrast with the electrode covering so that the numbers and letters are legible both before and after normal welding applications.

12.4 The prefix letter E in the electrode classification may be omitted from the imprint of the electrode covering.

Section D — DETAILS OF TESTS

13.0 Required Tests. The tests specified in 9.0 and 9.1 shall be conducted in accordance with the requirements of 13.1 through 13.11. Electrode sizes other than those shown shall be classified using the tests for the closest standard size which are required in 13.3 and Table 8. See also footnote k of Table 8.

13.1 Material for Test Plates. Steel to be used for test plates for all the required tests (chemical analysis, soundness, all-weld-metal tension, impact, transverse tension, longitudinal guided bend, and usability tests) shall conform to one of the following ASTM specifications or their equivalent:

13.1.1 Specification A285, Pressure Vessel Plates, Carbon Steel Low and Intermediate Tensile Strength, Grade C.

13.1.2 Specification A283, Low and Intermediate Tensile Strength Carbon Steel Plates of Structural Quality, Grade D.

13.1.3 Specification A36, Structural Steel.

13.2 Conditioning of Electrodes for Test. Electrodes shall be tested in the as-received condition except for the low hydrogen electrodes (classifications E7015, E7016, E7018, E7028, and E7048). Low hydrogen electrodes, if they have not been adequately protected against moisture pickup in storage, shall be held at a temperature of 500 to 800° F (260 to 427° C) for a period of 2 hours immediately prior to testing.

13.3 Chemical Analysis

13.3.1 Samples for chemical analysis of the weld metal shall be obtained for 5/32 and 1/4 in. (4.0 and 6.4 mm) electrodes according to Table 2, using each type of current shown in Table 8, for the classification being tested.

Table 8
Summary of mechanical tests required[a,*]

AWS Classification	Electrode: Current and polarity	Size[b] in.	Size[b] mm	Soundness test[c,d] all-weld-metal tension test[c,e]	Impact test[c,f]	Fillet weld test[c,g]
E6010	DCEP	3/32, 1/8	2.4, 3.2	Not required	Not required	Not required
		5/32, 3/16	4.0, 4.8	F	F	V and OH
		7/32	5.6	Not required	Not required	Not required
		1/4	6.4	F	F	H
		5/16	8.0	F	Not required	Not required
E6011	AC and DCEP	3/32, 1/8	2.4, 3.2	Not required	Not required	Not required
		5/32, 3/16	4.0, 4.8	F	F	V and OH
		7/32	5.6	Not required	Not required	Not required
		1/4	6.4	F	F	H
		5/16	8.0	F	Not required	Not required
E6012	AC and DCEN	1/16 to 1/8	1.6 to 3.2 inc.	Not required	Not required	Not required
		5/32, 3/16	4.0, 4.8	F[h]	Not required	V and OH
		7/32	5.6	Not required	Not required	Not required
		1/4	6.4	F[h]	Not required	H
		5/16	8.0	F[h]	Not required	H
E6013	AC and DC, both polarities	1/16 to 1/8	1.6 to 3.2 inc.	Not required	Not required	Not required
		5/32, 3/16	4.0, 4.8	F[m]	Not required	V and OH
		7/32	5.6	Not required	Not required	Not required
		1/4	6.4	F[m]	Not required	H
		5/16	8.0	F[m]	Not required	H
E6020	For H-fillets - AC and DCEN; For flat position - AC and DC, both polarities	1/8	3.2	Not required	Not required	Not required
		5/32, 3/16	4.0, 4.8	F[m]	Not required	H
		7/32	5.6	Not required	Not required	Not required
		1/4	6.4	F[m]	Not required	H
		5/16	8.0	F[m]	Not required	Not required
E6022	AC and DCEN	1/8	3.2	h	Transverse tension and bend tests required. See footnote "k."	
		5/32	4.0			
		3/16	4.8			
		7/32	5.6			

Table 8
Summary of mechanical tests required[a,*] (cont'd)

AWS Classification	Electrode: Current and polarity	Electrode: Size[b] in.	Electrode: Size[b] mm	Soundness test[c,d] all-weld-metal tension test[c,e]	Impact test[c,f]	Fillet weld test[c,g]
E7014	AC and DC, both polarities	3/32, 1/8	2.4, 3.2	Not required	Not required	Not required
		5/32	4.0	F[m]	Not required	V and OH
		3/16	4.8	F[m]	Not required	H
		7/32	5.6	Not required	Not required	Not required
		1/4	6.4	F[m]	Not required	H
		5/16	8.0	F[m]	Not required	H
E7015	DCEP	3/32, 1/8	2.4, 3.2	Not required	Not required	Not required
		5/32	4.0	F	F	V and OH
		3/16	4.8	F	F	H
		7/32	5.6	Not required	Not required	Not required
		1/4	6.4	F	F	H
		5/16	8.0	F	Not required	Not required
E7016	AC and DCEP	3/32, 1/8	2.4, 3.2	Not required	Not required	Not required
		5/32	4.0	F	F	V and OH
		3/16	4.8	F	F	H
		7/32	5.6	Not required	Not required	Not required
		1/4	6.4	F	F	H
		5/16	8.0	F	Not required	Not required
E7018	AC and DCEP	3/32, 1/8	2.4, 3.2	Not required	Not required	Not required
		5/32	4.0	F	F	V and OH
		3/16	4.8	F	F	H
		7/32	5.6	Not required	Not required	Not required
		1/4	6.4	F	F	H
		5/16	8.0	F	Not required	Not required
E7024	AC and DC, both polarities	3/32, 1/8	2.4, 3.2	Not required	Not required	Not required
		5/32, 3/16	4.0, 4.8	F[m,n]	F[j]	H
		7/32	5.6	Not required	Not required	Not required
		1/4	6.4	F[m,n]	F[j]	H
		5/16	8.0	F[m,n]	Not required	Not required

Table 8
Summary of mechanical tests required[a],* (cont'd)

AWS Classification	Electrode: Current and polarity	Size[b]: in.	Size[b]: mm	Soundness test[c,d] all-weld-metal tension test[c,e]	Impact test[c,f]	Fillet weld test[c,g]
E6027 and E7027	For H-fillets - AC and DCEN	1/8	3.2	Not required	Not required	Not required
		5/32, 3/16	4.0, 4.8	F[m]	F	H
	For flat position - AC and DC, both polarities	7/32	5.6	Not required	Not required	Not required
		1/4	6.4	F[m]	F	H
		5/16	8.0	F[m]	Not required	Not required
E7028	AC and DCEP	1/8	3.2	Not required	Not required	Not required
		5/32, 3/16	4.0, 4.8	F	F	H
		7/32	5.6	Not required	Not required	Not required
		1/4	6.4	F	F	H
E7048	AC and DCEP	1/8	3.2	Not required	Not required	Not required
		5/32	4.0	F	F	V-down and OH
		3/16	4.8	F	F	V-down and H

a. For electrodes smaller than 5/32 in. (4.0 mm) and for the 7/32 in. (5.6 mm) size, the specified tests would require detailed modification; the suitability of these sizes may be judged from the results of the tests on the 5/32 in. (4.0 mm) and 1/4 in. (6.4 mm) sizes, respectively.

b. Electrodes manufactured in sizes not shown shall be tested to the requirements of the nearest standard size.

c. The abbreviations, F, H, V-down, V, and OH are defined in footnote a of Table 1.

d. See 9.1.3, 13.4, and 13.5.

e. See 9.1.1, 13.4, and 13.6.

f. See 9.1.2, 13.4, and 13.7.

g. See 9.1.6 and 13.11.

h. A soundness test is not required for this classification.

j. Upon agreement between supplier and purchaser, electrodes classified as E7024 may be supplied to a minimum Charpy V-notch impact requirement of 20 ft · lb at 0° F (27 J at −18° C) and a minimum elongation of 22 percent. Such electrodes shall be identified as E7024-1.

k. A transverse tension test (see 9.1.4, 13.8, and 13.9) and a longitudinal guided bend test (see 9.1.5, 13.8, and 13.10) are required for classification of 5/32, 3/16, and 7/32 in. (4.0, 4.8, and 5.6 mm) E6022 electrodes. Welding shall be in the flat position. See footnote d of Table 3.

m. DCEN only, may be used when DC, both polarities, is specified.

n. Electrodes longer than 18 in. (450 mm) which are used for gravity welding will require 2 test assemblies, each made with the special procedure described in 13.4.4, to insure uniformity of the entire electrode.

* Standard electrode sizes having no test requirements can be classified provided at least two other sizes of that classification have passed the tests required for them, or the size to be classified meets specification requirements by having been tested in accordance with Figs. A1 and A2 and Table A3.

13.3.2 Samples for chemical analysis may be obtained from the weld pad specified in 13.3.3 or any other weld deposit, provided it produces results equivalent to those obtained from the weld pad. In case of dispute, samples shall be taken from the weld pad.

13.3.3 The weld pad shall be deposited in layers in the flat position. The width of each pass in each layer shall be 1-1/2 to 2-1/2 times the diameter of the core wire. After depositing each layer, the pad shall be immersed in water (temperature unimportant) for approximately 30 seconds and then dried before welding is resumed. The surface of each layer shall be cleaned of all foreign matter. The completed weld pad and the location from which the sample for analysis is taken shall conform to the requirements in Table 9.

13.3.4 The chemical analysis shall be made by any suitable method. In case of dispute, the procedure in the latest edition of ASTM Standard Method E350, Chemical Analysis of Carbon Steel, Low-Alloy Steel, Silicon Electrical Steel, Ingot Iron, and Wrought Iron, shall be the referee method.

13.4 Preparation of Test Assembly for Soundness Test, All-Weld-Metal Tension Test, and Impact Test

13.4.1 When required in Table 8, the test assembly detailed in Fig. 2 shall be prepared and welded as prescribed in 13.4.2 through 13.4.5 with the type of current shown in Table 8 for the classification of the electrode being tested.

13.4.2 The test assembly shall be welded in the flat position with the weld axis and the plates horizontal and shall be preset or restrained during welding to prevent warpage in excess of 5 degrees. A test assembly that has warped more than 5 degrees shall be discarded. Welded test assemblies shall not be straightened.

13.4.3 The test assembly shall be tack welded and preheated to 225 ± 25° F (110 ± 14° C). Welding shall be continued with an interpass temperature of not less than 225° F (110° C) nor more than 350° F (180° C) as measured by temperature indicating crayons or surface thermometers at the point specified in Fig. 2. The welding procedure shall be as prescribed in 13.4.4.

13.4.4 The pass sequence shall be as called for in Fig. 2. Each pass shall include at least one start and stop within the area of weld that must meet radiographic soundness requirements (see 13.5). The direction of welding to complete a pass shall not vary; however, the direction of welding for different passes may be alternated (see note below).

Note: Electrodes longer than 18 in. (450 mm) used for gravity welding shall be tested using two of the 10 in. (250 mm) test assemblies, Fig. 2, butted back-to-back. The specific electrode used for a particular pass in one assembly shall also be used for the corresponding pass in the other assembly. This is to be done by depositing the bead in one assembly using the first half of each electrode and without interruption depositing the corresponding bead in the second assembly, using the remaining half of the electrode. The welding speed shall be controlled to ensure that each electrode does in fact cover both assemblies. Both assemblies shall pass the mechanical property requirements listed in Table 3.

13.4.5 If it is necessary to interrupt the welding procedure prescribed in 13.4.4, the assembly (or assemblies) shall be allowed to cool in still air to room temperature. When welding is resumed, the assembly(ies) shall be preheated to a temperature of 225 ± 25° F (110 ± 14° C). The procedure used for completing the weld shall be as prescribed in 13.4.4.

13.5 Soundness Test

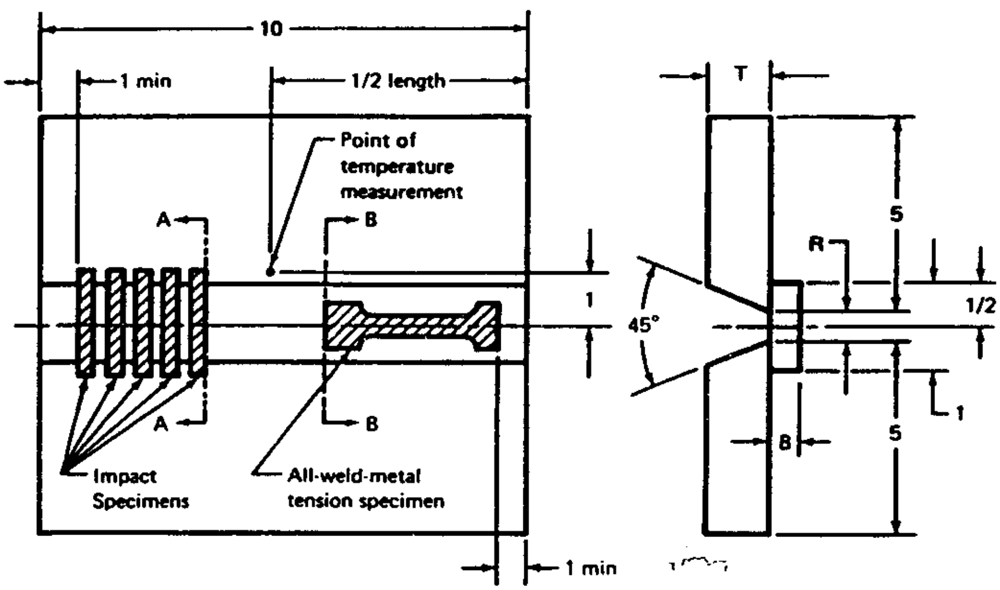
13.5.1 When required in Table 8, the assembly shall be prepared for radiographic examination in accordance with the following:

Note: For the optional 20 in. (500 mm) assembly, only the second half of the assembly need be radiographed.

13.5.1.1 The backing strip shall be removed prior to performing the radiography.

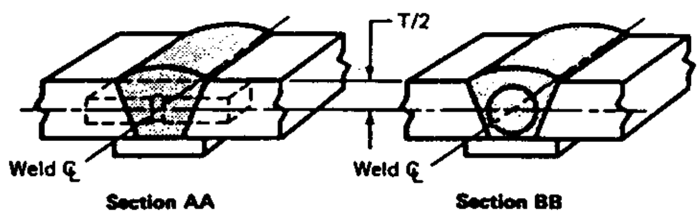
Table 9
Weld pad dimensions

Electrode size		Minimum pad size		Minimum distance of sample from surface of base plate	
in.	mm	in.	mm	in.	mm
5/32	4.0	1-1/2 x 1-1/2 x 1/2	40 x 40 x 13	1/4	6
1/4	6.4	2 x 2 x 1/2	50 x 50 x 13		



(a) Test plate showing location of test specimens

SI Equivalents	
in.	mm
1/16	1.6
1/2	13
1	25
5	125
10	250



(b) Orientation and location of impact specimen

(c) Location of all-weld-metal tension specimen

Notes:

1. All dimensions except angles are in inches.
2. Two test assemblies required for electrodes longer than 18 in. (450 mm)* that are used for gravity welding. As an option, a 20 in. (500 mm)* long assembly may be welded. One 10 in. (250 mm)* long portion of this optional assembly shall be used for the soundness test and the other 10 in. (250 mm)* long portion shall be used for the tension and impact tests.
3. Test assembly details on optional all-weld-metal tests on 3/32 in. (2.4 mm)*, 1/8 in. 3.2 mm)* and 7/32 in. (5.6 mm)* electrodes are shown by Fig. A1 in the Appendix.

Electrode size		(T) Plate thickness		(B) Backing thickness		Full weave	Split weave		
in.	mm	in. (min)	mm	in.	mm	for layer no.	Layer no.	Passes per layer	Number of layers
5/32	4.0	3/4	19	1/4	6.4	1	2 to top	2	7 to 9
3/16	4.8	3/4	19	1/4	6.4	1 and 2	3 to top	2	6 to 8
1/4	6.4	1 1	25	1/2	12.7	1, 2, and 3	4 to top	2	9 to 11
5/16	8.0	1-1/4	32	1/2	12.7	1, 2, and 3	4 to top	2	10 to 12

Fig. 2 — Details of test assembly for soundness test, all-weld-metal tension test, and impact test

13.5.1.2 The weld ripples or surface irregularities on both the face and the root of the weld shall be removed by any suitable mechanical process to a degree such that the resulting radiographic contrast due to any remaining irregularities cannot mask or be confused with that of any objectionable defect. Also, the weld faces shall merge smoothly into the plate surface. The finished surface of the weld may be flush with the plate or have a reasonably uniform reinforcement, not exceeding 3/32 in. (2.4 mm).

13.5.2 The radiographs shall be obtained in accordance with the 2-2T sensitivity level of inspection as stipulated in ASTM E142, Standard Method for Controlling Quality of Radiographic Testing.

13.5.3 When evaluating the radiographs, a 1 in. (25 mm) length on each end of the test welds shall be disregarded.

13.6 All-Weld-Metal Tension Test

13.6.1 For all electrode classifications, no thermal treatment other than that prescribed in 13.6.3 shall be performed on the test assembly subsequent to the welding operation.

13.6.2 One all-weld-tension test specimen as shown in Fig. 3 shall be machined from the same test assembly (Fig. 2) which was examined radiographically or from one-half of the optional 20 in. (500 mm) assembly.[2] For gravity feed electrodes, see Note under 13.4.4.

13.6.3 For all electrode classifications, except the low hydrogen classifications (E7015, E7016, E7018, E7028, and E7048), the machined tensile specimen shall be aged at 200 to 220° F (95 to 105° C) for 48 ± 2 hours. The specimen shall then be cooled to room temperature and subjected to tension until rupture. The tensile specimen from the low hydrogen classifications shall not be aged prior to testing.

13.6.4 The all-weld-metal tension test specimen shall be tested in accordance with the tension test section of the latest edition of AWS B4.0, Standard Methods for Mechanical Testing of Welds.

13.7 Impact Test

13.7.1 When required in Table 8, five Charpy V-notch impact test specimens, as shown in Fig. 4, shall be machined from the same test assembly (Fig. 2) which was examined radiographically or from one half of the optional 20 in. (500 mm) assembly.

13.7.2 No thermal treatment shall be performed on the test specimens.

13.7.3 The impact specimens shall be tested in accordance with the impact test sections of the latest edition of AWS B4.0, Standard Methods for Mechanical Testing of Welds.

13.7.4 The impact properties of the five specimens from the test assembly shall be obtained at the test temperature specified in Table 4 for the classification being tested.

13.7.5 When computing the average value of the impact properties from the set of five specimens, the lowest value and the highest value obtained shall be disregarded. Two of the three remaining values shall be greater than the specified 20 ft · lb (27 J) energy level; one of the three may be lower but shall not be less than 15 ft · lb (20 J). The computed average value of the three values shall be equal to, or greater than, the 20 ft · lb (27 J) energy level.

13.8 Preparation of Test Assembly for Transverse Tension and Longitudinal Guided Bend Test

13.8.1 When required in Table 8, a test assembly as detailed in Fig. 5 shall be prepared and welded as prescribed in 13.8.2 through 13.8.3 using each type of current specified in Table 8 for the classification of the electrode being tested.

13.8.2 The test assembly shall be welded in the flat position and shall be sufficiently preset or restrained during welding to prevent warpage in excess of 5 degrees. A welded test assembly that has warped more than 5 degrees shall be discarded. Welded test assemblies shall not be straightened.

13.8.3 The test assembly shall first be tack welded at each end. Welding shall be started with the assembly at a room temperature of 65° F (20° C) min. When the weld on one side of the test assembly is completed, the assembly shall be turned over and the weld on the reverse side completed, as shown in Fig. 5.

13.9 Transverse Tension Test

13.9.1 One transverse tension test specimen, as shown in Fig. 6, shall be removed from the test assembly.

13.9.2 No thermal treatment shall be performed on the test specimen.

13.9.3 The transverse tension test specimen shall be tested in accordance with the tension test section of the latest edition of AWS B4.0, Standard Methods for Mechanical Testing of Welds.

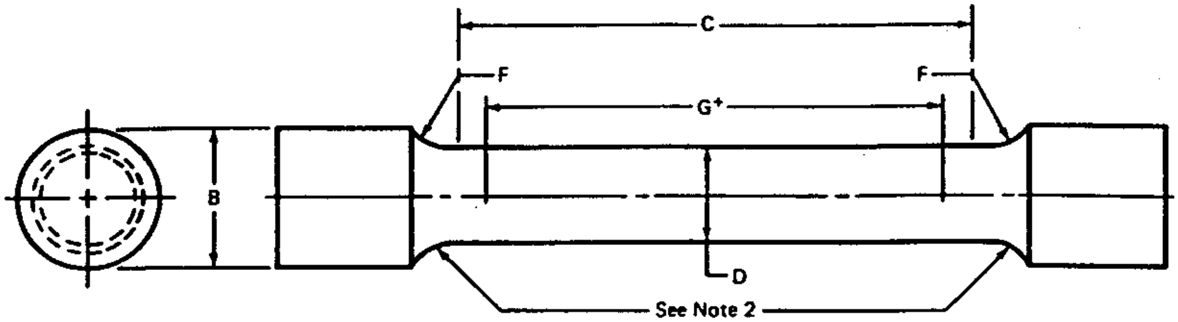
13.10 Longitudinal Guided Bend Test

13.10.1 One longitudinal guided bend test specimen, as shown in Fig. 7, shall be removed from the same test assembly, as shown in Fig. 5, from which the transverse tension test specimen was removed.

13.10.2 The machined specimen shall be aged at 200 to 220° F (95 to 105° C) for 48 ± 2 hours. The specimen shall be cooled to room temperature before testing.

13.10.3 The longitudinal guided bend test specimen shall be uniformly bent through 180 degrees over a radius of 3/4 in. (19 mm) in any suitable jig. The specimen may be positioned for bending so that the maximum bending occurs in either of the two weld passes. A typical bending jig is shown in the latest edition of AWS B4.0, Standard Methods for Mechanical Testing of Welds.

2. This half need not be the portion that was radiographed.



G^{+} = Gage length

Dimensions of specimen, in.						
Test plate thickness	D	G	C	B	F, min	Approximate area sq. in.
3/4	0.500 ± 0.010	2.000 ± 0.005	2-1/4	3/4	0.375 (3/8)	1/5

Dimensions of specimen, mm						
Test plate thickness	D	G	C	B	F, min	Approximate area sq. mm
19.1	12.7 ± 0.25	50.8 ± 0.13	57.1	19.1	9.5	129

Notes:

1. Dimensions G and C shall be as shown, but ends may be of any shape to fit the testing machine holders as long as the load is axial.
2. The diameter of the specimen within the gage length shall be slightly smaller at the center than at the ends. The difference shall not exceed one percent of the diameter.
3. When the extensometer is required to determine yield strength or other elastic properties, dimensions C and L may be modified. However, the percent of the elongation shall be based on dimension G.
4. The surface finish within the C dimension shall be no rougher than 63 μ in. (1.6 μm).

Fig. 3 — All-weld-metal tension test specimen dimensions

13.11 Fillet Weld Test

13.11.1 When required in Table 8, test assemblies, as detailed in Table 10 and Fig. 8, shall be prepared and welded as prescribed in 13.11.2 through 13.11.5 in the welding positions required in Table 10 (see Fig. 9 for welding positions), using each type of current specified in Table 8 for the classification of electrode being tested.

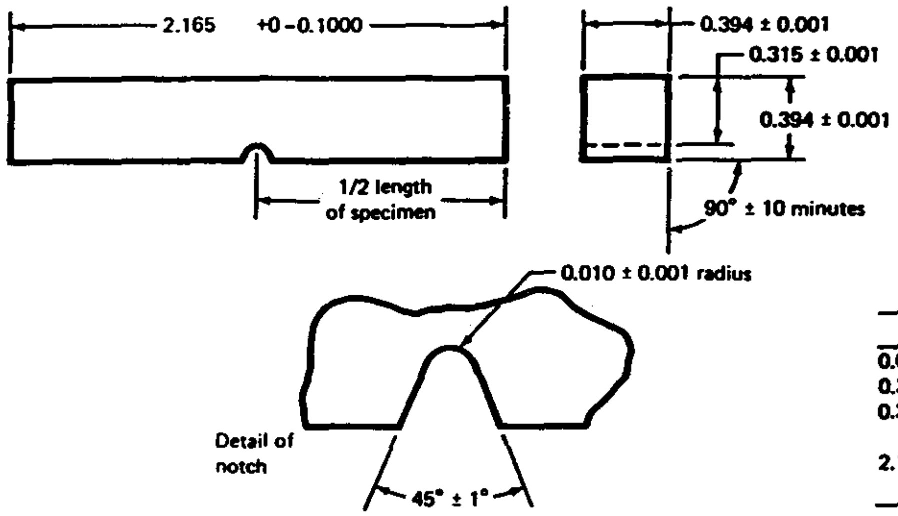
13.11.2 In preparing the two plates forming the test assembly, the standing member (web) shall have one edge machined throughout its entire length so that when the web is set upon the base plate (flange), which shall be straight and smooth, there will be intimate contact along the entire length of the joint.

13.11.3 A single pass fillet weld shall be deposited on one side of the joint. The minimum temperature of the assembly during welding shall be 65° F (20° C). The first electrode shall be continuously consumed to within the maximum permissible stub length of 2 in. (50 mm). Additional electrodes, if necessary, shall then be used to complete the weld for the full length of the joint, consuming each electrode completely as stated above, insofar as permitted by the length of the assembly.

13.11.4 When welding in the vertical position, the welding shall progress upwards, except for the E7048 classification. For this classification, welding shall progress downward.

13.11.5 The fillet weld shall be deposited using welding speeds compatible with the electrode classification being tested.

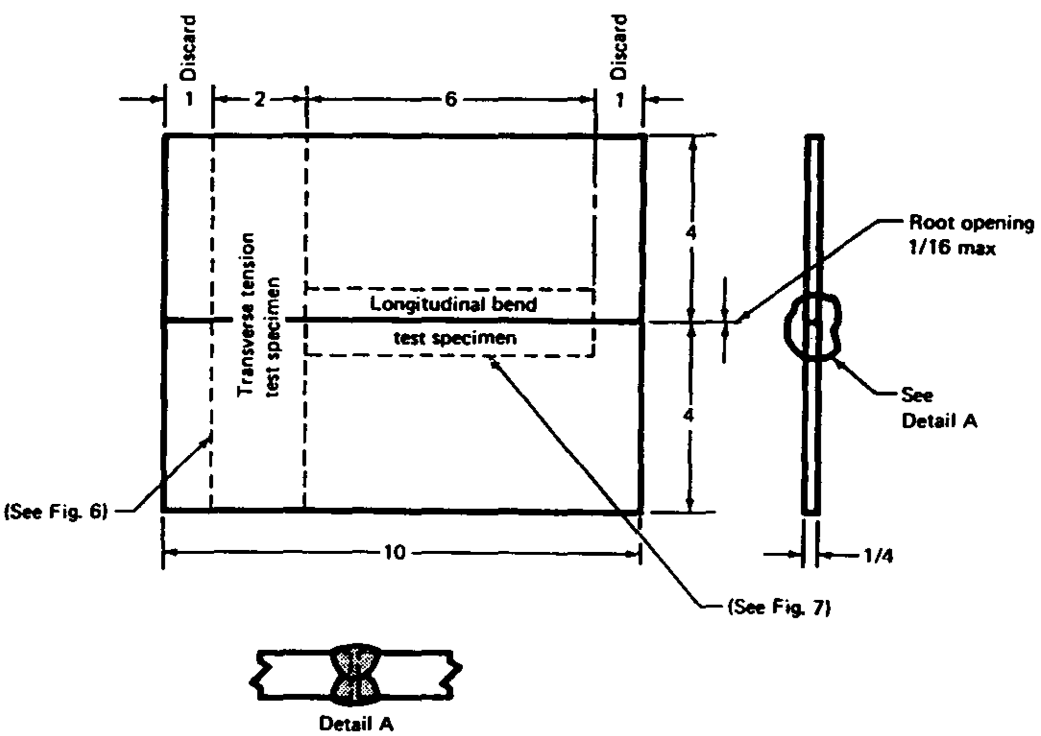
13.11.6 The completed weld first shall be visually examined. Then, a macrosection shall be removed from the deposit made with the first electrode at a point approximately 1 in. (25 mm) ahead of the crater end. The specimen shall be approximately 1 in. (25 mm) in width. One surface of the macrosection shall be polished, etched, and examined.



SI Equivalents	
in.	mm
0.010 ± 0.001	0.25 ± 0.025
0.315 ± 0.001	8 ± 0.025
0.394 ± 0.001	10 ± 0.025
2.165 +0 -0.100	55 +0 -2.5

Note: All dimensions except angles are in inches.

Fig. 4 — Details of V-notch impact test specimen

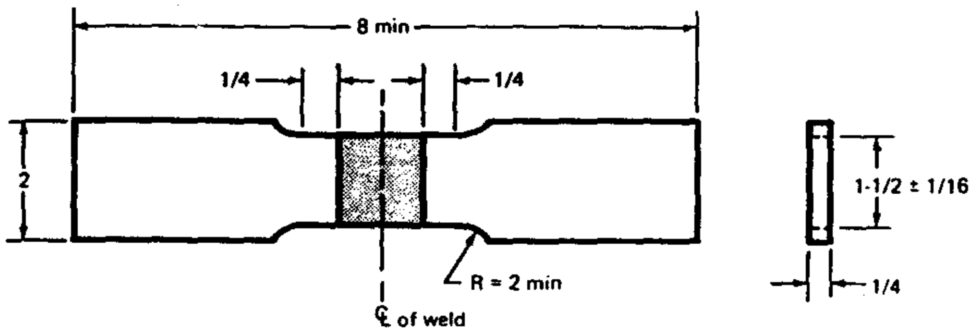


SI Equivalents	
in.	mm
1/16	1.6
1/4	6.4
1	25
2	50
4	100
6	150
10	250

Notes:

1. All dimensions are in inches.
2. Completed joint showing approximate weld configuration. See Footnote "K" of Table 8.

Fig. 5 — Details of test assembly for transverse tension and longitudinal guided bend tests



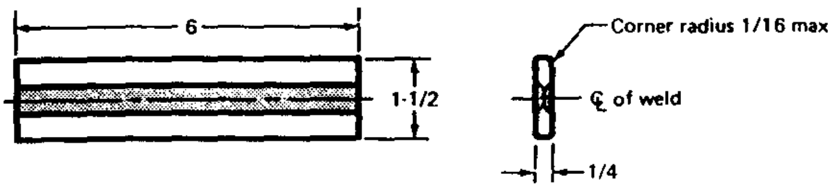
Notes:

1. All dimensions are in inches.
2. Weld reinforcement shall be ground or machined smooth and flush with the surfaces of the specimen. Grinding or machining marks shall be parallel to the length of the longest dimension of the specimen.
   Also, see Footnote "K" of Table 8.

Fig. 6 — Transverse tension test specimen (E6022)

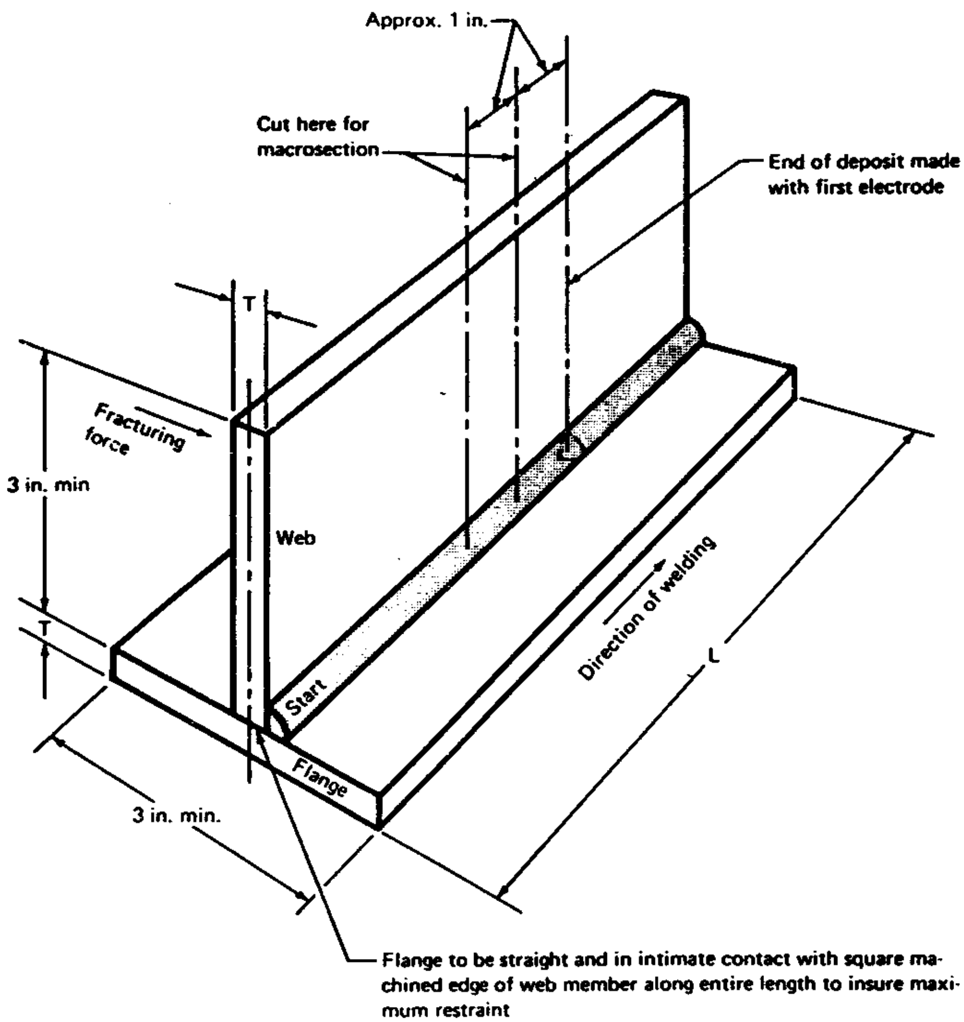
SI Equivalents

in.	mm
1/16	1.6
1/4	6.4
1-1/2 + 1/16	38 + 1.6
1-1/2	38
2	50
6	150
8	200



Note: Weld reinforcement shall be ground or machined smooth and flush with the surfaces of the specimen. Grinding or machining marks shall be parallel to the length of the weld.

Fig. 7 — Longitudinal guided bend test specimen



SI Equivalents	
in.	mm
1	25
3	75

Note: See Table 10 for values of T and L.

Fig. 8 — Preparation of fillet weld test specimen

13.11.7 Scribe lines shall be placed on the polished and etched surface, as shown in Fig. 10; and the weld size, the leg lengths, and the convexity (of convex fillet welds) shall be determined to the nearest 1/64 in. (0.5 mm) by actual measurement (see Fig. 10).

13.11.8 The remaining two joint sections shall be broken longitudinally through the fillet weld by a force exerted in the direction as shown in Fig. 8. The fractured surfaces shall be examined. If the weld pulls out of the test plate during bending, it shall not be considered as failure of the weld metal, and the test shall be repeated without penalty.

13.11.9 If necessary to facilitate fracture, one or more of the following procedures may be used:

13.11.9.1 Reinforcing welds, as shown in Fig. 11(a), may be added to each leg of the weld.

13.11.9.2 The position of the web on the flange may be changed as shown in Fig. 11(b).

13.11.9.3 The face of the weld may be notched, as shown in Fig. 11(c).

13.12 Coating Moisture Test

13.12.1 The following method shall be used to determine moisture content in an electrode covering: Oxygen shall be passed over the sample of covering in a nickel or clay boat placed in a fused silica or high temperature ceramic-type combustion tube which is then heated. Liberated water shall be collected in a weighed absorption U-tube, and the weight of water determined by the increase in the weight of the U-tube. The moisture content shall be expressed as a percentage of the weight of the covering sample.

Table 10
Requirements for preparation of fillet weld test assemblies

AWS Classification	Electrode size		Plate size[a] Thickness (T)		Plate size[a] Width, min		Plate size[a] Length[b], min (L)		Position of welding	Size of fillet weld	
	in.	mm	in.	mm	in.	mm	in.	mm		in.	mm
E6010 and E6011	3/32 & 1/8	2.4 & 3.2	Not required		–	–	–	–	–	–	–
	5/32	4.0	3/8	9.5	3	75	12	300	V and OH	1/4 max	6.4
	3/16	4.8	3/8	9.5	3	75	12	300	V and OH	5/16 max	8.0
	7/32	5.6	Not required		–	–	–	–	–	–	–
	1/4	6.4	1/2	12.7	3	75	18	450	H	1/4 min	6.4
	5/16	8.0	Not required		–	–	–	–	–	–	–
E6012 and E6013	1/16 to 1/8 (incl.)	1.6 to 3.2 (incl.)	Not required		–	–	–	–	–	–	–
	5/32	4.0	3/8	9.5	3	75	12	300	V and OH	1/4 max	6.4
	3/16	4.8	1/2	12.7	3	75	12	300	V and OH	3/8 max	9.5
	7/32	5.6	Not required		–	–	–	–	–	–	–
	1/4	6.4	1/2	12.7	3	75	18	450	H	5/16 min	8.0
	5/16	8.0	1/2	12.7	3	75	18	450	H	5/16 min	8.0
E7014	3/32 & 1/8	2.4 & 3.2	Not required		–	–	–	–	–	–	–
	5/32	4.0	3/8	9.5	3	75	12	300	V and OH	5/16 max	8.0
	3/16	4.8	3/8	9.5	3	75	12	300	H	1/4 min	6.4
	7/32	5.6	Not required		–	–	–	–	–	–	–
	1/4	6.4	1/2	12.7	3	75	18	450	H	5/16 min	8.0
	5/16	8.0	1/2	12.7	3	75	18	450	H	5/16 min	8.0
E7015 and E7016	3/32 & 1/8	2.4 & 3.2	Not required		–	–	–	–	–	–	–
	5/32	4.0	3/8	9.5	3	75	12	300	V and OH	5/16 max	8.0
	3/16	4.8	3/8	9.5	3	75	12	300	H	3/16 min	4.8
	7/32	5.6	Not required		–	–	–	–	–	–	–
	1/4	6.4	1/2	12.7	3	75	18	450	H	5/16 min	8.0
	5/16	8.0	Not required		–	–	–	–	–	–	–
E7018	3/32 & 1/8	2.4 & 3.2	Not required		–	–	–	–	–	–	–
	5/32	4.0	3/8	9.5	3	75	12	300	V and OH	5/16 max	8.0
	3/16	4.8	3/8	9.5	3	75	12	300	H	1/4 min	6.4
	7/32	5.6	Not required		–	–	–	–	–	–	–
	1/4	6.4	1/2	12.7	3	75	18	450	H	5/16 min	8.0
	5/16	8.0	Not required		–	–	–	–	–	–	–

Table 10
Requirements for preparation of fillet weld test assemblies (cont'd)

AWS Classification	Electrode size in.	Electrode size mm	Plate size[a] Thickness (T) in.	Thickness (T) mm	Width, min in.	Width, min mm	Length[b], min (L) in.	Length[b], min (L) mm	Position of welding	Size of fillet weld in.	Size of fillet weld mm
E6020	1/8	3.2	Not required		–	–	–	–	–	–	–
	5/32	4.0	3/8	9.5	3	75	12	300	H	5/32 min	4.0
	3/16	4.8	3/8	9.5	3	75	12 or 18[c]	300 or 450[c]	H	3/16 min	4.8
	7/32	5.6	Not required		–	–	–	–	–	–	–
	1/4	6.4	1/2	12.7	3	75	18	460	H	5/16 min	8.0
	5/16	8.0	Not required		–	–	–	–	–	–	–
E7024, E6027, E7027, and E7028	3/32[d] & 1/8	2.4[d] & 3.2	Not required		–	–	–	–	–	–	–
	5/32	4.0	3/8	9.5	3	75	12	300	H	3/16 min	4.8
	3/16	4.8	3/8	9.5	3	75	12 or 18[c]	300 or 460[c]	H	1/4 min	6.4
	7/32	5.6	Not required		–	–	–	–	–	–	–
	1/4	6.4	1/2	12.7	3	75	18	460	H	5/16 min	8.0
	5/16[e]	8.0[e]	Not required		–	–	–	–	–	–	–
E7048	1/8	3.2	Not required		–	–	–	–	–	–	–
	5/32	4.0	3/8	9.5	3	75	12	300	V-down & OH	5/16 max	8.0
	3/16	4.8	3/8	9.5	3	75	12 or 18[c]	300 or 460[c]	H & V-down	1/4 min	6.4

a. See Fig. 8.
b. In the event the end of the weld deposit made with the first electrode is closer than 4 in. (100 mm) from the end of the test plate, a starting tab or a longer test plate may be used.
c. When using 14 in. (350 mm) electrodes, the minimum length shall be 12 in. (300 mm); when using 18 in. (450 mm) electrodes, the minimum length shall be 16 in. (400 mm).
d. Class E7024 only.
e. Classes E6027, E7027, and E7024 only.

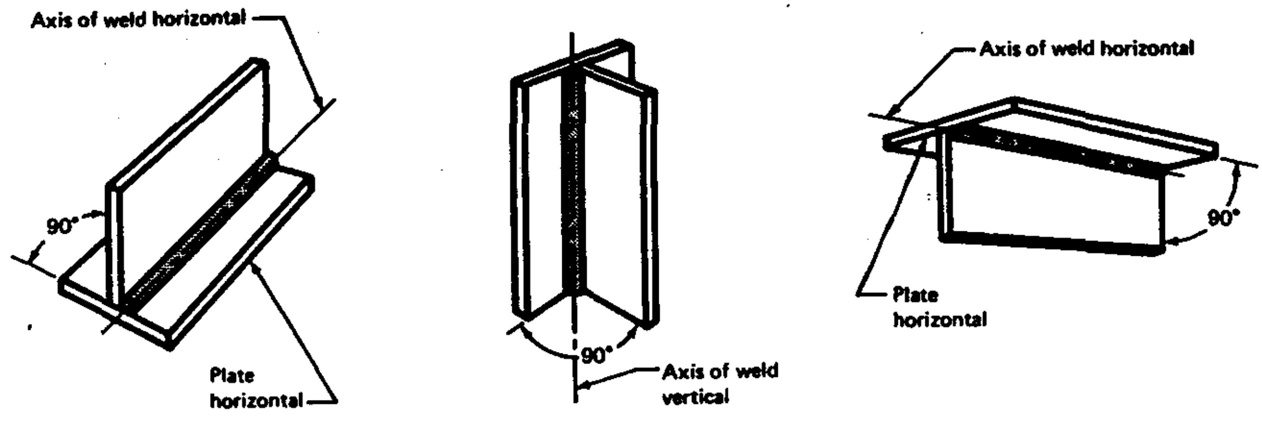
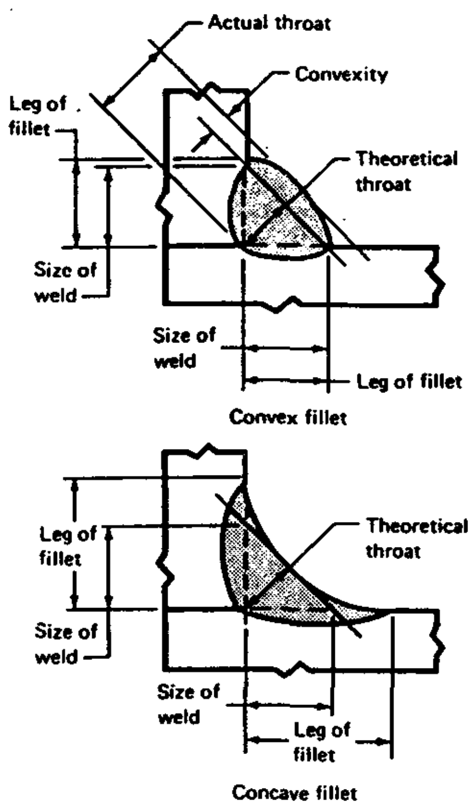


Fig. 9 — Positions of test plates for welding fillet welds



Note: Size of fillet weld = Leg length of largest inscribed isosceles right triangle. Fillet weld size, convexity, and leg lengths shall be determined by actual measurement (to nearest 1/64 in. (0.5 mm) on a section laid out with scribed lines as shown.

Fig 10 — Dimensions of fillet welds

13.12.2 The apparatus shall be as shown in Fig. 12[3] and shall consist of:

13.12.2.1 A tube furnace with a heating element of sufficient length to heat at least 8 in. (203 mm) of the middle portion of the combustion tube to 2000° F (1093° C).

13.12.2.2 An oxygen purifying train consisting of a needle valve, flow meter, 96 percent sulfuric acid wash bottle, spray trap, and anhydrous magnesium perchlorate drying tower.

13.12.2.3 Fused silica combustion tube 7/8 in. (22 mm) inside diameter with plain ends and a devitrification point above 2000° F (1093° C). (A high temperature ceramic-type tube can be used, but a higher blank value will result.) A plug of fine glass wool to filter the gases shall be inserted far enough into the exit end of the combustion tube to be heated to a temperature of 400 to 500° F (204 to 260° C).

13.12.2.4 Water absorption train consisting of a U-tube (Schwartz type) filled with anhydrous magnesium perchlorate and a concentrated sulfuric acid gas-sealing bottle.

13.12.3 The covering sample of approximately 4 grams shall be a composite of the middle portions of covering from three electrodes from the same package and shall be removed by bending or with clean, dry forceps. The sample shall be transferred immediately to a dried, stoppered vial or sample bottle.

3. Equivalent modifications may be used as described in Section A5.

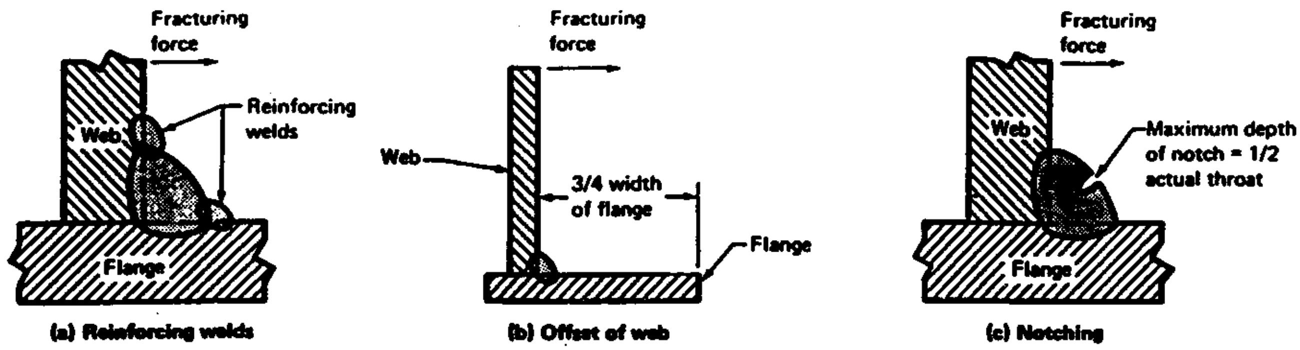


Fig. 11 — Alternate methods of facilitating fillet weld fracture

13.12.4 The furnace shall be operated at 1650 to 1800° F (900 to 982° C) with an oxygen flow of 200 to 250 ml per min. The nickel boat (see 13.12.1) shall be placed in the combustion tube for drying and the absorption U-tube shall be attached to the system for "conditioning." After 30 minutes, the absorption U-tube shall be removed and placed in the balance case. The nickel boat shall be removed and placed in a desiccator in which anhydrous magnesium perchlorate is used as the desiccant. After a cooling period of 20 minutes, the absorption U-tube shall be weighed.

13.12.5 In the blank determination, the procedure for an actual moisture determination shall be followed step by step with a single exception of omitting the sample. The nickel boat shall be removed from the desiccator and exposed to the atmosphere for a period approximating the time required to transfer the sample from the balance pan to the boat. The combustion tube shall be opened, the weighed absorption U-tube attached, the boat placed in the combustion tube, and the tube closed. After a heating period of 30 minutes, the absorption U-tube shall be removed and placed in the balance case. The nickel boat shall be transferred to the desiccator. After the 20 minute cooling period, the absorption U-tube shall be weighed and the gain in weight shall be taken as the blank value.

13.12.6 Immediately after weighing the absorption U-tube above, the sample covering shall be weighed on the balance dish and quickly transferred to the boat. The combustion tube shall be opened, the weighed absorption U-tube attached, the boat and sample transferred to the combustion tube, and the tube closed. After an ignition period of 30 minutes, the absorption U-tube shall be removed from the combustion tube and transferred to the balance case. If another sample is to be run, the boat shall be taken from the combustion tube, the ignited sample removed completely, and the boat transferred to the desiccator. The absorption U-tube shall be weighed after the 20 minute cooling period. Another determination may be started immediately. It is not necessary to repeat the blank determination since the same combustion boat can be used.

13.12.7 The calculation shall be made according to the following formula:

$$\text{Percent moisture} = \frac{A - B}{\text{Weight of sample}} \times 100$$

where:
A = gain in weight of absorption U-tube in moisture determination, and
B = gain in weight of absorption U-tube in blank determination.

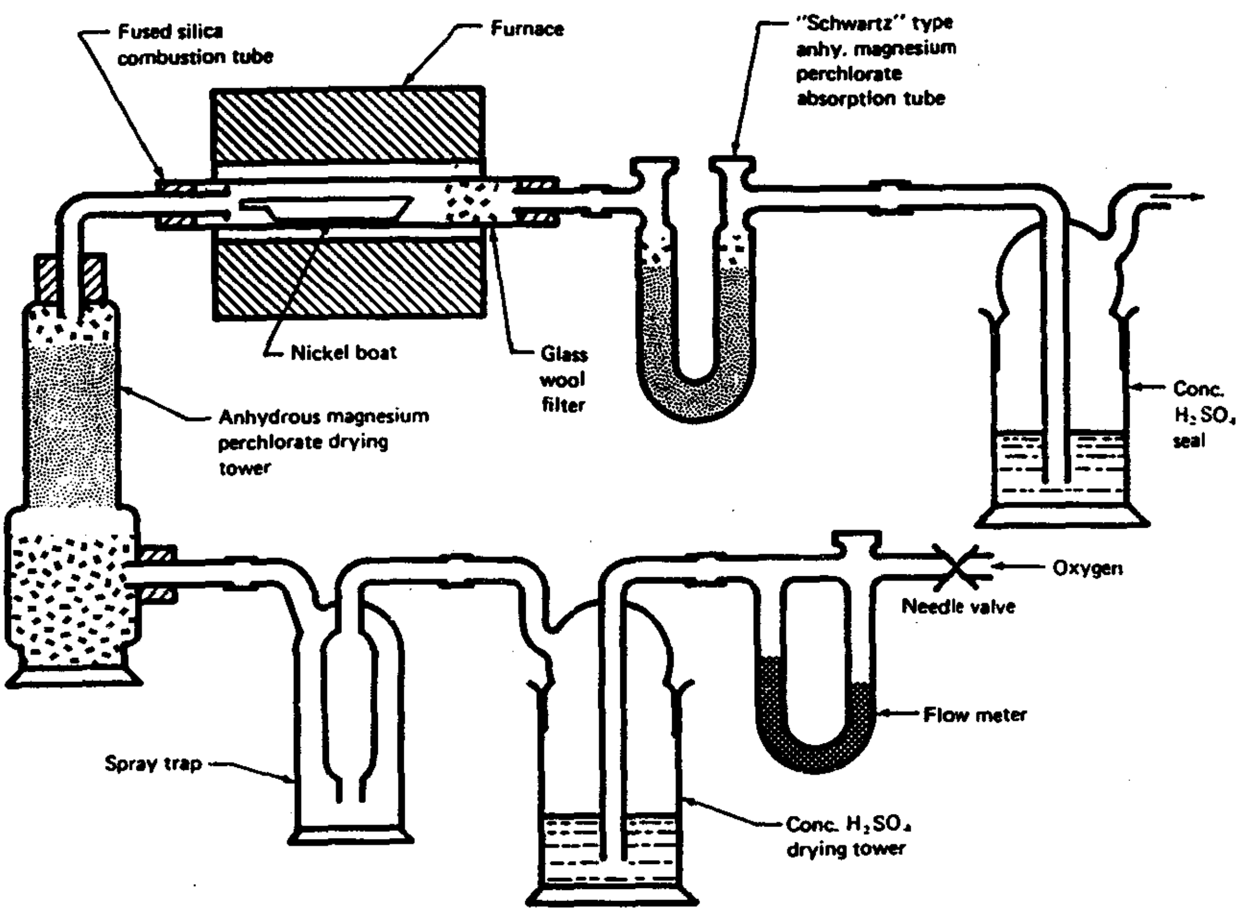


Fig. 12 — Schematic of train moisture determinations

Appendix: Guide to Classification of Carbon Steel Covered Arc Welding Electrodes

A1. Introduction and Method of Classification

A1.1 This guide is appended to the specification as a source of information. The guide is not mandatory and does not form a part of the specification.

A1.2 The classification system used in the specification follows the established pattern for AWS filler metal specifications. The letter E designates an electrode. The first two digits, 60, for example, designate tensile strength of at least 60 ksi of the deposited metal, in the as-welded condition. The third digit indicates the position in which satisfactory welds can be made with the electrode. Thus, the "1," as in E6010, means that the electrode is satisfactory for use in all positions (flat, vertical, overhead, and horizontal). The "2" as in E6020, indicates that the electrode is suitable for the flat position and also for making fillet welds in the horizontal position. The "4" in E7048 indicates that the electrode is suitable for vertical-down welding and for other positions (see Table 1). The last two digits taken together indicate the type current with which the electrode can be used and the type of covering on the electrode, as listed in Table 1.

A2. Welding Procedure and Classification Tests

A2.1 Weld metal properties may vary widely, according to the size of the electrode and amperage used, size of the beads in the weld, plate thickness, joint geometry, preheat and interpass temperatures, surface condition, base metal composition, dilution, etc. Because of the profound effect of these variables, a test procedure was chosen for this specification which would represent good welding practice and minimize variation of the most potent of these variables.

A2.2 It should be recognized, however that production practices may be different. The differences encountered may alter the properties of the weld metal. For instance, interpass temperatures may range from subfreezing to several hundred degrees Fahrenheit (Celsius). No single temperature or reasonable range of temperatures can be chosen for classification tests which will be representative of all of the conditions encountered in production work. Properties of production welds may vary accordingly, depending on the particular welding conditions. Weld metal properties may not duplicate, or even closely approach, the values listed and prescribed for test welds. For example, ductility in single pass fillets or welds in heavy plate made outdoors in chilly weather may drop to little more than half that required herein and normally obtained. This does not indicate that either the electrodes or the welds are below standard. It indicates only that the particular production conditions are more severe than the test conditions prescribed by this specification.

A2.3 Hydrogen is another factor involved. Weld metals, other than those from low hydrogen electrodes (E7015, E7016, E7018, E7028, and E7048), contain significant quantities of hydrogen for some period of time after they have been deposited. This hydrogen gradually escapes. After two to four weeks at room temperature or in 24 to 48 hours at 200 to 220° F (95 to 105° C), most of it has escaped. As a result of this change in hydrogen content, the yield, tensile, and impact strengths remain relatively unchanged, but the ductility of the weld metal increases towards its inherent value. This specification requires aging of the test bars at 200 to 220° F (95 to 105° C) for 48 hours before subjecting them to the tension test. This is done to minimize discrepancies in testing. Also, Table 3 (footnotes "c" and "e") provides for a lower yield strength or tensile strength, or both, when higher values of elongation are obtained. This approach recognizes the variation of the results which may be obtained when the electrodes are actually used in production.

A2.4 When weld deposits are given a postweld heat treatment, the temperature and time at temperature are very important. The following points concerning postweld heat treatment (stress relief in this case) should be kept in mind. The tensile and yield strengths generally are decreased as stress relief temperature and time at temperature are increased.

A2.5 Two welds made with low hydrogen electrodes of the same classification and the same welding procedure (including the same interpass temperature of 300 ± 25° F [150 ± 14° C]) will have significantly different tensile and yield strengths in the as-welded and stress-relieved conditions. Comparison of the values for as-welded and stress-relieved (1150 ± 25° F [620 ± 14° C] for one hour) weld metal will show the following:

A2.5.1 The tensile strength of the stress-relieved weld metal will be approximately 5000 psi (34.5 MPa) lower than that of the weld metal in the as-welded condition.

A2.5.2 The yield strength of the stress-relieved weld metal will be approximately 10,000 psi (69 MPa) lower than that of the weld metal in the as-welded condition.

A2.6 Conversely, stress-relieved weldments made with the same classification of low hydrogen electrode and using the same welding procedure excepting a variation in interpass temperature and stress relief time can have almost identical tensile and yield strengths. As an example, almost identical tensile and yield strengths will occur in two weldments, one using an interpass temperature of 300 ± 25° F (150 ± 14° C) stress relieved for one hour at 1150 ± 25° F (620 ± 14° C), and the other, using an interpass temperature of 200 to 225° F (93 to 107° C) and stress-relieved for 8 to 10 hours at 1150 ± 25° F (620 ± 14° C).

A2.7 Electrodes which meet all the requirements of any given classification may be expected to have similar characteristics. Certain minor differences continue to exist from one brand to another due to differences in production facilities and the usual differences in preferences that exist regarding specific operating characteristics. Furthermore, the only differences between the present E60 and E70 series are the differences in chemical composition and mechanical properties of the weld metal, as shown in Tables 2 and 3. In many applications, electrodes of either E60 or E70 series may be used.

A2.8 Since the electrodes within a given classification have similar operating characteristics and mechanical properties, the user can limit the study of available electrodes to those within a single classification after determining which classification best suits his particular requirements.

A2.9 This specification does not establish values for all characteristics of the electrodes falling within a given classification, but it does establish values to measure those of major importance. In some instances, a particular characteristic is common to a number of classifications and testing for it is not necessary. In other instances, the characteristics are so intangible that no adequate tests are available. This specification does not necessarily provide all the information needed to determine which classification will best fulfill a particular need. Therefore, a discussion of each classification is included in Section A4 to supplement information given elsewhere in the specification.

A2.10 Some important tests for measuring major electrode characteristics are as follows:

A2.10.1 Soundness Test. Nearly all of the carbon steel electrodes covered by this specification are capable of producing weld deposits that meet most radiographic soundness requirements when deposited in certain ways and under certain conditions. However, if incorrectly applied, unsound welds may be produced by any of the electrodes. For electrodes of some classifications, the radiographic requirements in Table 5 are not necessarily indicative of the average radiographic soundness to be expected in production use. Under most conditions, electrodes of the E6010, E6011, and E6020 classifications can be expected to produce the best radiographic results. Under certain conditions, notably in welding long, continuous joints in relatively heavy members, low hydrogen electrodes of the E7015, E7016, and E7018 classifications will often produce even better results. On the other hand, in joints open to the atmosphere on the back side, at the ends of joints, in short joints with many ends, and welds in small, thin, irregularly shaped joints, such as small diameter pipe, the low hydrogen electrodes tend to produce welds of poor radiographic soundness. E6013 electrodes usually produce the best radiographic soundness in welding small, thin parts. E6027 and E7028 electrodes produce welds which may be either quite good or rather inferior in radiographic soundness. The tendency seems to be in the latter direction. Of all types, the E6012 and E7024 electrodes generally produce welds with the least favorable radiographic soundness.

A2.10.2 Fillet Weld Test. This test is included as a means of demonstrating the usability of an electrode. This test is concerned with the appearance of the weld; i.e., weld surface contour and smoothness, undercut, overlap, size, and resistance to cracking. It also provides an excellent and inexpensive method of determining the adequacy of root penetration (one of the important usability considerations for an electrode).

A2.10.3 Notch Toughness. Notch toughness requirements are included in the specification. All classes of electrodes in this specification can deposit weld metal of sufficient notch toughness for most applications. The inclusion of impact requirements for certain classes of electrodes in this specification allows the specification to be used as a guide in selecting electrodes where low-temperature impact properties are specifically required for a certain steel. There can be considerable differences among the impact test results of a given electrode unless particular attention is given to the welding of the test assembly, the preparation of the specimens, and the testing itself. Note that the impact energy values are for Charpy V-notch specimens; these values should not be confused with values obtained with keyhole notch test specimens.

A2.11 Operating and usability characteristics in the various positions are measured by the soundness and fillet weld tests. In the case of the fillet weld test, it is necessary to obtain both proper fillet weld profile and adequate fusion at the root. Any electrode meeting the fillet weld test requirements and possessing the proper mechanical properties, as measured by the all-weld-metal tension test, will produce the proper fillet weld shear strength.

A2.12 Other areas where controls are required are as follows:

A2.12.1 Electrode Coating Moisture Content and Reconditioning

A2.12.1.1 Hydrogen can have adverse effects on welds in some steels under certain conditions. One source of this hydrogen is moisture in the electrode coverings. For this reason, the proper storage, treatment, and handling of electrodes is necessary.

A2.12.1.2 Electrodes are manufactured to be within acceptable moisture limits, consistent with the type of covering and strength of the weld metal. They are then normally packaged in a container which has been designed to provide the degree of moisture protection considered necessary for the type of covering involved.

A2.12.1.3 The low hydrogen electrodes E7015, E7016, E7018, E7028, and E7048 are the most critical types for moisture absorption. These types of inorganic covered electrodes are designed and developed to contain the very minimum amount of moisture in their coverings and should be stored and handled with considerable care. For this reason, a requirement limiting the moisture content of the coverings of low hydrogen electrodes to 0.6 percent maximum is included in this specification. Electrodes which have been exposed to humid atmospheres may absorb excess moisture. The moisture content of electrodes which have been exposed to the atmosphere should not exceed the 0.6 percent limit.

A2.12.1.4 Tests conducted to date indicate that E7018 low hydrogen electrodes may be left out of oven and held in open portable containers for up to 10 hours when joining carbon steels to carbon steels (0.30 max percent carbon). No adverse effects from this length of out-of-oven time under very humid conditions (80 percent relative humidity and 80° F [27° C]) has been evidenced when joining carbon steels. The user is cautioned that this may not be the case when joining carbon steels to alloy steels, or alloy steels to alloy steels.

A2.12.1.5 If there is a possibility that the electrodes may have picked up excessive moisture, they may be restored by rebaking. Some electrodes require rebaking at a temperature as high as 800° F (425° C) for approximately 2 hours. The manner in which the electrodes have been produced and the relative humidity and temperature conditions under which the electrodes are stored determine the proper length of time and temperature used for reconditioning. Some typical storage and drying conditions are included in Table A1.

A2.12.1.6 Coverings for E6010 and E6011 electrodes have moisture levels of 3 to 7 percent; therefore, storage or conditioning above ambient temperature may dry them too much and adversely affect their operation (see Table A1).

A2.12.2 Core Wire. The core wire for all the electrodes in this specification is usually a rimmed or capped steel having a typical composition of 0.10 percent carbon, 0.45 percent manganese, 0.03 percent sulphur, 0.02 percent phosphorous, and 0.01 percent silicon.

A2.12.3 Coverings

A2.12.3.1 Electrodes of some classifications have substantial quantities of iron powder added to their coverings. The iron powder fuses with the core wire and the other metal in the covering as the electrode melts down and is deposited as weld metal, just as is the core wire. Relatively high currents can be used since a considerable portion of the electrical energy passing through the electrode is used to melt the larger covering and iron powder therein. The result is that electrodes with iron powder in their covering usually have higher deposition rates than electrodes without iron powder.

A2.12.3.2 Due to the thick covering and deep arc cup produced, iron powder electrodes can be used very effectively with a "drag" technique. This technique consists of keeping the electrode covering in contact with the workpiece (both members, in fillet welds) at all times, which makes for easy handling. However, a "close arc" technique is preferable if the 3/32 in. (2.4 mm) or 1/8 in. (3.2 mm) sizes are to be used in out-of-position welding or for making groove welds. Tests conducted to date have not indicated any significant difference in mechanical properties for the two techniques.

A2.12.3.3 The E70XX electrodes were included in this specification to acknowledge the higher strength levels obtained with many of the iron powder and low hydrogen electrodes, as well as to recognize the industry demand for electrodes with 70000 psi (485 MPa) minimum tensile strength. Unlike the E70XX classification in AWS A5.5, Specification for Low Alloy Steel Covered Arc Welding Electrodes, these electrodes do not contain deliberate alloy additions, nor are they required to meet minimum tensile properties after postweld heat treatment.

A2.12.3.4 E70XX low hydrogen electrodes have mineral coverings which are high in limestone and other ingredients that are low in moisture and hence "low in hydrogen content." Low hydrogen electrodes were developed for welding low alloy high-strength steels, some of which were high in carbon content. Electrodes with other than low hydrogen coverings produce "hydrogen-induced cracking" in those steels. These "underbead" cracks occur in the base metal, usually just below the weld bead, and are caused by the hydrogen absorbed from the arc atmosphere. The elimination of hydrogen, with its consequent underbead cracking, permits "difficult-to-weld steels" to be welded with less preheat than is required for other electrodes. Although these cracks do not generally occur in carbon steels which have a low carbon content, they may occur whenever other electrodes are used on high-strength steels. Low hydrogen electrodes are also used to weld high-sulphur and enameling steels. Electrodes with other than low hydrogen coverings give porous welds on high-sulphur steels. With

Table A1
Typical storage and drying conditions for covered arc welding electrodes

AWS Classifications	Storage conditions* Ambient air	Holding ovens	Drying[a]
E6010, E6011	Ambient temperature	Not recommended	Not recommended
E6012, E6013, E6020, E6022, E6027, E7014, E7024	80 ± 20° F (30 ± 10° C) 50 percent max relative humidity	20° F (10° C) to 40° F (20° C) above ambient temperature	275 ± 25° F (135 ± 15° C) 1 hour at temperature
E7015, E7016, E7018, E7028, E7048	80 ± 20° F (30 ± 10° C) 50 percent max relative humidity	50° F (30° C) to 250° F (140° C) above ambient temperature	475 ± 25° F (245 ± 15° C) 2 hours at temperature

a. Because of inherent differences in manufacturer, the suppliers of these electrodes should be consulted for the exact drying conditions.
* After removal from manufacturer's packaging.

enameling steels, the hydrogen that escapes after welding with other than low hydrogen electrodes produces holes in the enamel.

A2.12.4 Amperage Ranges. Table A2 gives amperage ranges which are satisfactory for most classes. When welding vertically upward, currents near the lower limit of the range are generally used.

A2.13 Details of Tests for 3/32, 1/8, and 7/32 in. (2.4, 3.2, and 5.6 mm) Diameter Electrodes

A2.13.1 The details of testing provided below may be used to demonstrate the mechanical properties and soundness of deposited weld metal and the usability of electrodes in sizes for which testing is not mandatory under Section D of this specification. These sizes of electrodes are not normally tested for classification under this specification, since the tests specified in Section D for adjacent sizes usually provide sufficient evidence of compliance with the specification to make testing of these sizes unnecessary. These details of testing are provided so that the purchaser of these sizes of electrodes may test them at his own option and expense. The results of these tests should conform to the requirements set forth in Section A of the specification.

A2.13.2 Samples for chemical analysis may be obtained by using the testing procedure outlined in 13.3 of the specification.

A2.13.3 The test assembly for the soundness test, all-weld-metal tension, and impact tests may be prepared as detailed in Fig. A1. When an electrode classification permits its use with AC or DC either polarity, the electrode should be tested on both AC and DCEN (electrode negative). DCEN only may be used where either polarity of DC is permitted for an electrode classification. The assembly should be prepared essentially in accordance with Section 13.4, except that the pass sequence used should conform with that shown in the table in Fig. A1 as applicable. Test specimens should be removed as detailed in Fig. A1, and testing should be performed as outlined in Section D of the specification. The impact specimens should be prepared in accordance with Fig. 4. The sub-size tensile strength specimen for 3/32 and 1/8 in. electrodes may be prepared in accordance with Fig. A2. The strength of 7/32 in. electrodes should be determined using the standard sized tension specimen of Fig. 3.

A2.13.4 The test assembly for the fillet weld test, Fig. 8, should be prepared as detailed in Table A3. Preferred test positions of welding and required sizes of fillet also are shown.

A3. Ventilation During Welding

A3.1 Five major factors govern the quantity of fumes to which welders and welding operators can be exposed during welding. These are:

A3.1.1 Dimensions of the space in which welding is done (with special regard to the height of the ceiling).

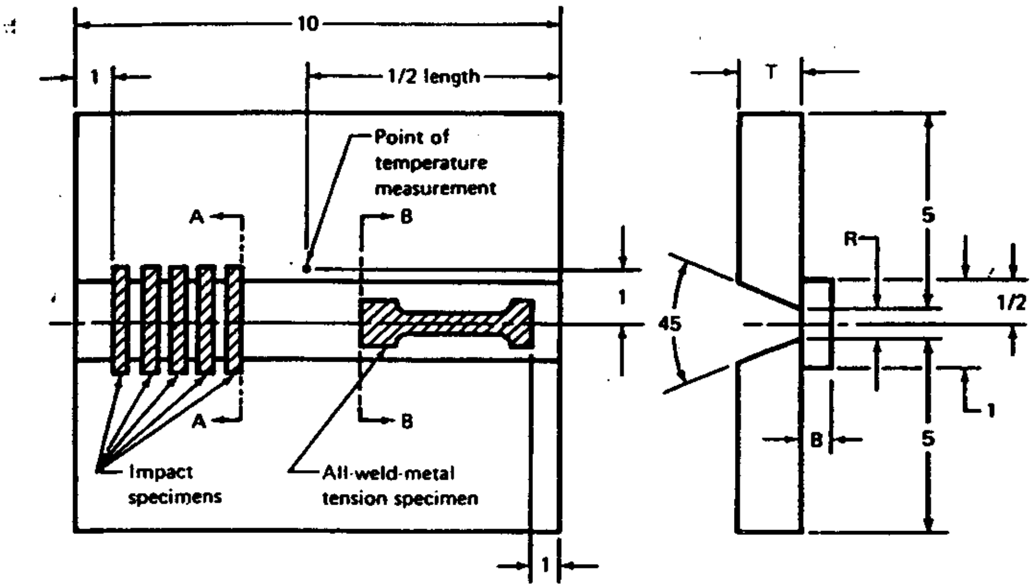
A3.1.2 Number of welders and welding operators working in that space.

A3.1.3 Rate of evolution of fumes, gases, or dust, according to the materials and processes involved.

Table A2
Typical amperage ranges

Electrode diameter in.	Electrode diameter mm	E6010 and E6011	E6012	E6013	E6020	E6022	E6027 and E7027	E7014	E7015, E7016, and E7016-1	E7018 and E7018-1	E7024-1, E7024, and E7028	E7048
1/16	1.6	–	20 to 40	20 to 40	–	–	–	–	–	–	–	–
5/64	2.0	–	25 to 60	25 to 60	–	–	–	–	–	–	–	–
3/32[a]	2.4[a]	40 to 80	35 to 85	45 to 90	–	–	–	80 to 125	65 to 110	70 to 100	100 to 145	–
1/8	3.2	75 to 125	80 to 140	80 to 130	100 to 150	110 to 160	125 to 185	110 to 160	100 to 150	115 to 165	140 to 190	80 to 140
5/32	4.0	110 to 170	110 to 190	105 to 180	130 to 190	140 to 190	160 to 240	150 to 210	140 to 200	150 to 220	180 to 250	150 to 220
3/16	4.8	140 to 215	140 to 240	150 to 230	175 to 250	170 to 400	210 to 300	200 to 275	180 to 255	200 to 275	230 to 305	210 to 270
7/32	5.6	170 to 250	200 to 320	210 to 300	225 to 310	370 to 520	250 to 350	260 to 340	240 to 320	260 to 340	275 to 365	–
1/4	6.4	210 to 320	250 to 400	250 to 350	275 to 375	–	300 to 420	330 to 415	300 to 390	315 to 400	335 to 430	–
5/16[a]	8.0[a]	275 to 425	300 to 500	320 to 430	340 to 450	–	375 to 475	390 to 500	375 to 475	375 to 470	400 to 525	–

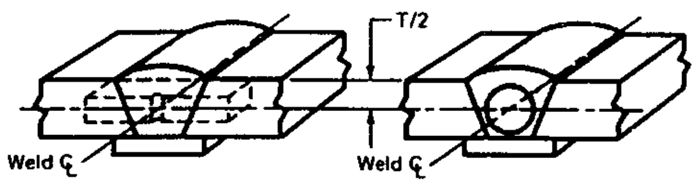
a. These diameters are not manufactured in the E7028 classification.



(a) Test plate showing location of test specimens

Note: All dimensions except angles are in inches.

SI Equivalents	
in.	mm
1/16	1.6
1/2	13
1	25
5	125
10	250



Section AA

(b) Orientation and location of impact specimen

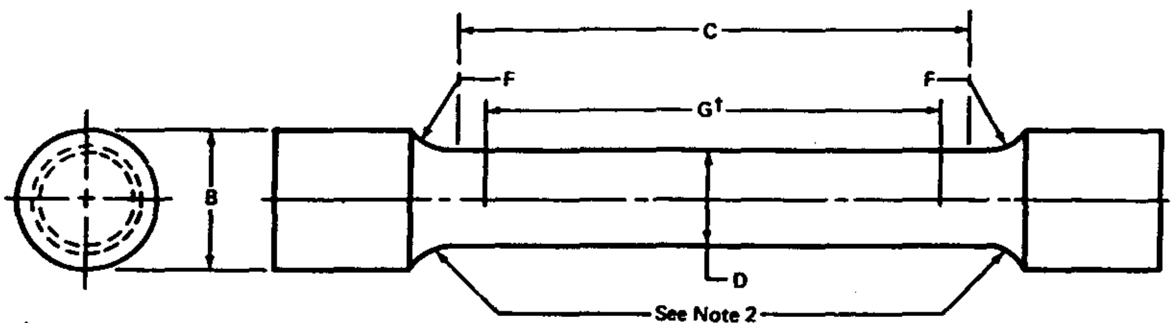
Section BB

(c) Location of all-weld-metal tension specimen

Electrode size in.	Electrode size mm	(T) Plate thickness min in.	(T) Plate thickness min mm	(R) Root opening in.	(R) Root opening mm	(B) Backing thickness in.	(B) Backing thickness mm	Full weave for layer no.	Split weave Layer no.	Split weave Passes per layer	Split weave Number of layers
3/32[a]	2.4	1/2	13	1/4	6	1/4	6	b	b	b	b
1/8	3.2	1/2	13	1/4	6	1/4	6	1	3 to top	2	5 to 7
7/32	5.6	3/4	19	1/2	13	1/2	13	1 and 2	3 to top	2	6 to 8

a. For the soundness test, the test plate thickness shall be 1/2 in. (6.4 mm).
b. Record pass and layer thickness.

Fig. A1 — Details of test assembly for mechanical testing of 3/32 in. (2.4 mm), 1/8 in. (3.2 mm), and 7/32 in. (5.6 mm) diameter electrodes



G† = Gage length

Dimensions of specimen, in.						
Test plate thickness	D	G	C	B	F, min	Approximate area sq. in.
1/2	0.250 + 0.005	1.000 + 0.005	1-1/4	3/8	0.18	1/20

Dimensions of specimen, mm						
Test plate thickness	D	G	C	B	F, min	Approximate area sq. mm
12.7	6.4 ± 0.13	25.4 + 0.13	31.8	9.5	4.6	32

Notes:

1. Dimensions G and C shall be as shown, but ends may be of any shape to fit the testing machine holders as long as the load is axial.
2. The diameter of the specimen within the gage length shall be slightly smaller at the center than at the ends. The difference shall not exceed one percent of the diameter.
3. When the extensometer is required to determined yield strength or other elastic properties, dimensions C and L may be modified. However, the percent of the elongation shall be based on dimension G.
4. The surface finish within the C dimension shall be no rougher than 63 μ in. (1.6 μm).

Fig. A2 — Sub-size all-weld-metal tension test specimen dimensions

A3.1.4 The proximity of the welder or welding operator to the fumes as they issue from the welding zone and to the gases and dusts in the space in which he is working.

A3.1.5 The ventilation provided to the space in which the welding is done.

A3.2 American National Standard Z49.1, Safety in Welding and Cutting (published by the American Welding Society), discusses the ventilation that is required during welding and should be referred to for details. Attention is particularly drawn to Section 8 of that document, Health Protection and Ventilation.

A4. Description and Intended Use of Electrodes

A4.1 E6010 Classification

A4.1.1 E6010 electrodes are characterized by a deeply penetrating, forceful, spray type arc and readily removable, thin, friable slag which may not seem to completely cover the deposit. Fillet welds are usually relatively flat in profile and have a rather coarse, unevenly spaced ripple. The coverings are high in cellulose, usually exceeding 30 percent by weight. The other

Table A3
Preparation of fillet weld test assemblies

AWS Classification	Electrode size in.	Electrode size mm	Plate, size[a] Thickness (T) in.	Thickness (T) mm	Width, min in.	Width, min mm	Length[b], min (L) in.	Length[b], min (L) mm	Position of welding	Size of fillet weld in.	Size of fillet weld mm
E6010 and E6011	3/32	2.4	1/8	3.2	3	75	10	250	V & OH	5/32 max	4.0
	1/8	3.2	3/16	4.8	3	75	12	300	V & OH	3/16 max	4.8
	7/32	5.6	1/2	12.7	3	75	12 or 18	300 or 460[c]	H	1/4 min	6.4
	5/16	8.0	1/2	12.7	3	75	18	460[c]	H	1/4 min	6.4
E6012 and E6013	1/16-5/64	1.6-2.0	1/8	3.2	3	75	6	150	V & OH	1/8 max	3.2
	3/32	2.4	1/8	3.2	3	75	10	250	V & OH	1/8 max	3.2
	1/8	3.2	3/16	4.8	3	75	12	300	V & OH	3/16 max	4.8
	7/32	5.6	1/2	12.7	3	75	12 or 18	300 or 460[c]	H	1/4 min	6.4
E7014	3/32	2.4	1/8	3.2	3	75	12	300	V & OH	5/32 max	4.0
	1/8	3.2	3/16	4.8	3	75	14	360	V & OH	3/16 max	4.8
	7/32	5.6	3/8	9.5	3	75	12 or 18	300 or 460[c]	H	1/4 min	6.4
E7015 and E7016	3/32	2.4	1/8	3.2	3	75	10	250	V & OH	5/32 max	4.0
	1/8	3.2	1/4	6.4	3	75	12	395	V & OH	3/16 max	4.8
	7/32	5.6	1/2	12.7	3	75	12 or 18	300 or 460[c]	H	1/4 min	6.4
	5/16	8.0	1/2	12.7	3	75	18	460	H	5/16 min	8.0
E7018 and E7018-1	3/32	2.4	1/8	3.2	3	75	10 or 12	250 or 300[f]	V & OH	3/16 max	4.8
	1/8	3.2	1/4	6.4	3	75	12	300	V & OH	1/4 max	6.4
	7/32	5.6	1/2	12.7	3	75	12 or 18	300 or 460[c]	H	1/4 min	6.4
	5/16	8.0	1/2	12.7	3	75	18	460	H	5/16 min	8.0
E6020	1/8	3.2	1/4	6.4	3	75	12	300	H	1/8 min	3.2
	7/32	5.6	1/2	12.7	3	75	18	460	H	1/4 min	6.4
	5/16	8.0	1/2	12.7	3	75	18	460	H	5/16 min	8.0
E6027, E7024, E7027, and E7028	3/32	2.4[d]	1/4	6.4	3	75	10	250	H	5/32 min	4.0
	1/8	3.2	1/4	6.4	3	75	12	300	H	5/32 min	6.4
	7/32	5.6	1/2	12.7	3	75	18	460	H	1/4 min	6.4
	5/16	8.0[e]	1/2	12.7	3	75	18	460	H	5/16 min	8.0
E7048	1/8	3.2	1/4	6.4	3	75	12	300	OH & V-down[d]	1/4 max	6.4

a. See Fig. 8.
b. In the event the end of the weld deposit made with the first electrode is closer than 4 in. (100 mm) from the end of the test plate, a starting tab or a larger test plate may be used.
c. When using 14 in. (350 mm) electrodes, the minimum length shall be 12 in. (300 mm); when using 18 in. (460 mm) electrodes, the minimum length shall be 16 in. (406 mm).
d. Class E7024 only.
e. Classes E6027 and E7024 only.
f. When using 12 in. (300 mm) electrodes, the minimum length shall be 10 in. (250 mm); when using 14 in. (350 mm) electrodes, the minimum length shall be 12 in. (300 mm).

materials generally used in the covering include titanium dioxide, metallic deoxidizers such as ferromanganese, various types of magnesium or aluminum silicates, and liquid sodium silicate as a binder. Because of their covering composition, these electrodes are generally classified as the high-cellulose sodium type.

A4.1.2 These electrodes are recommended for all-position work, particularly on multiple pass applications in the vertical and overhead positions and where welds of radiographic soundness are required.

A4.1.3 The majority of applications for these electrodes is in joining carbon steel. However, they have been used to advantage on galvanized plate and on some low alloy steels. Typical applications include shipbuilding, structures such as buildings and bridges, storage tanks, piping, and pressure vessel fittings. Since the applications are so widespread, a discussion of each is impractical. Sizes larger than 3/16 in. (4.8 mm) generally are not used in all positions.

A4.1.4 These electrodes have been designed for use with DCEP (electrode positive). The maximum amperage that can generally be used with the larger sizes of these electrodes is limited in comparison to that for other classifications due to the high spatter loss that occurs with high amperage.

A4.2 E6011 Classification

A4.2.1 E6011 electrodes are designed to duplicate the usability characteristics and mechanical properties of the E6010 classification using AC. Although also usable with DCEP (electrode positive), a decrease in penetration will be noted when compared to the E6010 electrodes. Penetration, arc action, slag, and fillet weld appearance are similar to those of the E6010 electrodes.

A4.2.2 The coverings are also high in cellulose and are classified as the high-cellulose potassium type. In addition to the other ingredients normally found in E6010 coverings, small quantities of calcium and potassium compounds usually are present.

A4.2.3 Sizes larger than 3/16 in. (4.8 mm) generally are not used in all positions. The amperage and voltage ranges are identical with those of the E6010 electrode. High amperage results in high spatter loss.

A4.3 E6012 Classification

A4.3.1 E6012 electrodes are characterized by medium penetration and dense slag which completely covers the bead. The coverings are high in titania, usually exceeding 35 percent by weight, and usually are referred to as the "titania" or "rutile" type. The coverings generally also contain small amounts of cellulose and ferromanganese, and various silicious materials such as feldspar and clay with sodium silicate as a binder. Also, small amounts of certain calcium compounds may be used to produce satisfactory arc characteristics on DCEN (electrode negative).

A4.3.2 Fillet welds tend to be convex in profile with a smooth even ripple in the horizontal position, and a widely spaced convex ripple in the vertical position which becomes smoother and more uniform as the size of the weld is increased. Ordinarily, a larger size fillet must be made in the vertical and overhead positions using E6012 electrodes compared to welds with E6010 and E6011 electrodes of the same diameter.

A4.3.3 The E6012 electrodes are all-position electrodes. However, more of the larger sizes are used in the flat and horizontal positions than in the vertical and overhead positions. The larger sizes often are used for single pass, high-speed, high current, horizontal fillet welds. Their ease of handling, good fillet weld profile, and ability to bridge gaps under conditions of poor fit-up and to withstand high amperages make them very well suited to this type of work. The electrode size used for vertical and overhead welding is frequently one size smaller than would be used with an E6010 or E6011 electrode.

A4.3.4 Weld metal from these electrodes is generally lower in ductility and may be higher in yield strength (1 to 2 ksi [690 to 1380 kPa]) than weld metal from the same size of either the E6010 or E6011 electrodes.

A4.4 E6013 Classification

A4.4.1 E6013 electrodes, although very similar to the E6012 electrodes, have distinct differences. Their slag system promotes better slag removal and a smoother arc transfer than E6012 electrodes. This is particularly the case for the small diameters (1/16, 5/64, and 3/32 in. [1.6, 2.0, and 2.4 mm]). This permits satisfactory operation with lower open-circuit AC voltage. E6013 electrodes were designed specifically for light sheet metal work. However, the larger diameters are used on many of the same applications as E6012 electrodes and provide similar penetration. The smaller diameters provide less penetration than is obtained with E6012 electrodes.

A4.4.2 Coverings of E6013 electrodes contain rutile, cellulose, ferromanganese, potassium silicate as a binder, and other silicious materials. The potassium compounds permit the electrodes to operate with AC at low amperages and low open-circuit voltages.

A4.4.3 E6013 electrodes are similar to the E6012 electrodes in operating characteristics and bead appearance. The arc action tends to be quieter and the bead surface smoother with a finer ripple. The operating characteristics of E6013 electrodes vary slightly from brand to brand. Some are usually recommended for sheet metal applications where their ability to weld satisfactorily in the vertical-down position is an advantage. Others, with a more fluid slag, are used for horizontal fillet welds and other general purpose welding. These electrodes produce a flat fillet weld rather than the convex contour characteristic of E6012 electrodes. They are also suitable for making groove welds because of their concave bead and easily removed slag. In addition, the weld metal is definitely freer of slag and oxide inclusions than E6012 weld metal and gives better radiographic soundness. Welds with the smaller diameter E6013 electrodes often meet the Grade 1 radiographic requirements of this specification.

A4.4.4 E6013 electrodes usually cannot withstand the high amperages that can be used with E6012 electrodes in the flat and horizontal positions. Amperages in the vertical and overhead positions, however, are similar to those used with E6012 electrodes.

A4.5 E7014 Classification

A4.5.1 E7014 electrode coverings are similar to those of E6012 and E6013 electrodes, but with the addition of iron powder for obtaining higher deposition rates. The covering thickness and the amount of iron powder in it are less than for E7024 electrodes (see A4.12).

A4.5.2 E7014 electrodes are similar to E6013 electrodes, except for the addition of iron powder for obtaining higher deposition rates. The iron powder also permits the use of higher amperages than are used for E6012 and E6013 electrodes. The amount and character of the slag permit E7014 electrodes to be used in all positions.

A4.5.3 The E7014 electrodes are suitable for welding carbon and low alloy steels. Typical weld beads are smooth with fine ripples. Penetration is approximately the same as that obtained with E6012 electrodes, which is advantageous when welding over gaps due to poor fit-up. The profile of fillet welds tends to be flat to slightly convex. The slag is easy to remove. In many cases, it removes itself.

A4.6 E7015 Classification

A4.6.1 E7015 electrodes are low hydrogen electrodes to be used with DCEP (electrode positive). The slag is chemically basic.

A4.6.2 E7015 electrodes are commonly used for making small welds on heavy sections, since they are less susceptible to cracking (see A2.12.3.4). They are also used for welding high sulphur and enameling steels. Welds with E7015 electrodes in high sulphur steels may produce a very tight slag and a very rough or irregular bead appearance in comparison to welds with the same electrodes in steels of normal sulphur levels.

A4.6.3 The arc of E7015 electrodes is moderately penetrating. The slag is heavy, friable, and easy to remove. The weld beads are convex, although fillet welds may be flat.

A4.6.4 E7015 electrodes are used in all positions through the 5/32 in. (4.0 mm) size. Larger electrodes are used for groove welds in the flat position and fillet welds in the horizontal and flat positions.

A4.6.5 Amperages for E7015 electrodes are higher than those used with E6010 electrodes of the same diameter. The shortest possible arc should be maintained for best results with E7015 electrodes. This reduces the risk of porosity. The necessity for preheat is reduced; therefore, better welding conditions are provided.

A4.7 E7016 Classification

A4.7.1 E7016 electrodes have all the characteristics of E7015 electrodes, plus the ability to operate on AC. The core wire and coverings are very similar to those of E7015, except for the use of a potassium silicate binder or other potassium salts in the coverings to facilitate their use with AC. Most of the preceding discussion on E7015 electrodes applies equally well to the E7016 electrodes. The discussion in A2.12.3.4 also applies.

A4.7.2 Electrodes identified as E7016-1 have the same usability and design characteristics as E7016 electrodes except that the manganese content is set at the high end of the range. They are intended for use in situations requiring a lower transition temperature than is normally available from E7016 electrodes when used out-of-position or with high heat input.

A4.8 E7018 Classification

A4.8.1 E7018 electrode coverings are similar to E7015 coverings, except for the addition of a high percentage of iron powder. The coverings on these electrodes are slightly thicker than those of the E7015 and E7016 electrodes. The iron powder in the coverings usually amounts to between 25 and 40 percent of the covering weight.

A4.8.2 E7018 low hydrogen electrodes can be used with either AC or DCEP. They are designed for the same applications as the E7015 electrodes. As is common with all low hydrogen electrodes, a short arc should be maintained at all times.

A4.8.3 In addition to their use on carbon steel, the E7018 electrodes are also used for dissimilar joints involving high-strength, high carbon, or alloy steels (see also A2.12.3.4). The fillet welds made in the horizontal and flat positions are slightly convex in profile, with a smooth and finely rippled surface. The electrodes are characterized by a smooth, quiet arc, very low spatter, and adequate penetration. E 7018 electrodes can be used at high travel speeds.

A4.8.4 Electrodes identified as E7018-1 have the same usability and design characteristics as E7018 electrodes, except that the manganese content is set at the high end of the range. They are intended for use in situations requiring a lower transition temperature than is normally available from E7018 electrodes when used out of position or with high-heat input.

A4.9 E7048 Classification. Electrodes of the E7048 classification have the same usability, composition, and design characteristics as E7018 electrodes, except that E7048 electrodes are specifically designed for exceptionally good vertical-down welding (see Table 1).

A4.10 E6020 Classification

A4.10.1 E6020 electrodes have a high iron oxide covering. They produce flat or slightly concave, horizontal fillet and groove welds with either AC or DCEN (electrode negative). They are characterized by a spray type arc and a heavy slag, well honeycombed on the underside, which completely covers the deposit and can be readily removed.

A4.10.2 Medium penetration will be obtained with normal amperages. However, these electrodes are capable of operating at high amperages and in that case will penetrate deeply. The E6020 electrodes are generally considered better than all other classifications for deep penetration fillet welds.

A4.10.3 E6020 electrodes contain manganese compounds and silica in their covering, along with large amounts of iron oxide and sufficient deoxidizers. The slag coverage is so extensive and the slag-metal reaction of such a nature that the electrodes do not normally depend on gaseous protection.

A4.10.4 Fillet welds tend to have a flat or concave profile and a smooth, even ripple. In many cases, the surface of the deposit is dimpled. The more restricted the opening in which the metal is deposited, the greater the tendency toward the dimples. Dimples are to be expected in practically all cases on the first few passes of deep groove welds. This tendency decreases as the weld nears completion. The use of AC tends to promote dimpling. No undesirable mechanical or physical defects are associated with these dimples.

A4.10.5 E6020 electrodes are recommended for horizontal fillet and flat groove welds where radiographic soundness is important. Radiographic quality welds can be obtained even with high deposition rates in heavy plate. These electrodes are not usually used on thin sections because of the higher amperages that are generally used.

A4.10.6 Amperages nearer the lower end of the indicated range should be used if undercutting is to be held to a minimum in horizontal fillet welds. The higher currents are used for the deep penetration fillet welds.

A4.10.7 Applications include pressure vessels, heavy machine bases, and structural parts.

A4.11 E6022 Classification

A4.11.1 Electrodes of the E6022 classification are recommended for single pass, high-speed, high current, flat groove and horizontal lap, and fillet welds in sheet metal.

A4.11.2 The weld bead profile tends to be more convex and less uniform, especially since the welding speeds are higher.

A4.12 E7024 Classification

A4.12.1 E7024 electrode coverings contain large amounts of iron powder in combination with ingredients similar to those used in E6012 and E6013 electrodes. The coverings on E7024 electrodes are very heavy and usually amount to about 50 percent of the weight of the electrode.

A4.12.2 The E7024 electrodes are well suited for making fillet welds. The welds are slightly convex to flat in profile, with a very smooth surface and an extremely fine ripple. These electrodes are characterized by a smooth, quiet arc, very low spatter, and low penetration. They can be used with high travel speeds.

A4.12.3 Electrodes identified as E7024-1 have the same general usability characteristics as E7024 electrodes. They are intended for use in situations requiring greater ductility and a lower transition temperature than normally is available from E7024 electrodes.

A4.12.4 Electrodes of these classifications can be operated on AC or DC, either polarity.

A4.13 E6027 Classification

A4.13.1 E6027 electrode coverings contain large amounts of iron powder in combination with ingredients similar to those found in E6020 electrodes. The coverings on E6027 electrodes are also very heavy and usually amount to about 50 percent of the weight of the electrode.

A4.13.2 The E6027 electrodes are designed for fillet or groove welds in the flat position with AC or DC, either polarity, and will produce flat or slightly concave horizontal fillets with either AC or DCEN.

A4.13.3 E6027 electrodes have a spray-type arc. They will operate at high travel speeds. Penetration is medium. Spatter loss is very low. E6027 electrodes produce a heavy slag which is honeycombed on the underside. The slag is friable and easy to remove.

A4.13.4 Welds produced with E6027 electrodes have a flat to slightly concave profile with a smooth, fine, even ripple, and good wash up the sides of the joint. The weld metal may be slightly inferior in radiographic soundness to that from E6020 electrodes. High amperages can be used, since a considerable portion of the electrical energy passing through the electrode is used to melt the covering and the iron powder it contains. These electrodes are well suited for fairly heavy sections.

A4.14 E7027 Classification. E7027 electrodes have the same usability and design characteristics as E6027 electrodes, except they are intended for use in situations requiring slightly higher tensile and yield strengths than are obtained with E6027 electrodes. They must also meet chemical composition requirements (see Table 2). In other respects, all previous discussions for E6027 electrodes also apply to E7027 electrodes.

A4.15 E7028 Classification. E7028 electrodes are very much like the E7018 electrodes. They differ as follows:

A4.15.1 The slag system of E7028 electrode is similar to that of E7016 electrodes, rather than E7018 electrodes.

A4.15.2 E7028 electrodes are suitable for horizontal fillet and flat groove welding only, whereas E7018 electrodes are suitable for all positions.

A4.15.3 The E7028 electrode coverings are much thicker. They make up approximately 50 percent of the weight of the electrodes. The iron content of E7028 electrodes is higher (approximately 50 percent of the weight of the coverings). Consequently, on horizontal fillet and flat position groove welds, E7028 electrodes give a higher deposition rate than the E7018 electrodes for any given size of electrode.

A5. Modification of Moisture Test Apparatus

A5.1 Some laboratories have modified test apparatus for determining the moisture content of electrode coverings. The following are some of the modifications which have been successfully used:

A5.1.1 This specification recommends that only nickel boats be used rather than clay boats because lower blank values can be obtained. Some laboratories use zirconium silicate combustion tubes in preference to fused silica or mullite because zirconium silicate will not devitrify or allow the escape of combustible gases at temperatures up to 2500° F (1370° C). Some combustion tubes are reduced at the exit end and a separate dust trap is used. This dust trap consists of a 200 mm drying tube filled with glass wool which is inserted between the Schwartz absorption bulb and the combustion tube. A suitable 300° F (149° C) heater is mounted around the dust trap to keep the evolved water from condensing in the trap. The dust trap is filled with glass wool which can be easily inspected to determine when the glass wool should be replaced.

A5.1.2 On the ingoing side of the combustion tube, a pusher rod can be used consisting of a 1/8 in. (3.2 mm) stainless steel rod mounted in a 1/4 in. (6.4 mm) copper tee fitting. This is used at the entrance of the combustion tube and permits gradual introduction of the sample into the tube while oxygen is passing over the sample. In this way, any free moisture will not be lost, which can happen if the sample is introduced directly into the hot zone before closing the end of the tube.

lecture 1

WELDING RESEARCH

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Analysis of Metal Transfer in Shielded Metal Arc Welding

Through a better understanding of transfer modes, performance characteristics of covered electrodes can be improved

BY S. BRANDI, C. TANIGUCHI AND S. LIU

ABSTRACT. In this work, a conventional rectifier-type power source was used with an automatic covered electrode feeder to investigate metal transfer in shielded metal arc (SMA) welding with commercial AWS E6011, E6013 and E7018 grade electrodes. The arc was established between the electrode and a rotating copper disk. The individual metal droplets transferred across the arc were collected in water and then processed using standard mineral dressing techniques to remove the slag coverings and to determine the droplet size and size distribution. The tips of the electrodes used in the experiments were examined metallographically for internal defects such as gas bubbles and evidence of liquid metal flow. Experiments were conducted following a 2^4 factorial matrix and Yates's analysis was carried out to determine the effects of electrode coating, electrode diameter, welding current, welding position, and polarity on metal transfer.

The three major types of transfer identified were explosive transfer, short-circuiting transfer, and slag-guided transfer. In all three electrodes, the size distributions of the metal droplets collected were found to be nonuniform, with unusually high spatter-size droplets, supporting the explosive transfer conclusion. However, E6013 grade electrodes produced droplets with comparably more uniform size distribution (than the other electrodes) with intermediate characteristic diameter. The droplets from E7018 grade electrodes showed more slag covering than those collected from the other electrodes, which can be related to the higher volume of slag and the thicker coating on the electrodes. This is also the reason why the core wire diameter showed the strongest influence on metal transfer in E7018 grade electrodes. Finally, polarity has the strongest effect on droplet diameter in E6011 electrode, while welding current affected E6013 electrode the most.

Metal Transfer Mode Classification

Since the discovery of arc welding at the beginning of this century, metal transfer has been a topic of research interest. In fact, metal transfer can be related to weld quality because it affects the arc stability. It also determines weld spatter, weld penetration, deposition rate and welding position. Thus, the knowledge of how metal transfer affects the arc welding processes is important for welding control and process automation, as well as in the development of improved welding consumables.

Based on the transfer characteristics of individual metal droplets, the International Institute of Welding (IIW) (Ref. 1) proposed to classify metal transfer modes in three major groups: 1) free flight; 2) bridging; and 3) slag-protected transfer. In free flight transfer, molten metal droplets detach from the tip of the welding electrode and travel across the arc length. Bridging transfer, on the other hand, is characterized by momentary contacts of the electrode with the weld pool. During the short-circuiting cycle, the electrode tip is melted by ohmic heating and transferred into the molten pool. In SMA and

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Short-Circuiting Transfer
Slag-Guided Transfer
Polarity
Current

submerged arc (SA) welding, where metal droplets are commonly covered by a layer of molten slag, slag-protected transfer can predominate. Table 1 shows the detailed classification of metal transfer modes.

Models of Metal Transfer

In each metal transfer mode, there is a group of forces that act on the arc (Refs. 2-26) and provide the characteristics of the transfer. The major ones include gravitational force, surface tension, electromagnetic force, plasma jet force and vapor pressure. Gas-generating chemical reactions may also occur in the metal droplets leading to porosity formation and pressure buildup in the droplets. The resulting force is known as the gas expansion force. These forces are schematically illustrated in Fig. 1. Depending on the balance of these forces, the mode of transfer, size of droplets, rate of transfer, amount of spatter, etc., may be different. Table 2 shows the predominating forces that act on metal transfer in SMA welding.

Several models were proposed to explain metal transfer in bare electrode and covered electrode welding. Conrady (Ref. 17) proposed that welding with a bare electrode using straight polarity and in an overhead position, metal transfer was promoted by the cathode spot. The pressure of the cathode spot would cause the surface of the droplet to oscillate and eventually transfer by short-circuiting. Larson (Ref. 21) extended Conrady's model to include the effect of a gas bubble inside the molten electrode tip. As the bubble expanded, transfer of the droplet would occur by explosion of the droplet or short-circuiting. Becken (Refs. 27, 28) further discussed the interaction of surface tension forces (γ_{slag} and γ_{metal}) with the cathode spot pressure, both responsible for droplet transfer. Besides, there is also evidence of liquid metal flow inside the molten electrode tip (Refs. 2, 5, 7, 9, 27, 29-32), which affect the metal transfer behavior. The hydrodynamic instability of a liquid metal droplet can be induced by the Marangoni effect (Refs. 31, 33, 34). Sharp surface tension gradients in the molten electrode tip may result from temperature gradient, composition difference, for example, of surface active elements (Refs. 31, 33-35), and surface distribution of electric charges (Refs. 4, 36, 37). In recent years, most of the research work has been directed toward gas metal arc (GMA) welding instead of SMAW. The presence of a slag covering complicates significantly the investigation of metal transfer in covered electrode welding.

Table 1—IIW Classification of Metal Transfer in Arc Welding (Ref. 1)

Designation of Transfer Type		Welding Processes (Examples)
Free flight transfer		
Globular		
	Drop	Low current GMA
	Repelled	CO_2 shielded GMA
Spray		
	Projected	Intermediate-current GMA
	Streaming	Medium-current GMA
	Rotating	High-current GMA
Explosive		SMA (Coated electrodes)
Bridging transfer		
Short-circuiting		Short-arc GMA
Bridging without interruption		Welding with filler wire addition
Slag-protected transfer		
Flux-wall guided		SAW
Other modes		SMA, Cored-wire, Electroslag

Table 2—Forces That Act on SMA Welding (Ref. 2)

	Process Variables			Transfer Characteristics		
	Polarity[a]	Current Density	Shielding Gas	Type[b]	Droplet Size	Forces Present[c]
Acid coating				(SC)-E	Small	S,V,G
Rutile coating	DCEP	Low	CO_2 type	(SC)-E	Medium	S,V,G
Basic coating	DCEN			SC-E	Large	S,V,G

(a) DCEP—direct current electrode positive; DCEN—direct current electrode negative.
(b) (SC)—limited short-circuiting transfer; SC—short-circuiting transfer; E—explosive transfer.
(c) S—surface tension; V—vapor pressure; G—gas expansion force.

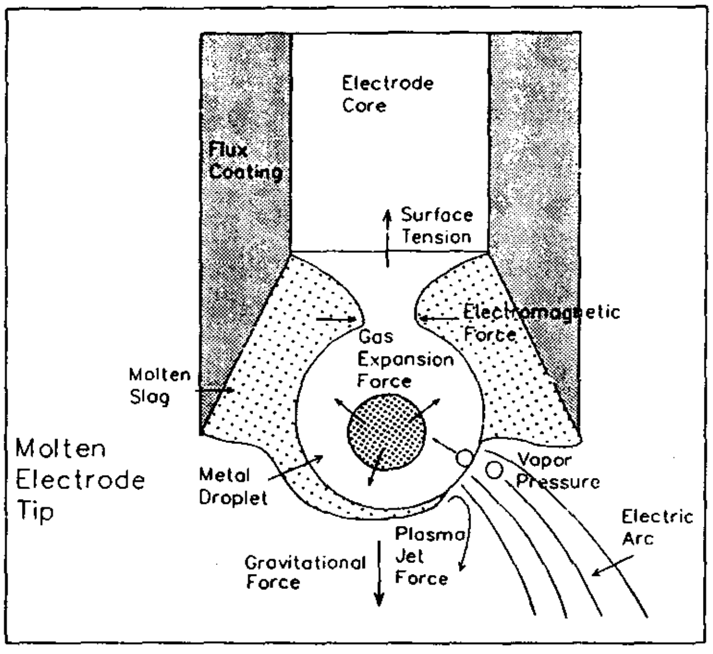

Fig. 1—Schematic drawing of a molten electrode tip illustrating the different forces involved in metal droplet transfer during welding.

Techniques in Observing Metal Transfer

Metal transfer can be observed by direct and indirect methods. Examples of direct techniques are photography (Ref. 21), high-speed cinematography (Refs. 7,23,38-43), high-speed video (Refs. 44-46), deposition on a metal plate (Refs. 8, 47-50), deposition with double electrodes (Ref. 51), and deposition against a carbon electrode (Ref. 52). The first three methods examine the in-flight conditions of metal droplets and the latter ones analyze the physical evidence of metal transfer, that is, the metal droplets collected in the experiments. Indirect techniques rely basically on the variations of arc current and voltage with the transfer of each metal droplet. The arc signals are recorded, in the form of oscillograms (Refs. 27, 38, 41, 43, 49, 53, 54), and analyzed to determine the transfer behavior. Attempts have also been made to use acoustic signals to monitor metal transfer (Refs. 55, 56).

Table 3 compares the different techniques used in observing metal transfer in SMA welding. Each method has its own advantages and shortcomings. Direct observations, however, are generally preferred. Despite the fair-to-good optical resolution that can be obtained by photography, high-speed cinematography and high-speed video, the time of each sampling (period of active arc observation) is generally limited to a few seconds or less, thus requiring a large number of samples for statistical significance. Indirect methods are generally conducted as weld simulations that do not actually correspond to a real welding situation. Therefore, it is not unusual to combine several of the direct and indirect techniques to characterize the predominating metal transfer mode in a welding process.

Objectives of this Research

The main objective of this work was to characterize metal transfer in SMA welding by studying the metal droplets collected during welding. The effect of welding process parameters (current, polarity and position) and electrode conditions (composition and diameter) on the size of the droplets transferred and the amount of spatter were investigated. It is anticipated that: 1) the methodology established in this research can be used to evaluate the performance of commercial and experimental electrodes; and 2) the knowledge gained in this study can be used to improve shielded metal arc welding process control with smooth metal droplet transfer and minimum spatter.

Experimental Procedure

A rectifier-type power supply and an automated SMA welding system (Ref. 57) were used to perform the welding experiments with commercial AWS E6011, E6013, and E7018 grade covered electrodes. The deposition was made against a rotating copper disk as shown in Fig. 2. The metal droplets were ejected by the spinning disk into cold water. The rotation speed of the copper disk was fixed at 890 rpm because at that speed, no metal droplet was observed to coalesce or fragment (Ref. 57) during contact with the disk. After the transferred droplets were dried, the slag coverings were separated by hand crushing with a mortar and pestle. The metal droplets were then magnetically separated from the slag particles. The samples acquired using a splitter were classified according to size following standard particulate processing techniques (ASTM Standard B-215). U.S. sieve series (ASTM) number 5, 7, 10, 14, 18, 20 and 35,

Table 3—Comparison of the Different Techniques Used in Observing Metal Droplet Transfer

Techniques	Advantages	Disadvantages
High-speed video and cinematography	Direct observation of droplet transfer Medium-to-good optical resolution	Complex experimental setup Short sampling time Imprecise droplet size measurement Incapable of distinguishing droplet from slag covering
Photography	Direct observation of droplet transfer Simple experimental setup Good optical resolution	Short sampling time Imprecise droplet size measurement Incapable of distinguishing droplet from slag covering
Current and voltage oscillogram	Simple experimental setup Large sampling possible	Indirect observation and correlation Transfer event difficult to characterize Incapable of droplet size and shape determination Incapable of distinguishing droplet from slag covering
Deposition on metal plates	Direct observation of droplet transfer Simple experimental setup Physical evidence of individual droplets Large sampling possible Capable of quantifying metal transfer Capable of distinguishing droplets from slag covering	Simulated welding Droplet may coalesce or fracture at contact with chill
Double electrode	Direct observation of droplet transfer Simple experimental setup	Simulated welding AC welding Electrodes covered by slag
Carbon electrode	Direct observation of droplet transfer Simple experimental setup	Simulated welding Oxidation of the carbon electrode causing changes in arc atmosphere

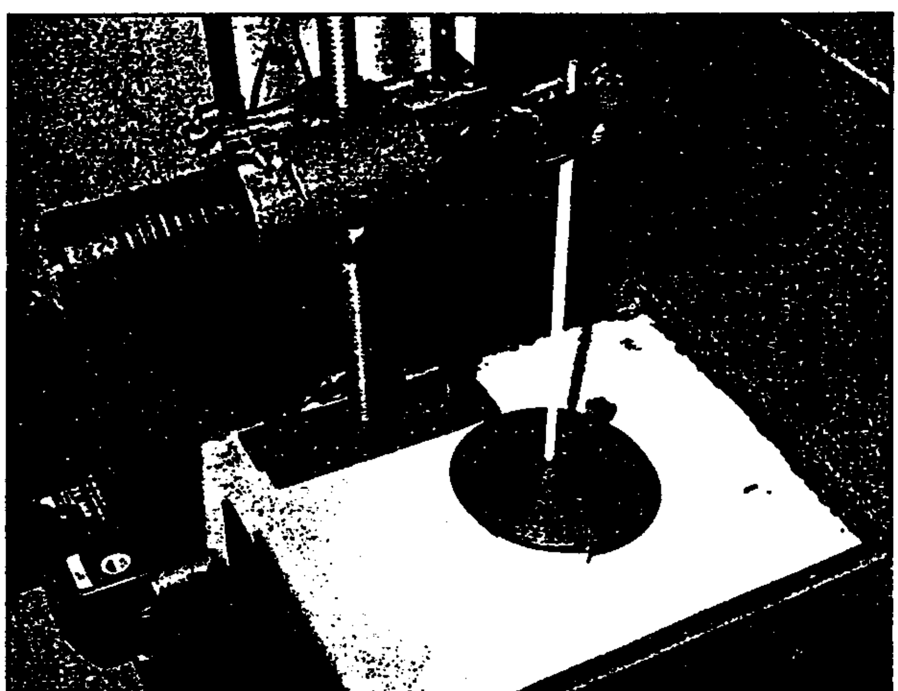

Fig. 2 — Welding equipment setup showing the SMA electrode and the rotating copper disk.

droplets retained in each sieve (n), the average diameter (D) of the droplets in each sieve was determined using the equation below.

$$D = \left[\frac{6m}{\pi n d_g}\right]^{1/3} \qquad (1)$$

The characteristic volume (V_c) of the droplets for each experiment, as defined in the following equation (Refs. 40, 41),

$$V_c = \frac{\Sigma N_i V_i^2}{\Sigma N_i V_i} \qquad (2)$$

can be used to determine the characteristic diameter (D_c) of the droplets.

$$D_c = \left(\frac{3V_c}{4\pi}\right)^{1/3} \qquad (3)$$

In Equation 2, N_i is the number of droplets and V_i is the total volume of droplets collected in each sieve.

Table 4—Range of the Variables Chosen for the Study (Ref. 57)

Main Variables	Range of Study: Low Level	High Level
Electrode diameter (A)	4 mm	5 mm
Welding current (B)	150 A	200 A
Welding position (C)	Flat	Nonflat
Polarity (D)	DCEP[a]	DCEN[a]

(a) DCEP—direct current electrode positive; DCEN—direct current electrode negative.

A summary of the characteristic diameters of the droplets collected are given in Table 7 (Ref. 57). The F_0 values and the estimated effects were obtained using Yates's algorithm (Refs. 58–62). Of the three consumables investigated, welding with E6011 grade electrodes resulted in the smallest droplets, while E7018 grade electrodes produced the largest, independent of the welding parameters. Additionally, the present findings compared very favorably with the literature data. For the welds made in Experiment 1, that is, welding at 150 A with 4-mm-diameter electrodes, using reversed polarity and in a flat position, the mean characteristic diameter of the droplets from the E6011 grade electrodes was 1.82 mm, slightly larger than the 1.73 mm reported by Wyant, *et al.* (Ref. 63). In the case of E6013 and E7018 grade electrodes, the results of 2.18 and 2.97 mm were well within the ranges reported in the literature of 1.24 to 2.35 mm and 2.0 to 3.0 mm, respectively (Refs. 9, 40, 41, 64, 65). In the column of estimated effects, a minus sign means that the experiment decreases the characteristic diameter of the droplets, and a plus sign increases the diameter. The effects of the different process parameters will be further discussed in a later section.

Amount of Spatter

As indicated earlier, weld spatter is related to the stability of the welding arc and metal transfer. Experimental observations showed that these fine metal droplets were between 500 μm (+20 mesh) and 212 μm (−70 mesh) in size. Therefore, the total number of droplets within the above size range, assumed to be the total amount of spatter, were counted and reported in Table 8. Of the three electrodes, welding with E6013 grade electrodes resulted in the smallest amount of spatter, independent of the welding conditions—Fig. 5. The effects of welding parameters on spatter will be discussed in the section on analysis of variance (ANOVA) results.

Table 5—2^4 Factorial Design Matrix Used to Study the Influence of Welding Process Variables on Metal Transfer (Ref. 57)

Experiment Designation	Electrode Diameter (mm)	Welding Current (A)	Welding Position	Polarity
	-A-	-B-	-C-	-D-
1	4	150	F[a]	+[b]
A	5	150	F	+
B	4	200	F	+
AB	5	200	F	+
C	4	150	H[a]	+
AC	5	150	H	+
BC	4	200	H	+
ABC	5	200	H	+
D	4	150	F	−[b]
AD	5	150	F	−
BD	4	200	F	−
ABD	5	200	F	−
CD	4	150	H	−
ACD	5	150	H	−
BCD	4	200	H	−
ABCD	5	200	H	−

(a) F—Flat; H—nonflat.
(b) + DCEP; − DCEN.

Table 6—Mean Apparent Density (g/cm³) and Mean Apparent Porosity (%) as a Function of Electrode Coating and USA Sieve Series (Ref. 67)

USA Sieve Series Number	Mean Apparent Density (g/cm³): E6011	E6013	E7018	Mean apparent porosity (%): E6011	E6013	E7018
5	−	2.98 ± 0.27	3.84 ± 0.22	−	62.09	51.15
7	5.73 ± 0.76	4.33 ± 0.39	4.83 ± 0.32	27.10	44.91	38.55
10	6.75 ± 0.40	6.04 ± 0.32	6.49 ± 0.29	14.12	23.16	17.43
14	7.32 ± 0.13	7.27 ± 0.27	7.29 ± 0.15	6.87	7.51	7.25
18	7.45 ± 0.28	7.47 ± 0.22	7.48 ± 0.20	5.22	4.96	4.83

Table 7—Summary of the Analysis of Variance Results of the Characteristic Diameters of the Droplets (Ref. 57)

Experiment	Mean Characteristic Diameter (mm): E6011	E6013	E7018	Estimated F_0: E6011	E6013	E7018	Estimated Effects(1): E6011	E6013	E7018
1	2.15	2.48	2.85	−	−	−	1.82	2.18	2.97
A	2.05	2.59	3.34	7.02	10.62	177.95	0.1100[d]	0.1294[b]	0.5984[a]
B	1.85	2.01	2.37	10.97	73.09	23.98	−0.1375[b]	−0.3394[a]	−0.2197[a]
AB	1.92	2.01	3.37	1.76	1.88	1.05	−	−	−
C	1.84	2.18	2.12	<1	2.53	14.73	−	−	−0.1722[b]
AC	2.29	2.55	3.21	8.80	6.27	13.17	0.1231[c]	0.0994[d]	0.1628[b]
BC	1.89	1.84	2.42	1.14	4.79	5.91	−	−	−0.1091[d]
ABC	1.86	2.26	2.92	4.01	<1	18.23	−	−	−0.1916[a]
D	1.59	2.00	3.08	60.81	8.67	41.71	−0.3238[a]	−0.1169[c]	0.2897[a]
AD	1.60	2.04	3.17	<1	5.65	15.27	−	−	−0.1753[b]
BD	1.65	2.06	3.06	2.55	4.00	6.11	−	−	−0.1109[d]
ABD	1.60	2.02	3.21	<1	1.18	<1	−	−	−
CD	1.65	2.38	2.98	2.13	9.82	10.13	−	0.1244[c]	0.1428[c]
ACD	1.94	2.60	3.89	<1	3.05	9.61	−	−	0.1391[c]
BCD	1.51	1.99	2.49	1.96	23.67	25.79	−	−0.1931[a]	−0.2278[a]
ABCD	1.73	1.90	3.04	3.77	1.55	3.67	−	−	−

(1) Levels of significance: a = 0.1%; b = 0.5%; c = 1.0%; d = 2.5%.

Table 8—Summary of the Analysis of Variance Results of the Amount of Spatter (Ref. 57)

Experiment	Mean Spatter (Number of Droplets) E6011	E6013	E7018	Estimated F_o E6011	E6013	E7018	Estimated Effects(1) E6011	E6013	E7018
1	1886	576	1170	–	–	–	2189	1068	1080
A	1052	504	1288	56.20	2.59	12.30	−778.25[a]	–	−252.10[b]
B	1780	1010	1424	8.70	23.13	<1	306.34[c]	357.53[a]	–
AB	1119	962	688	<1	<1	<1	–	–	–
C	1976	1016	1149	<1	3.39	<1	–	–	–
AC	1276	684	783	5.79	<1	<1	–	–	–
BC	2324	1503	1310	<1	<1	6.90	–	–	188.84[d]
ABC	1661	1152	1013	<1	2.31	<1	–	–	–
D	2654	1191	1508	114.28	14.59	<1	1110.59[a]	283.96[b]	–
AD	2638	940	883	<1	1.20	<1	–	–	–
BD	3453	1338	869	1.63	1.97	<1	–	–	–
ABD	2847	1474	873	1.71	<1	3.22	–	–	–
CD	3021	993	981	9.99	6.45	<1	−328.29[c]	−188.79[d]	–
ACD	1789	1209	1115	7.41	1.16	<1	−282.85[d]	–	–
BCD	3538	1394	1234	1.55	<1	<1	–	–	–
ABCD	2018	1139	986	<1	1.88	11.32	–	–	−241.85[b]

(1) Levels of significance: a = 0.1%; b = 0.5%; c = 1.0%; d = 2.5%.

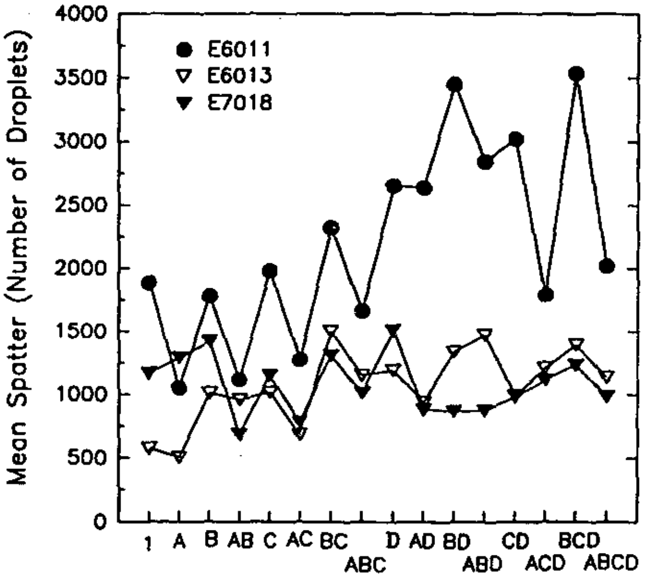

Fig. 5 – The amount of spatter generated by each electrode used in this investigation. Independent of the welding conditions, E6011 electrodes produced consistently the largest amount of spatter.

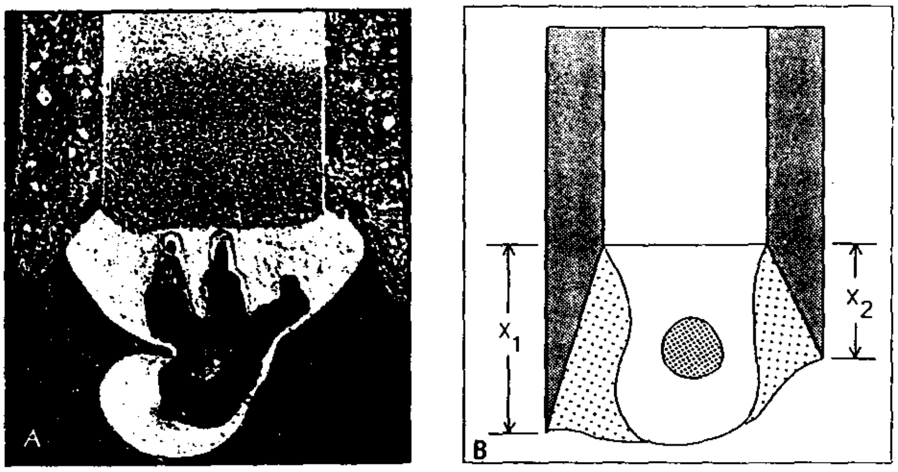

Fig. 6 – Schematic drawing and photomacrograph of the tip of an electrode showing the arc barrel and internal gas porosity.

Table 9—Summary of the Measurement of Crater Depths at the Tip of the Electrodes (Ref. 57)

		Electrode Type E6011	E6013	E7018
Electrode diameter (mm)	4.0	1.63 ± 0.08	1.79 ± 0.18	2.17 ± 0.29
	5.0	1.64 ± 0.19	2.08 ± 0.16	2.98 ± 0.15
Welding current (A)	150	1.70 ± 0.12	1.82 ± 0.14	2.44 ± 0.40
	200	1.59 ± 0.06	1.91 ± 0.18	2.68 ± 0.36
Welding position	Flat	1.53 ± 0.05	1.68 ± 0.23	2.52 ± 0.42
	Non-flat	1.70 ± 0.13	2.03 ± 0.36	2.50 ± 0.45
Polarity	DCRP	1.73 ± 0.18	1.93 ± 0.25	2.60 ± 0.32
	DCSP	1.59 ± 0.08	1.96 ± 0.37	2.66 ± 0.38

Flux Coating Cup (Arc Barrel) at the Electrode Tip

At the end of each welding experiment, the tip of the electrode was also examined to determine the presence of porosity in the undetached molten metal droplet and the cup of flux coating (arc barrel) formed at the tip of the electrode during welding, as shown in Fig. 6. To avoid breakage of the cup, the electrode tip was first filled with adhesive and mounted in resin. Careful sectioning of the electrode tip along a diametral plane and light grinding revealed the features described above. The depth of the cups were measured using an optical profilometer. A schematic profile of the tip of a SMA electrode is also shown in Fig. 6. Table 9 shows the average cup depths for the three electrodes investigated. As expected, basic electrodes such as E7018 showed the deepest cup. This can be related to the chemical composition and viscosity of the flux coating and the thickness of the coatings. It is also important to notice the presence of a large internal porosity in the metal droplet in Fig. 6. This seems to support Larson's model of gas expansion leading to metal droplet transfer.

Analysis of Variance (ANOVA) Results

Table 10 summarizes the results of the ANOVA calculations of the characteristic diameters and the amount of spatter. Based on the ranking in Table 10, only the first five most important results will be discussed in this paper. These are experiments D, B, A, AC, and BCD. In Table 10, ↑ indicates an increase and ↓ a decrease of the effect when compared to the results of Experiment 1. The number between brackets indicates the relative order of significance of the experiment; smaller numbers represent tests more heavily influenced by the specific welding conditions. Note that the order of significance for each one of the three types of electrode coating is not necessarily the same.

Polarity Effect (Experiment D)

In the case of E6011 and E6013 grade electrodes, a change in polarity, from electrode positive (reverse) to electrode negative (straight), caused a decrease in the characteristic diameter of the metal droplets and an increase in the amount of spatter. This can be related to the surface temperature of the metal droplets (Refs. 2, 66–73). Figure 7 shows the difference in droplet surface temperature distribution under electrode positive and electrode negative polarity conditions. Temperature gradient in the molten electrode tip is known to give rise to other temperature-sensitive forces and promote gas circulation and metal flow in the molten electrode tip, as illustrated in Fig. 8. Additionally, surface charge distribution can also change surface tension and alter the liquid metal flow pattern. With all these effects, a large number of the metal droplets explode before short-circuiting occurs, which reduces the characteristic diameter of the droplets and increases spatter.

In E7018 grade electrodes, the characteristic diameter of the droplets increased when welded at electrode negative polarity. The presence of fluorides in the flux coating might have been the cause of this opposite behavior. First of all, fluoride ions have been reported to make the electron emission process more difficult (Refs. 14, 53, 54). Additionally, because of their small size (r_{F^-} = 1.36 Å), fluoride ions have high mobility and tend to migrate toward the anode. They react with the layer of positive charges there and reduce the cathode spot size. This is schematically illustrated in Fig. 9. The combination of these effects causes the droplets to explode after transfer, resulting in larger characteristic diameters. Furthermore, the viscosity of the molten metal also played a complex role in the transfer, because it can be related to the deoxidizers present in the electrode coating or electrochemical reactions that occur at the electrode tip prior to transfer.

Current Effect (Experiment B)

The increase from 150 to 200 A in welding current caused a decrease in the characteristic diameter of the droplets for all three types of electrodes. The amount of spatter observed for E6011 and E6013 grade electrodes, however, increased. This is reasonable because metal vapor pressure, droplet temperature, and liquid circulation velocity in the droplet all increased with increasing welding current. The interaction of these forces, as illustrated in Fig. 10, would generate compressive forces and cause the droplets to explode at the moment of short-circuiting.

Table 10—Summary of the Results Obtained in This Investigation

	Electrode Type					
	E6011		E6013		E7018	
Significant Experiments	Characteristic Diameter	Amount of Spatter	Characteristic Diameter	Amount of Spatter	Characteristic Diameter	Amount of Spatter
D	↓ (1)[a]	↑ (1)	↓ (5)	↑ (2)	↑ (2)	–
B	↓ (2)	↑ (4)	↓ (1)	↑ (1)	↓ (4)	–
AC	↑ (3)	–	↑ (6)	–	↑ (8)	–
A	↑ (4)	↓ (2)	↑ (3)	–	↑ (1)	↓ (1)
CD	–	↓ (3)	↑ (4)	↓ (3)	↑ (9)	–
ACD	–	↓ (5)	–	–	↑ (10)	–
BCD	–	–	↓ (2)	–	↓ (3)	–
AD	–	–	–	–	↓ (6)	–
C	–	–	–	–	↓ (7)	–
BD	–	–	–	–	↓ (11)	–
BC	–	–	–	–	↓ (12)	↑ (3)
ABC	–	–	–	–	↓ (5)	–
ABCD	–	–	–	–	–	↑ (2)

(a) ↓ Decrease; ↑ increase; (number) in decreasing order of importance of the effect.

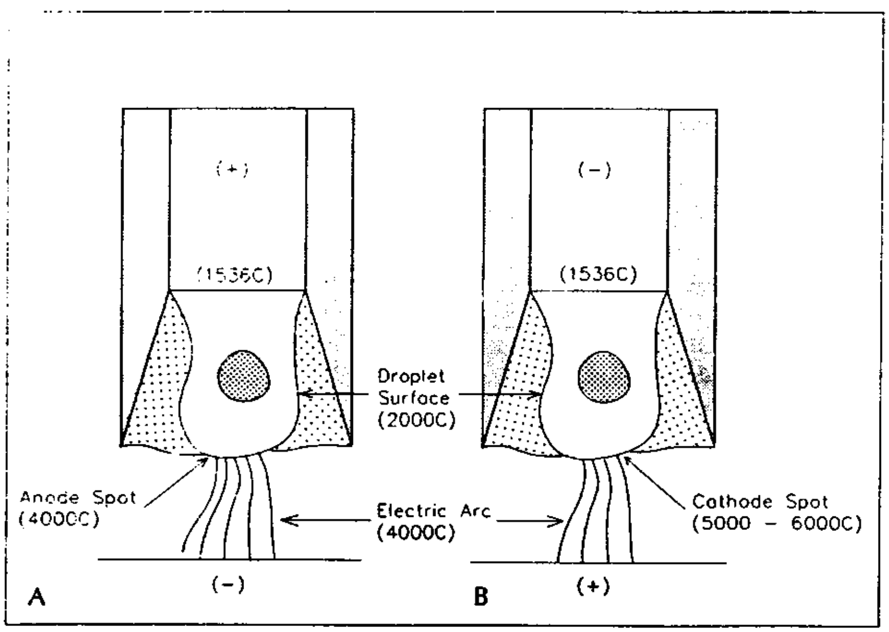

Fig. 7 – Droplet surface temperature as a function of polarity. A – DC electrode positive; (B) – DC electrode negative. (Refs. 2, 66-73)

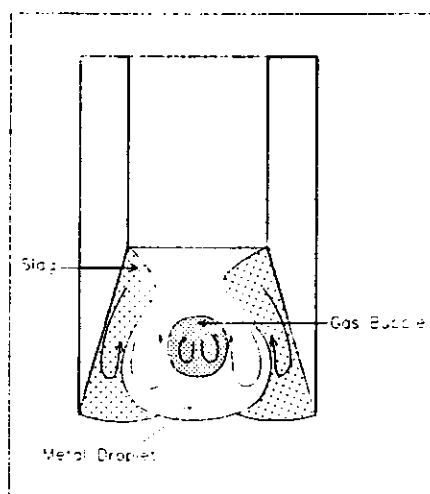

Fig. 8 – Gas circulation and metal flow in the molten electrode tip set up by temperature-sensitive forces and temperature gradient in the metal droplet.

Electrode Diameter Effect (Experiment A)

A larger diameter core wire also resulted in an increase in the characteristic diameter of the droplets for all three types of electrodes, and a decrease in the amount of spatter for E6011 and E7018 electrodes. At a constant welding current, the current density and droplet temperature will be higher for the smaller diameter electrode. Combining these effects with the surface tension forces, necking can be resisted to a greater extent in the five millimeter diameter electrode, resulting in larger volume of molten metal at the electrode tip. Subsequent short-circuiting transfer will result in less spatter. Since E7018 grade electrodes generally contain larger amounts of deoxidizers for oxygen control, liquid circulation in the metal droplet may be accelerated by the Marangoni effect. Eventually, the droplets would be transferred by short-circuiting without explosion.

Interaction Effect (Experiments BCD)

When the current was increased to 200 A, polarity changed from electrode positive to electrode negative, and the welding position changed from flat to nonflat, the characteristic diameters from E6013 and E7018 welding were observed to decrease. Since all other factors had already been discussed as single effects previously, only the effect of welding position will be discussed. The change in welding position resulted in the deformation of the droplets, which together with liquid circulation in the droplet, vapor pressure in the internal cavity, and compressive force, caused the droplets to explode at the moment of short-circuiting, as shown in Figure 11, resulting in smaller droplets transferred.

Interaction Effect (Experiment AC)

Changing from a 4-mm-diameter electrode welding in the flat position to a 5-mm diameter electrode welding in the nonflat position, the characteristic diameters were observed to increase for the E6011 electrodes. Electrode diameter (as shown in Experiment A) was without question the prevailing effect. In this case, spatter was reduced because the transfer of droplets occurred by short-circuiting before exploding.

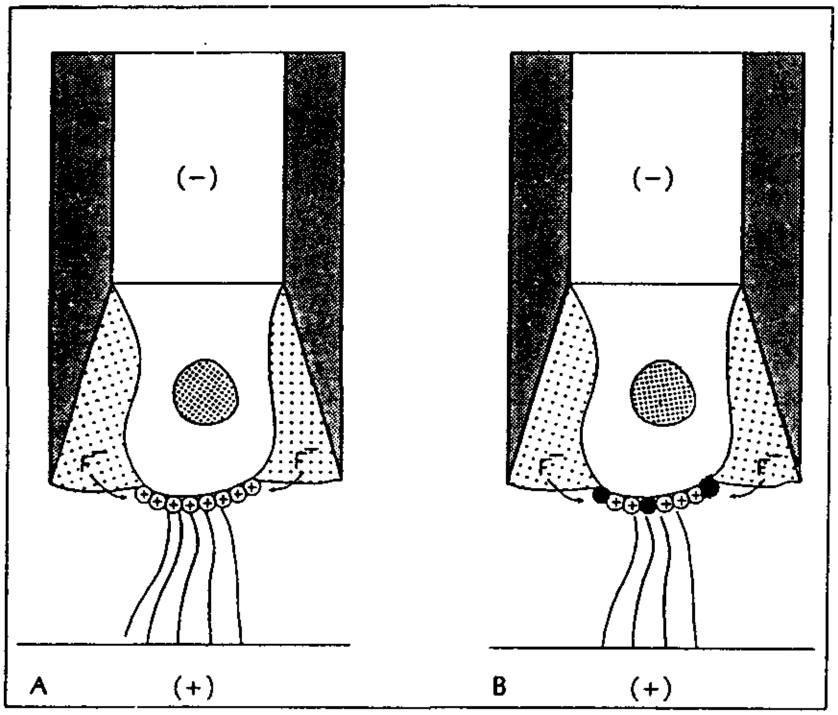

Fig. 9 — As a result of fluoride ions (F) migrating to the anode and reacting with the layer of positive charges there, the cathode size is reduced.

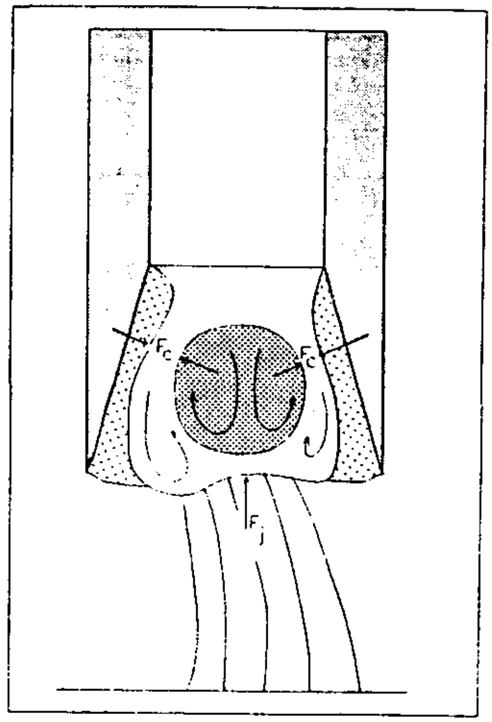

Fig. 10 — Metal vapor pressure (F_j), electromagnetic pinch fo... (F_c), and liquid circulation within the molten droplet generate compressive forces which cause the droplet to explode at the moment of short-circuiting.

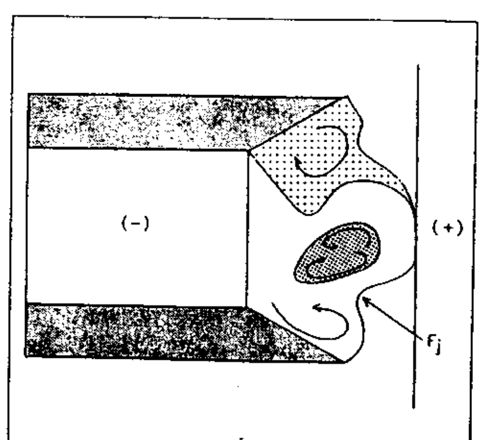

Fig. 11 — Welding position effect: distortion of the metal droplet together with liquid circulation, vapor pressure (F_j) in the gas porosity and compressive force, cause the droplet to explode at the moment of short-circuiting.

Conclusions

The major findings of this work are summarized in the following conclusions:

1) Explosive, short-circuiting and slag-guided were the three transfer modes observed in SMA welding with E6011, E6013 and E7018 grade electrodes.

2) Explosive transfer was the predominate mechanism, evidenced by the heterogeneous size distribution of the droplets for all experiments.

3) Slag-protected transfer was most significant in welding with E7018 grade electrodes, with a large number of the droplets covered entirely by slag.

4) Polarity was the variable that most affected the size of the droplets transferred, as well as the amount of spatter for welding E6011 grade electrodes.

5) For E7018 grade electrodes, polarity has an opposite effect on characteristic diameters of the droplets transferred. This is due to the flux coating composition (presence of fluoride ions) and chemical reactions that occur between the metal and molten slag at the tip of the electrode.

6) Current was the variable that most affected the size of the droplets transferred, as well as the amount of spatter for welding with E6013 grade electrodes.

7) Electrode diameter was the variable that most affected the size of the droplets transferred, as well as the amount of spatter for welding with E7018 grade electrodes.

8) E6013 electrodes produced the most stable arc with low spatter because of the relatively small droplet size transferred.

9) Porosity in the molten electrode tip was detected in all three electrodes, being more frequently observed in the E6013 and E7018 electrodes.

10) Independent of the type of welding electrode, small characteristic diameters were observed when droplets explosion preceded the transfer. If droplets exploded after short-circuiting with the weld pool, the characteristic diameters were generally bigger.

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Lecture 2.

Evaluating E71T-11 Flux Cored Electrodes for Structural Carbon Steel Applications

BY TIM SCHINDLER

Companies involved with welding constantly search for better, cheaper and faster methods of joining metals. Additionally, alternative welding processes have become even more crucial given the increasingly competitive climate of the welding fabrication industry. Nearly all such companies are investigating the most viable alternatives to the predictable, but slow, manual welding processes. Many fabrication and construction companies now commonly use the semiautomatic flux cored arc welding (FCAW) process. Only a few years ago, these companies would have utilized a completely manual process such as shielded metal arc welding (SMAW).

It is commonly known that the FCAW process can be utilized in two different ways — with supplemental gas shielding and without gas shielding. Many papers, technical documents and articles have been published regarding the use of the gas shielded version of this process. However, it is much more difficult to locate up-to-date technical literature regarding the general use of self-shielded flux cored electrodes. Indeed, many companies (including our own) have historically prohibited use of the self-shielded version due to the lack of documented performance of these products. Additionally, the negative and positive feedback associated with the overall quality of the self-shielded FCAW deposit has a tendency to confuse even those knowledgeable of the process. For example, one large U.S. constructor will not allow the process on any site, while other companies successfully complete major offshore platforms and buildings every day using the self-shielded FCAW process. Obviously, the fundamental question of "whom I believe" becomes a very real hurdle to overcome in persuading a company to use self-shielded FCAW on any type of critical structure.

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Testing the Process

Because of the conflicting information and unknown potential regarding this process, it was decided that the process should be evaluated to determine its overall applications and limitations. The initial considerations for selecting the electrode classification to be tested were:

- ◆ Readily available on the market — sold by more than one manufacturer.
- ◆ High-quality deposit equivalent to SMAW E7018 electrode.
- ◆ Inexpensive.
- ◆ Universal applications on carbon steel up to 1 in. thick.
- ◆ All position, multipass characteristics.
- ◆ Impact properties not required.

After a thorough review of manufacturers' literature, electrode classification AWS E71T-11 was selected as the wire that best fit the criteria. We selected three diameters of wire (0.045, 1/16 and 5/64 in.), and three of the most common brands of E71T-11 to be tested on both groove and fillet welds.

More than 200 ASTM A36 plates were purchased and prepared for welding, with three different thicknesses (3/8, 1/2 and 1 in.) representing the actual thicknesses considered for production welding. The joint design selected for the groove welds was a 60-deg single-bevel butt joint with backgouging, in conformance to AWS D1.1 *Structural Welding Code — Steel*, Joint Designation B-U2-GF. The fillet weld coupons were all prepared as T joints, per AWS D1.1, Figure 5.16. All four groove weld and fillet weld positions (1G–4G, 1F–4F) were used to evaluate the out-of-position characteristics of the electrode.

The welders selected to perform the test welding were both experienced metal fabricators. Welder "A" has more than 30 years of welding experience, but had little experience using the self-shielded FCAW process. Welder "B" has more than ten years of welding experience and does have extensive experience using the process. Both welders were allowed to practice for at least eight hours prior to actual test welding, and both were specifically counseled regarding the welding parameters established by each electrode manufacturer in its written welding procedures.

The overall goal was to duplicate the conditions that could normally be expected in a production environment, without the formalities and allowances usually accepted in a strict testing atmosphere, *i.e.,* no inordinate grinding permitted, no unnecessary external aids, excessive time per coupon not allowed, etc. Each welded coupon was closely monitored by an AWS Certified Welding Inspector to ensure proper adherence to the variables and ranges specified by each electrode manufacturer. Additionally, external factors, such as humidity and wind velocity, were measured to ascertain their effects on the welding being performed.

Testing Performed to Code Requirements

A total of 57 groove weld coupons and 50 fillet weld coupons were completed. All completed coupons were visually examined by an AWS Certified Welding Inspector to the criteria specified in AWS D1.1, and all groove weld coupons were radiographed to the same code. Eighteen groove weld coupons were randomly selected (based on different electrode manufacturers) for bend and tensile testing per AWS D1.1. All fillet weld coupons were cut, polished and acid etched per the requirements stated in the code. Acceptance criteria for visual inspection was as stated in paragraph 9.25.1 of AWS D1.1. Radiography acceptance was based on paragraph

Table 1—55 FCAW R&D Welded Coupon Test Summary

Total number of coupons		Groove	57
		Fillet	50
Percent of coupons passing all tests performed		Groove	44%
		Fillet	76%
Percent of coupons failing one/all tests		Groove	56%
		Fillet	24%
Percent of electrode brand #1 coupons failed		Groove	57%
		Fillet	5%
Percent of electrode brand #2 coupons failed		Groove	64%
		Fillet	44%
Percent of electrode brand #3 coupons failed		Groove	47%
		Fillet	13%
Percent of coupons failed by position	1G	(Groove)	47%
	2G	(Groove)	46%
	3G	(Groove)	53%
	4G	(Groove)	83%
	1F	(Fillet)	14%
	2F	(Fillet)	12%
	3F	(Fillet)	36%
	4F	(Fillet)	44%
Percent of coupons failed by Welder "A"		Groove	51%
		Fillet	33%
Percent of coupons failed by Welder "B"		Groove	60%
		Fillet	15%
Percent of coupons failed by wire diameter		Groove 0.045 in.	64%
		1/16 in./0.068 in.	50%
		5/64 in.	55%
		Fillet 0.045 in.	10%
		1/16 in./0.068 in.	21%
		5/64 in.	33%
Percent of coupons failing radiography		(Groove only)	54%
Percent of coupons failing bend tests		(Groove only)	33%
Percent of coupons failing macro-etch		(Fillet only)	18%
Percent of coupons failing tensile tests		(Groove only)	0% (All passed)
Percent of coupons failing as a result of porosity		Groove	75%
		Fillet	58%

9.25.2. Macroetch specimens were inspected visually to the criteria specified in paragraph 5.12.3; however, as this paragraph does not provide guidance concerning porosity limitations, the requirements of paragraph 5.28.3 (for Welder Qualifications) were applied for porosity allowances.

Results of Tests Performed

The results of the tests were tabulated and statistical percentages were applied to various categories — Table 1. Failure to meet one or more of the acceptance criteria specified in AWS D1.1 totaled 56% of the groove weld coupons and 24% of the fillet weld coupons. Interestingly, of the groove weld failures, 75% were directly attributable to excessive porosity observed during radiographic evaluations — Fig. 1. Porosity was also a factor in 58% of the fillet weld failures (Fig. 2), detected on the face of the welds and/or during macroetch evaluation of the weld metal deposit. Of the eight welding positions used, 83% of the 4G position groove weld coupons and 44% of the 4F fillet weld coupons failed to meet the acceptance criteria, which were the highest failure percentages of any position used. Of the 18 groove weld coupons that were destructively tested, all 36 tension test specimens passed; however, only 67% of the 72 bend tests met the acceptance criteria. A direct correlation between bend test failures and excessive porosity was determined, as nearly all failures were

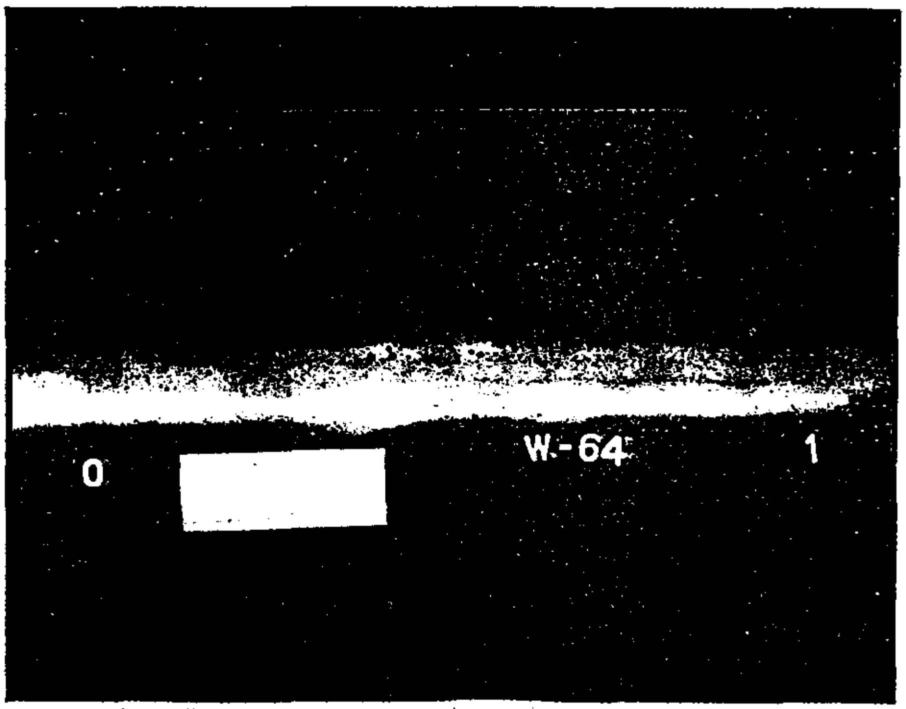

Fig. 1 — Typical porosity observed in radiographs on groove weld coupons.

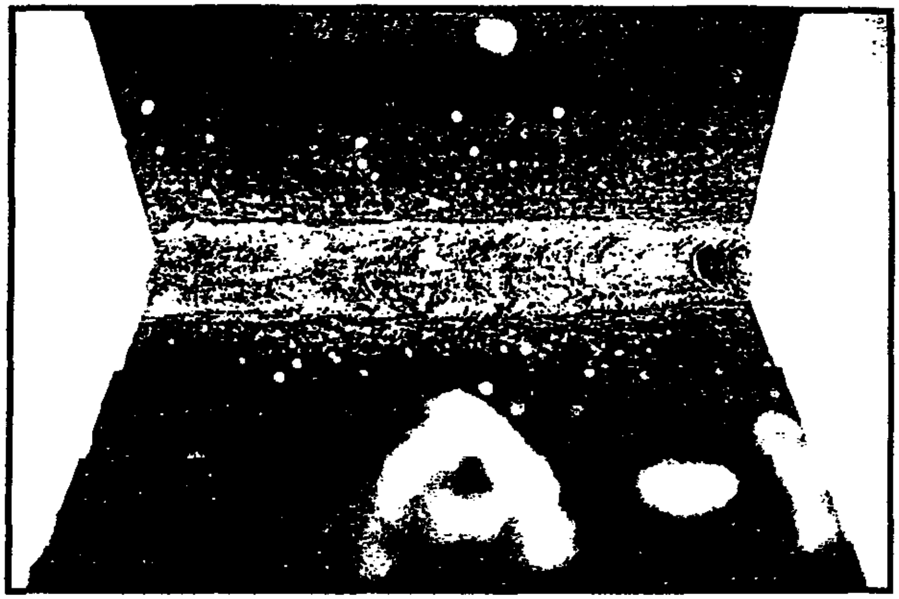

Fig. 2 — Typical porosity observed in surface of fillet weld coupons.

shown to have excessive porosity in the coupon radiograph prior to cutting and preparation for bending. Humidity, wind and plate thickness did not appear to [illegible] served. Specific trends could not be ascertained from the data generated, as the failures occurred nearly equally in all [illegible] ternal environmental conditions prevalent at the time of welding.

Analysis of Test Results

During a detailed analysis of the test parameters and results obtained, several trends emerged that provided reasons for the inordinate amount of failures, particularly those relating to excessive porosity. These statistics were discussed with a technical representative from each electrode manufacturer. The consensus opinion developed as to the causes, and corrective actions suggested to the problems, were:

◆ **E71T-11 electrode is not the best choice of self-shielded FCAW for relatively thick structural steel.** Although only one manufacturer's written documentation specifically limits the base metal thickness applicable to this wire (½ in. maximum), all technical representatives agreed that this electrode was not an ideal choice for the thicknesses [illegible] quality level expected. All representatives stated that an E71T-7 or T-8 electrode would have yielded much better results than those experienced with the T-11 wire.

◆ **Electrode extension range is especially critical when using T-11 wire.** The electrode extension ranges listed on each manufacturer's welding procedure were followed as closely as possible. However, at various times during the welding of the coupons, these ranges [illegible] or shortened due to operator fatigue. Both welders stated fatigue was definitely more pronounced in the 4G and [illegible] count for the excessive failures observed in those positions.

◆ **E71T-11 is very voltage sensitive.** A very narrow voltage range is listed on each manufacturer's welding procedure (± 1V, in some cases). Therefore, prior to welding, and at various times during welding, the two constant voltage welding machines that were used were checked with a calibrated multimeter to ensure accuracy. Each check revealed that each machine was producing voltage at the gun tip equivalent to that stated on the dial or meter (+ 1 V). However, in some cases, the voltage ranges were exceeded by the welder (+ 1–4 V) to obtain better stability of the arc and maintain a more uniform control of the deposit. This may have caused some of the failures experienced with the 0.045-in.-diameter wire used on the 1-in.-thick coupons, as the increase in voltage was more prevalent in these coupons than any others.

◆ **E71T-11 is much better for fillet** [illegible] The test results obtained proved this statement to be true — 76% of the fillet weld coupons passed, while only 44% of the groove weld coupons passed. Although porosity was evident in the failed fillet weld coupons, it did not appear to be as pronounced as that appearing in the [illegible] only four fillet weld coupons were rejected for fusion-type defects, which are usually much more detrimental to ser[illegible]

Conclusions

Potential and current users of E71T-11 self-shielded flux cored electrode should be guided primarily by the old axiom "the right product for the right circumstances." Although E71T-11 is usually less expensive than E71T-7 or T-8, the overall limitations of this wire may make selection of a more expensive wire a cost-effective decision in the long run. However, this wire does appear to have many applications, and can produce [illegible] turer's instructions are strictly applied, and base metal thicknesses are not excessive.

The authorized supplier or manufacturer's representatives should always be consulted prior to final selection of any cored wire. These individuals may have additional information or guidance not published in the written documents applicable to that particular product. ◆

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