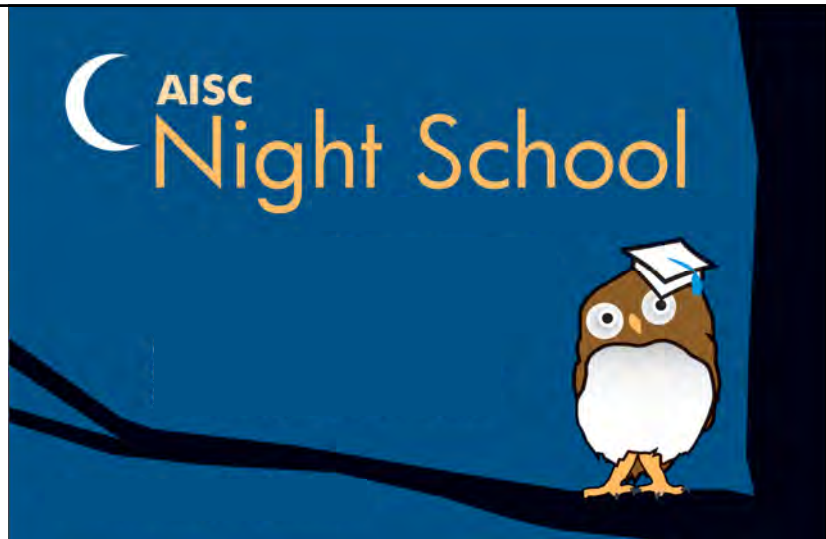


Thank you for joining our live webinar today.

We will begin shortly.  
Please standby. Thank you.

Need Help?  
Call ReadyTalk Support:  
800.843.9166



## Welded Connections

A Primer for Engineers



Smarter.  
Stronger.  
Steel.



### Audio Options

Today's audio will be broadcast through the internet.

Alternatively, to hear the audio through the phone, dial:

(866)-519-2796  
Passcode: 254072



Smarter.  
Stronger.  
Steel.



**Today's live webinar will begin shortly. Please stand by.**

As a reminder, all lines have been muted. Please type any questions or comments through the chat feature on the left portion of your screen.

Today's audio will be broadcast through the internet.  
Alternatively, to hear the audio through the phone, dial:

(866)-519-2796  
Passcode: 254072



## **AIA Credit**

AISC is a Registered Provider with The American Institute of Architects Continuing Education Systems (AIA/CES). Credit(s) earned on completion of this program will be reported to AIA/CES for AIA members. Certificates of Completion for both AIA members and non-AIA members are available upon request.

This program is registered with AIA/CES for continuing professional education. As such, it does not include content that may be deemed or construed to be an approval or endorsement by the AIA of any material of construction or any method or manner of handling, using, distributing, or dealing in any material or product.

Questions related to specific materials, methods, and services will be addressed at the conclusion of this presentation.





## Copyright Materials

This presentation is protected by US and International Copyright laws. Reproduction, distribution, display and use of the presentation without written permission of AISC is prohibited.

© The American Institute of Steel Construction 2019

The information presented herein is based on recognized engineering principles and is for general information only. While it is believed to be accurate, this information should not be applied to any specific application without competent professional examination and verification by a licensed professional engineer. Anyone making use of this information assumes all liability arising from such use.



## Course Description

21.4 Metallurgy and Cracking  
November 5, 2019

This session will focus on two topics: metallurgy and cracking. Many metallurgical issues are associated with steel construction and the first part of the session will focus on the welding-related issues associated with the various steels that are commonly used in structural applications. The second half of the session will review the issue of cracking. Cracking rarely occurs when fabrication is properly done in accordance.





## Learning Objectives

- Identify the three major weld crack types.
- Identify AISC and AWS provisions that address metallurgy.
- List the elements that affect weldability.
- Explain the role of notch toughness.



## Night School 21 Course Schedule

- 10/8/2019 1. Introduction and Weld Processes  
10/15/2019 2. Principles of Welded Connections  
10/29/2019 3. Welded Connection Details  
**11/5/2019 4. Metallurgy and Cracking**  
11/19/2019 5. Fatigue of Welded Connections  
11/26/2019 6. Seismic Welding Issues  
12/3/2019 7. Special Welding Applications  
12/10/2019 8. Problems and Fixes



# Night School 21 Welded Connections -- A Primer for Engineers

Session 4: Metallurgy and Cracking  
November 5, 2019



Duane K. Miller, PE, ScD  
Manager of Engineering Services and Welding  
Design Consultant



Smarter.  
Stronger.  
Steel.

## METALLURGICAL ISSUES

### Chapter 5: Metallurgical Issues

- 5.1 Introduction
- 5.2 Steel—Properties of Interest
- 5.3 Descriptions of Steel Groups
- 5.4 Welding Requirements for Specific Steels



## WELD CRACKING



### Chapter 6: Weld Cracking

- 6.1 Introduction
- 6.2 Shrinkage and Restraint
- 6.3 Types of Weld Cracks
- 6.4 Lamellar Tearing
- 6.5 Reducing Shrinkage Stresses
- 6.6 Reducing Restraint
- 6.7 Post-Welding Stress Reduction Measures



11

## METALLURGY AND CRACKING

### Outline

- ➔ • Welding and Metallurgy
- Steel Categories
- Cracking
- Special Steels



12

## METALLURGY AND CRACKING

### Metallurgy in a nutshell....

- Composition (alloys and carbon)
- Cooling Rate



13

## WELDING AND METALLURGY


### Properties of Interest:

- Mechanical properties
- Chemical composition



14


## PROPERTIES OF INTEREST



Welded Connections—  
A Primer for  
Engineers


**Mechanical Properties:**

- **Strength** (yield, tensile)
- **Ductility** (elongation, reduction in area)
- **Toughness** (CVN, CTOD)
- **Stiffness** (modulus of elasticity)




15

## TENSILE TEST



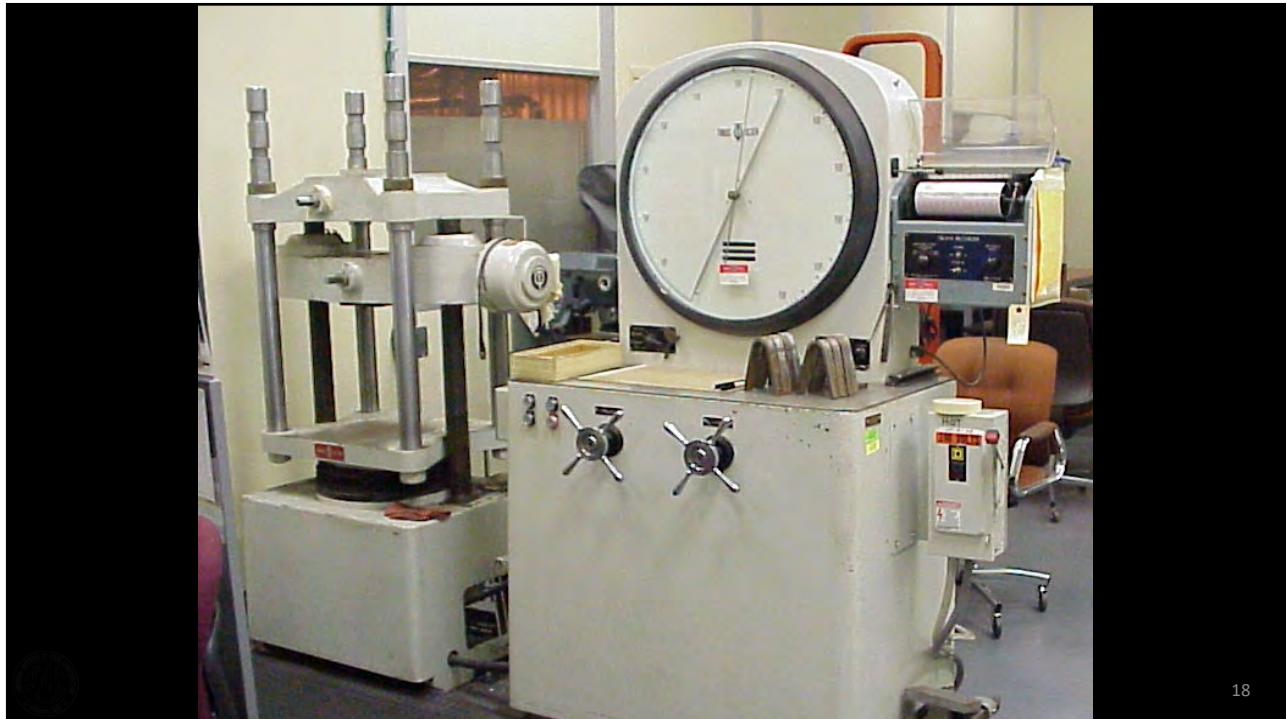
Welded Connections—  
A Primer for  
Engineers



16



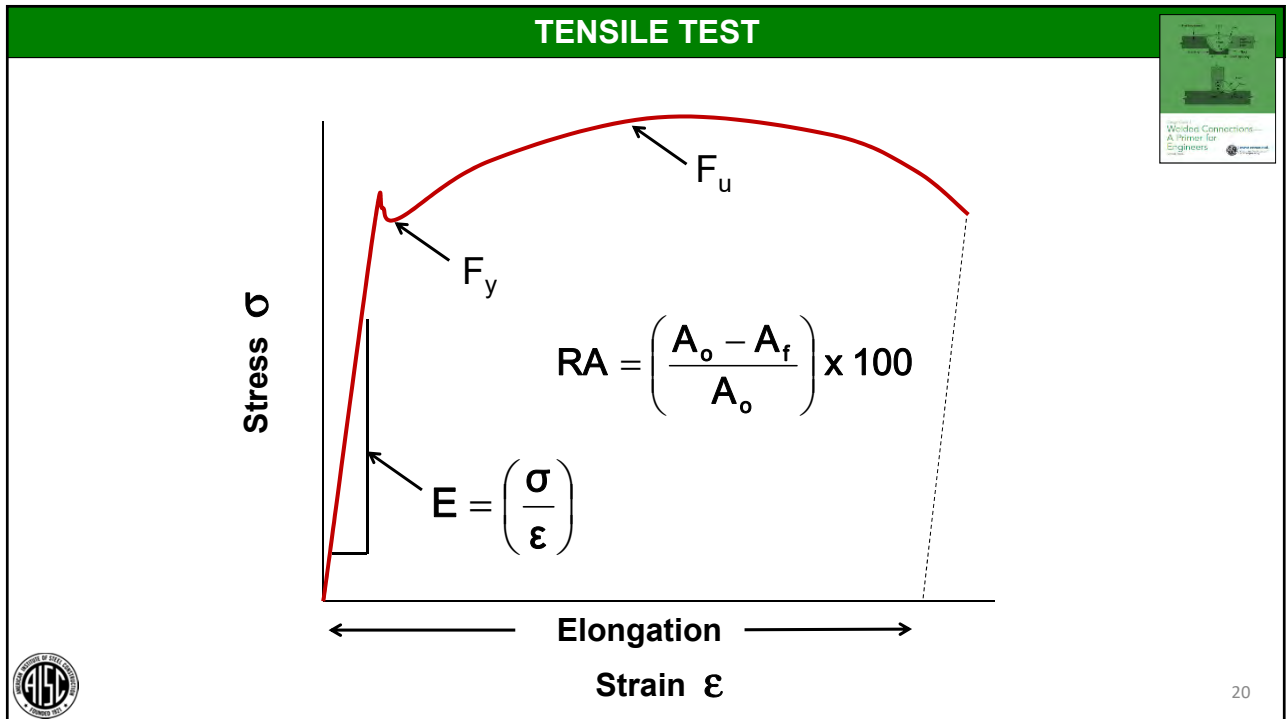
17



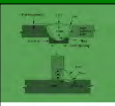
18




19



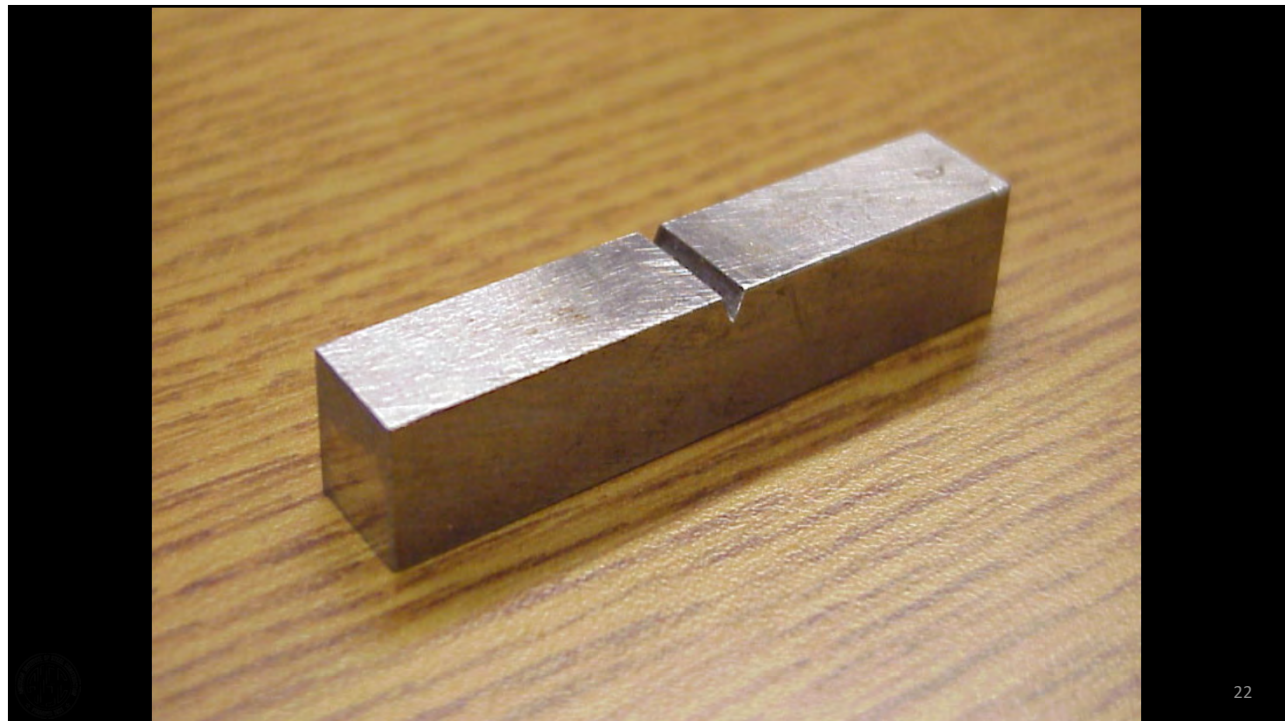
## CHARPY IMPACT TEST

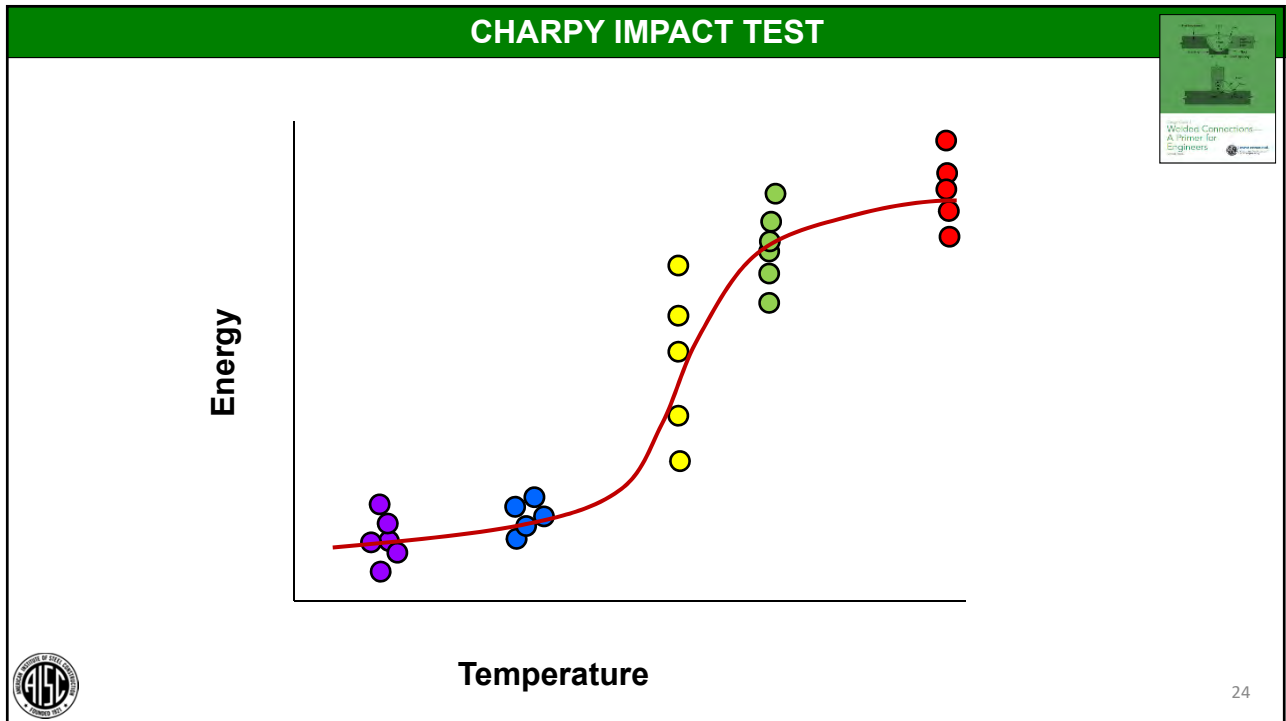


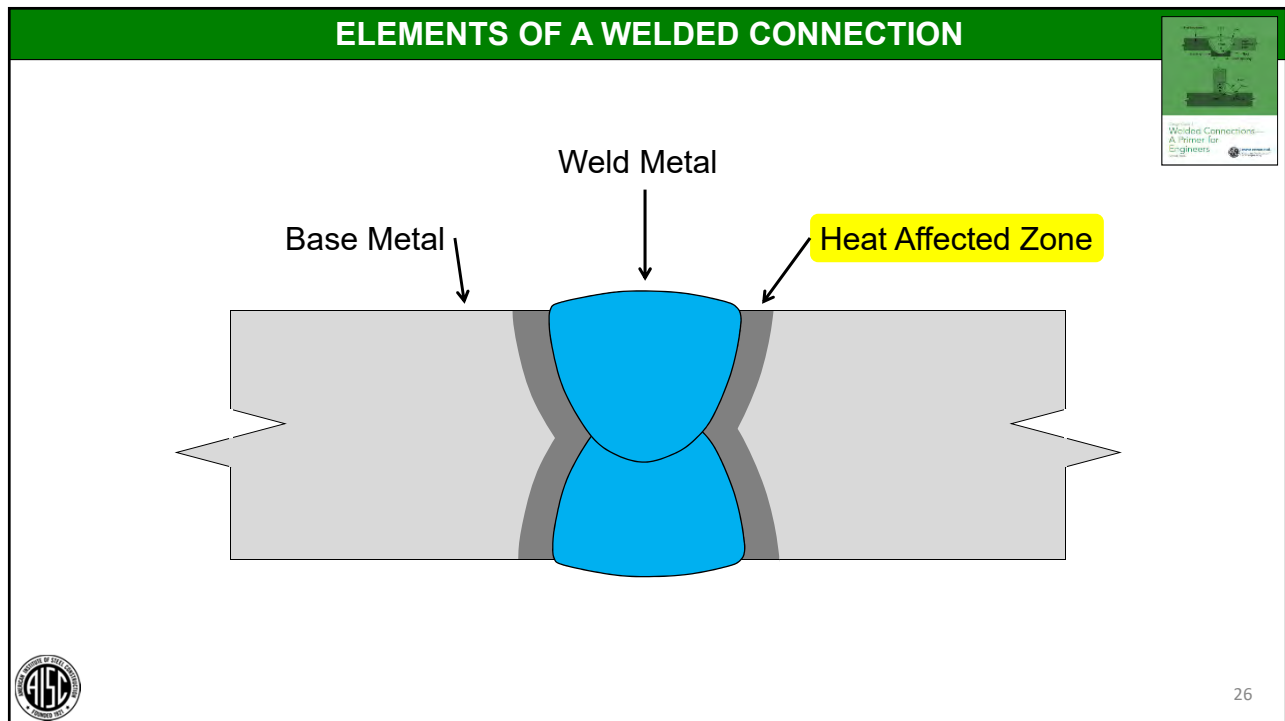
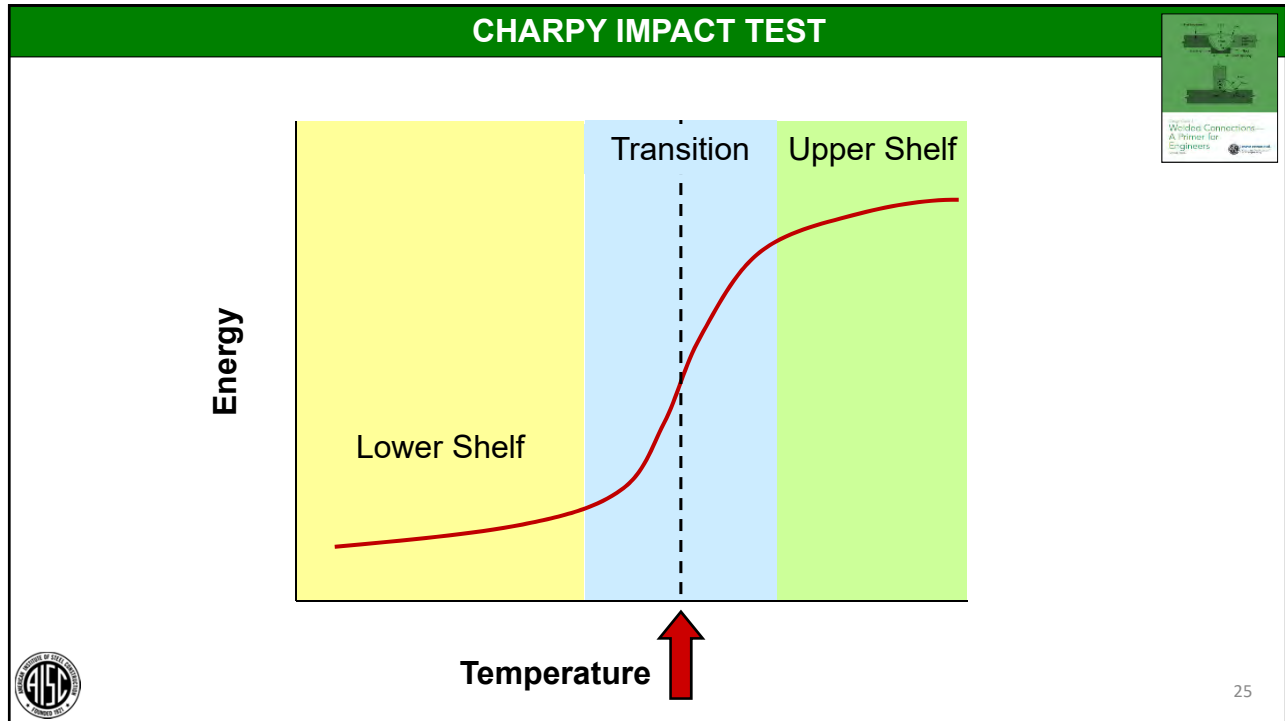
Welded Connections—  
A Primer for  
Engineers



21



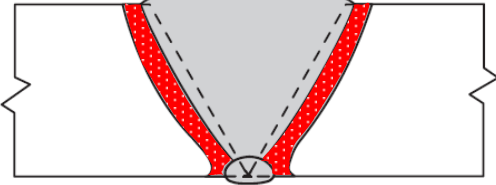







### AWS STANDARD WELDING TERMS & DEFINITIONS (A3.0:2010)

**heat-affected zone (HAZ).**

The portion of **base metal** whose **mechanical properties** or microstructure have been **altered by the heat of welding**, brazing, soldering or thermal cutting.

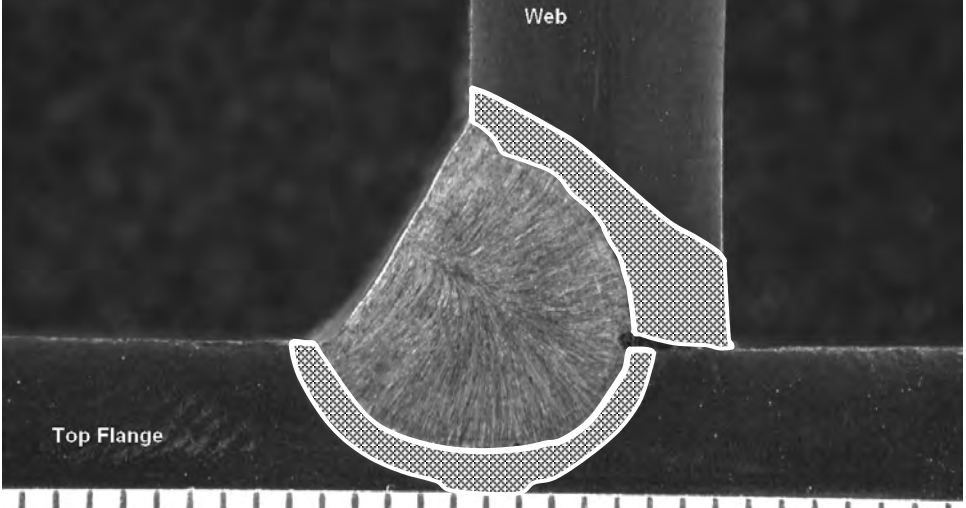








27

### HEAT AFFECTED ZONE (HAZ)

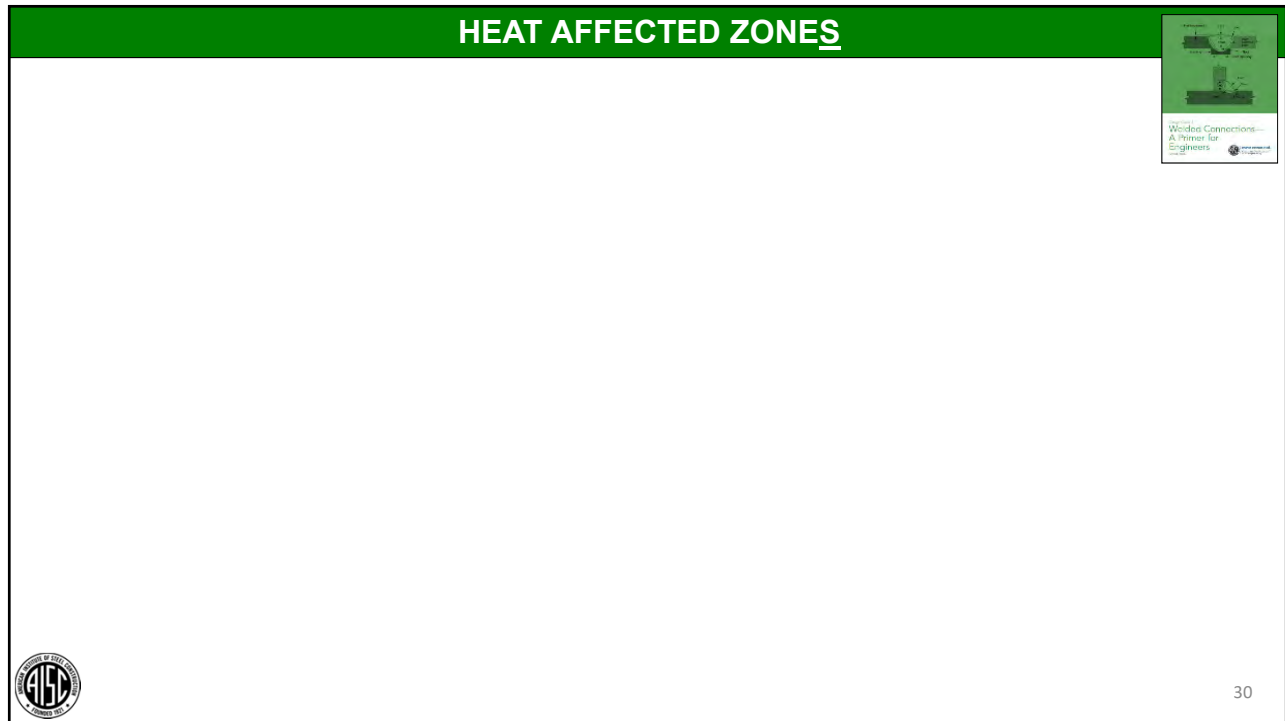
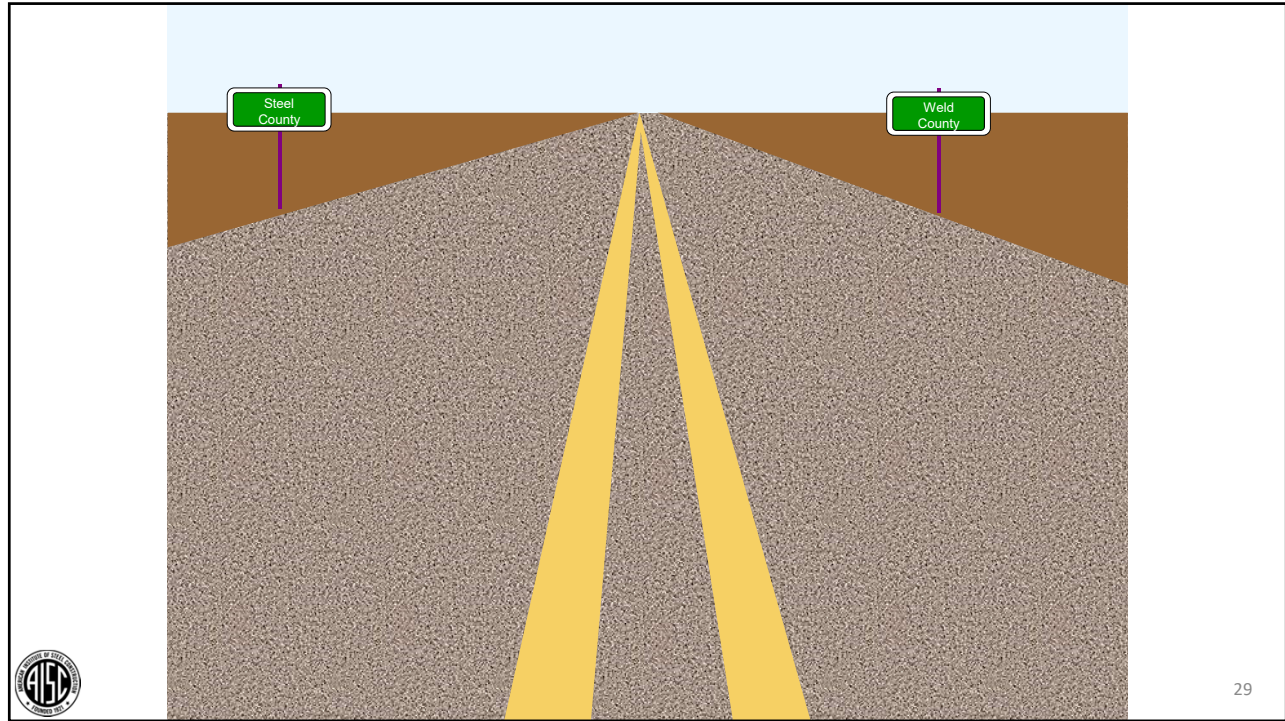


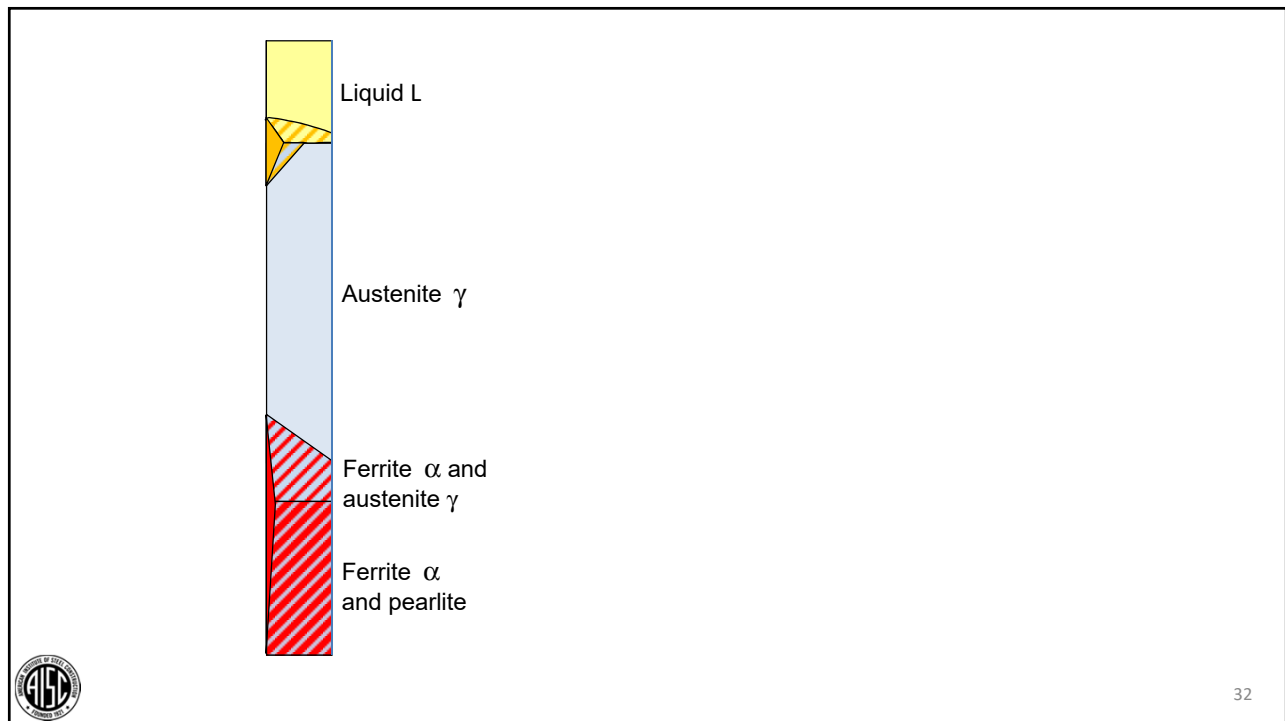
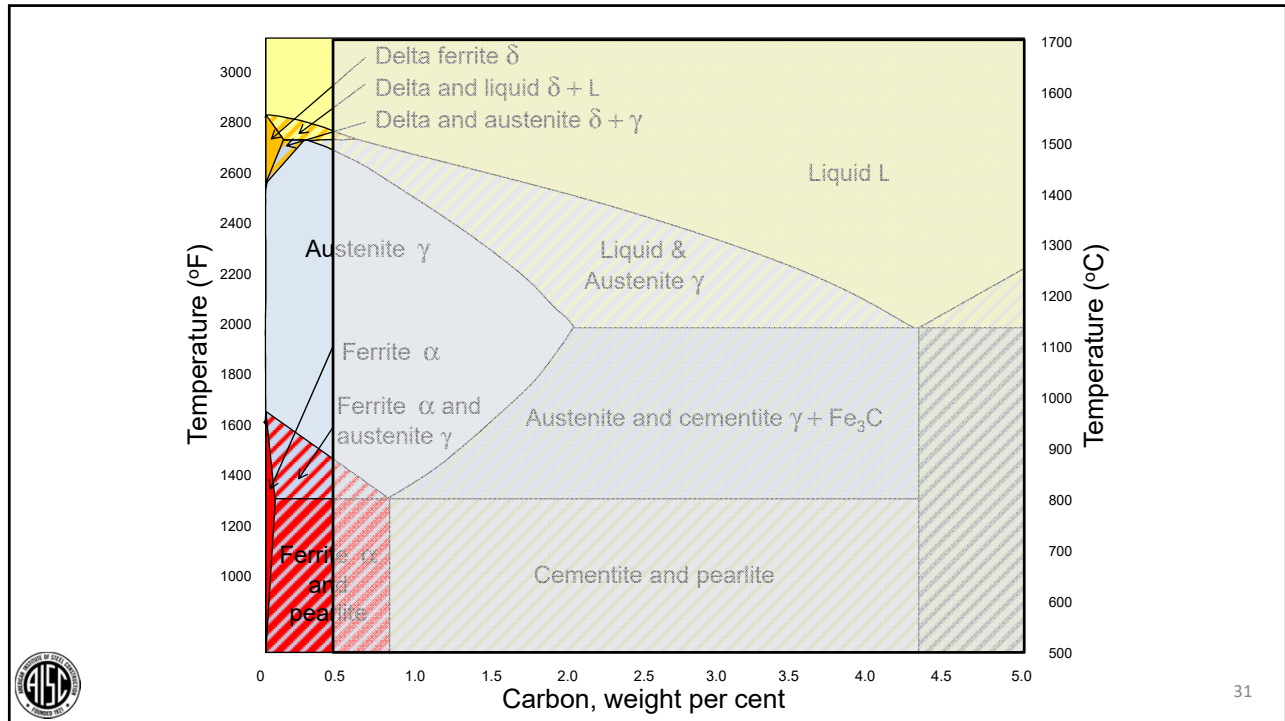
Web

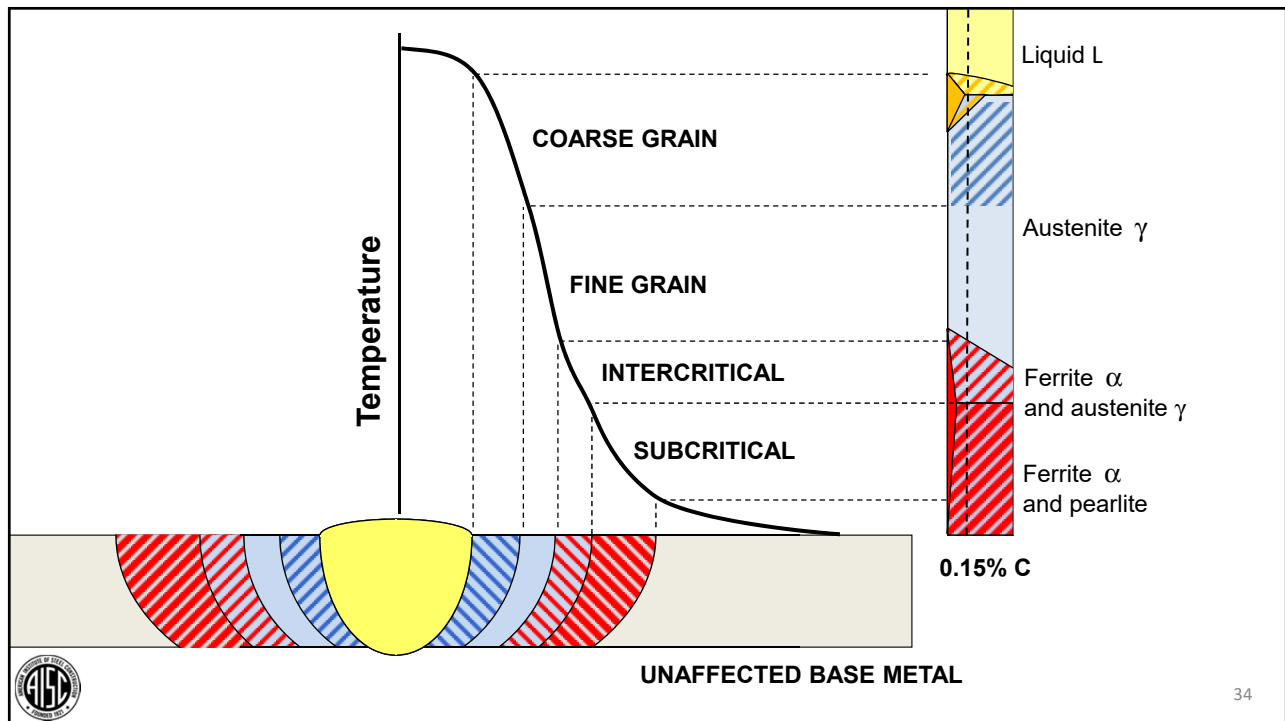
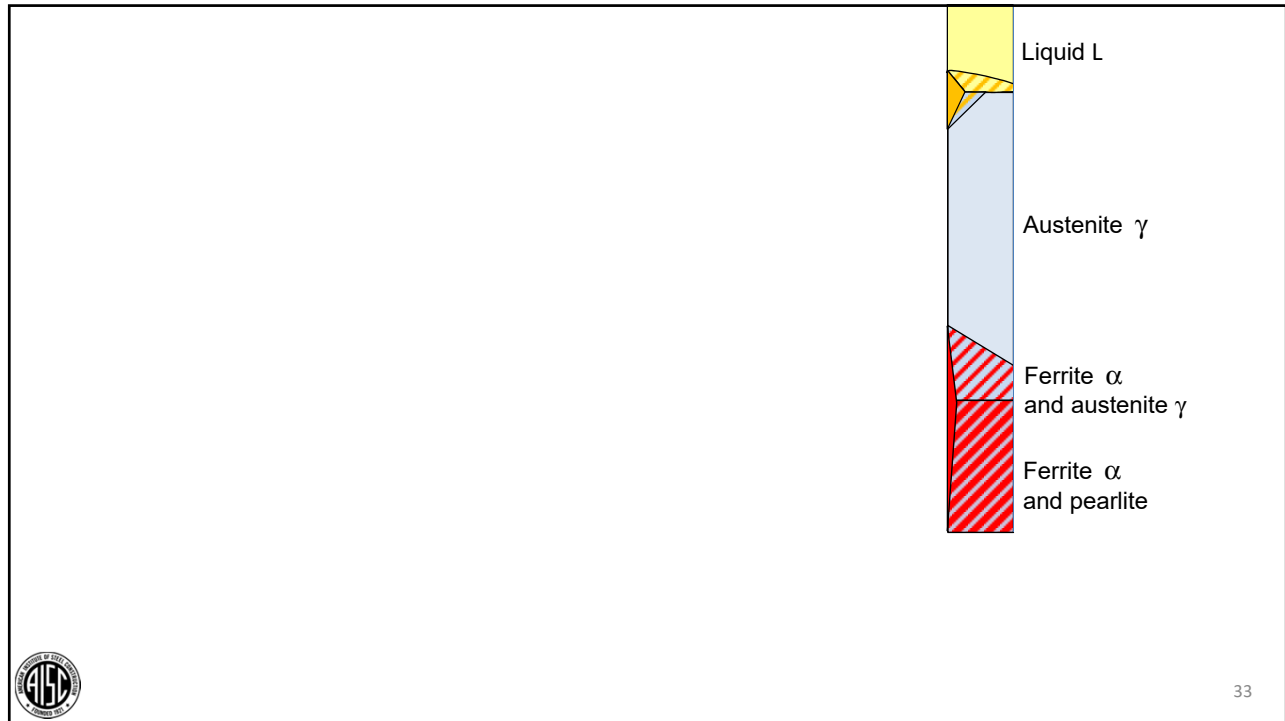
Top Flange

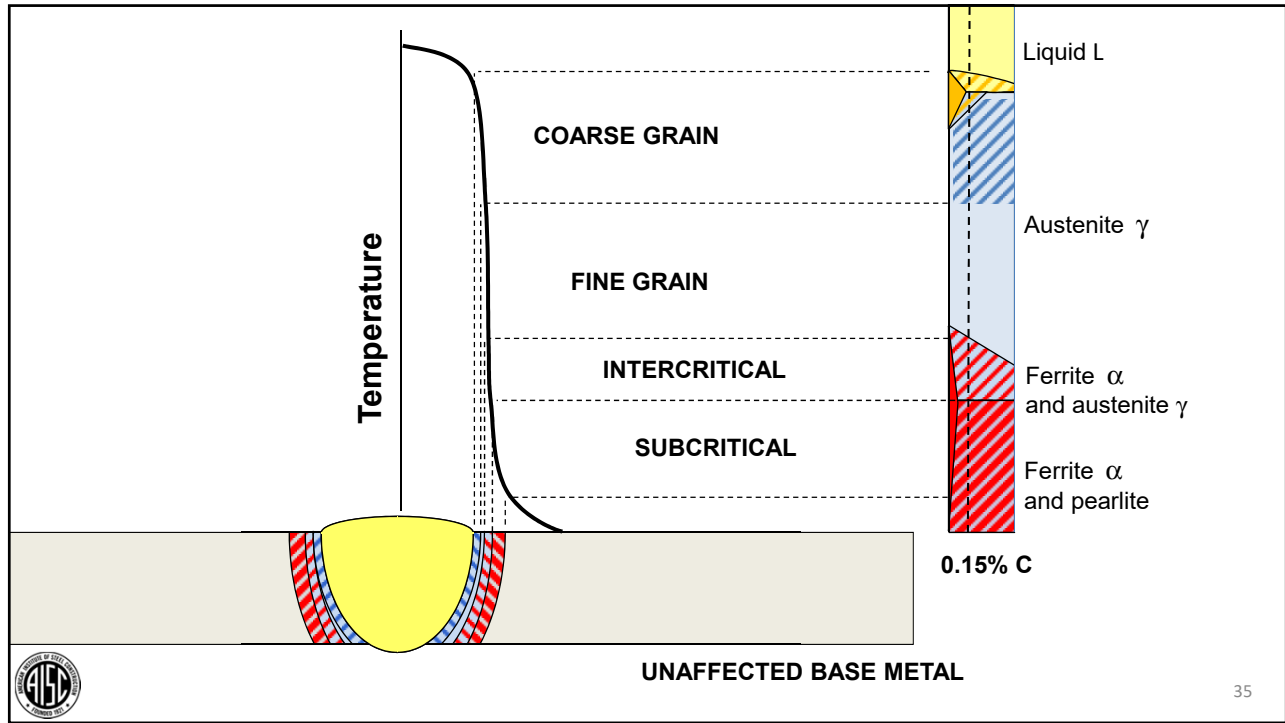


28










**HEAT AFFECTED ZONE—IN A SINGLE PASS WELD**

**Coarse Grain Zone**


**Fine Grain Zone**

**Intercritical Zone**

**Subcritical Zone**



Welded Connections—  
A Primer for  
Engineers


36

## METALLURGY AND CRACKING

### Metallurgy in a nutshell....

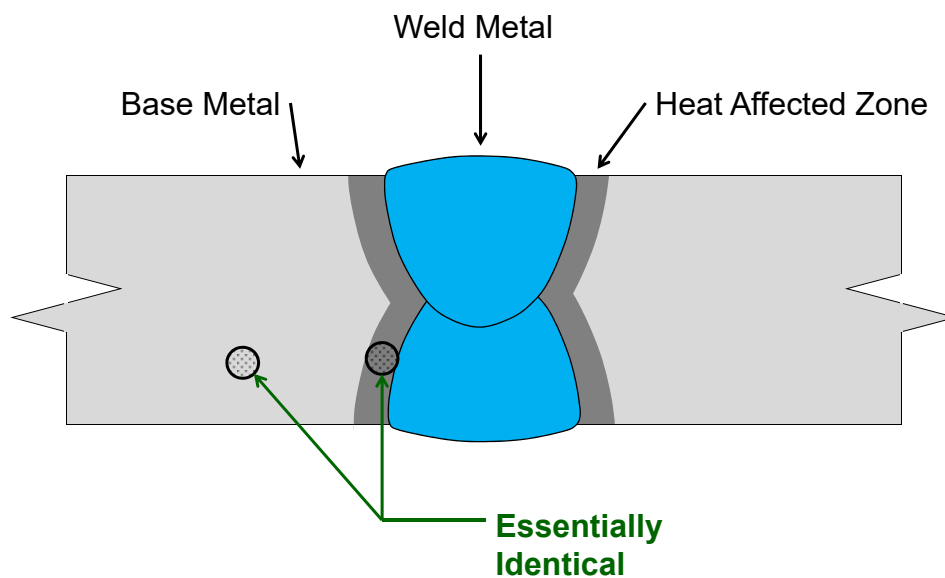
- **Composition** (alloys and carbon)
- Cooling Rate



37

## HEAT AFFECTED ZONE: CHEMISTRY

### HAZ Chemistry = Base Metal Chemistry




38

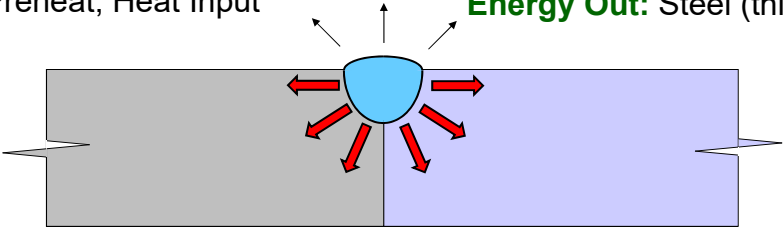
## METALLURGY AND CRACKING


**Metallurgy in a nutshell....**

- Composition (alloys and carbon)
- **Cooling Rate**



**Energy In:** Preheat, Heat Input      **Energy Out:** Steel (thickness), Air




39

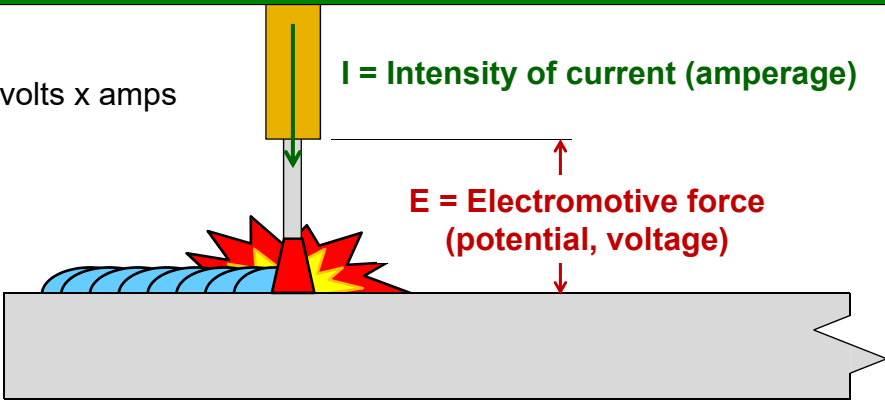
## HEAT INPUT (ENERGY INPUT)

Energy = volts x amps


**I = Intensity of current (amperage)**

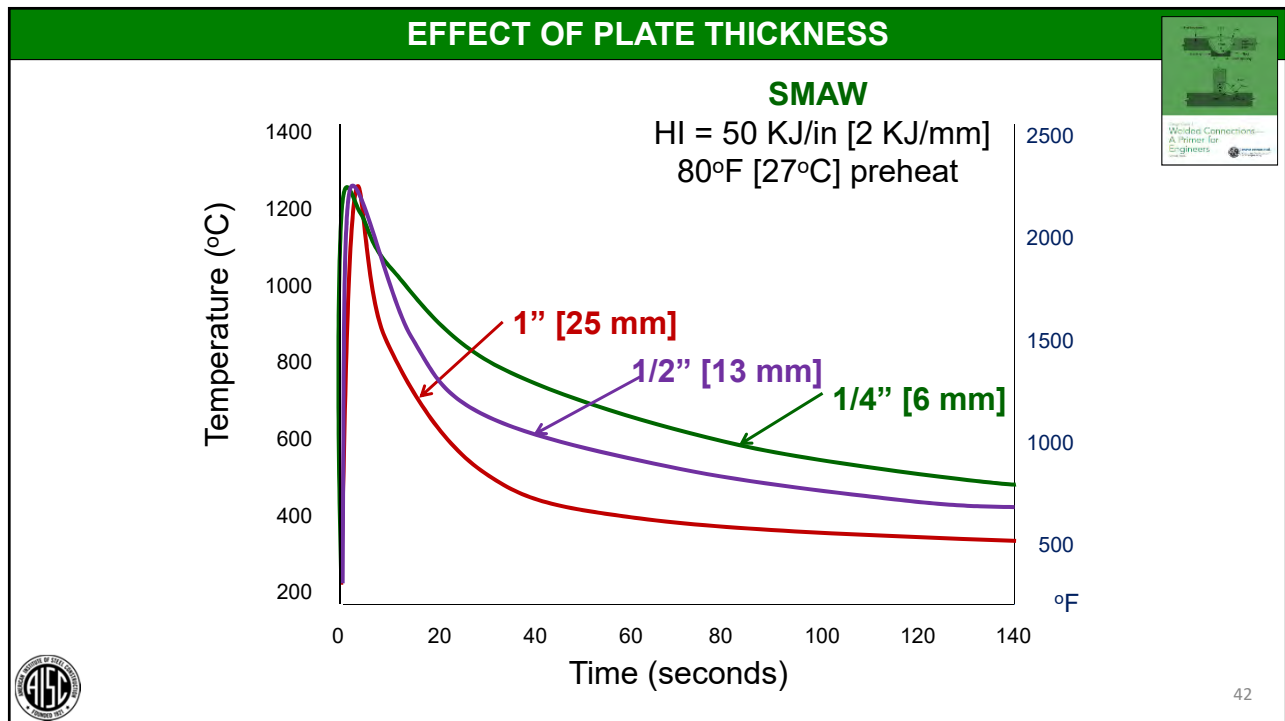
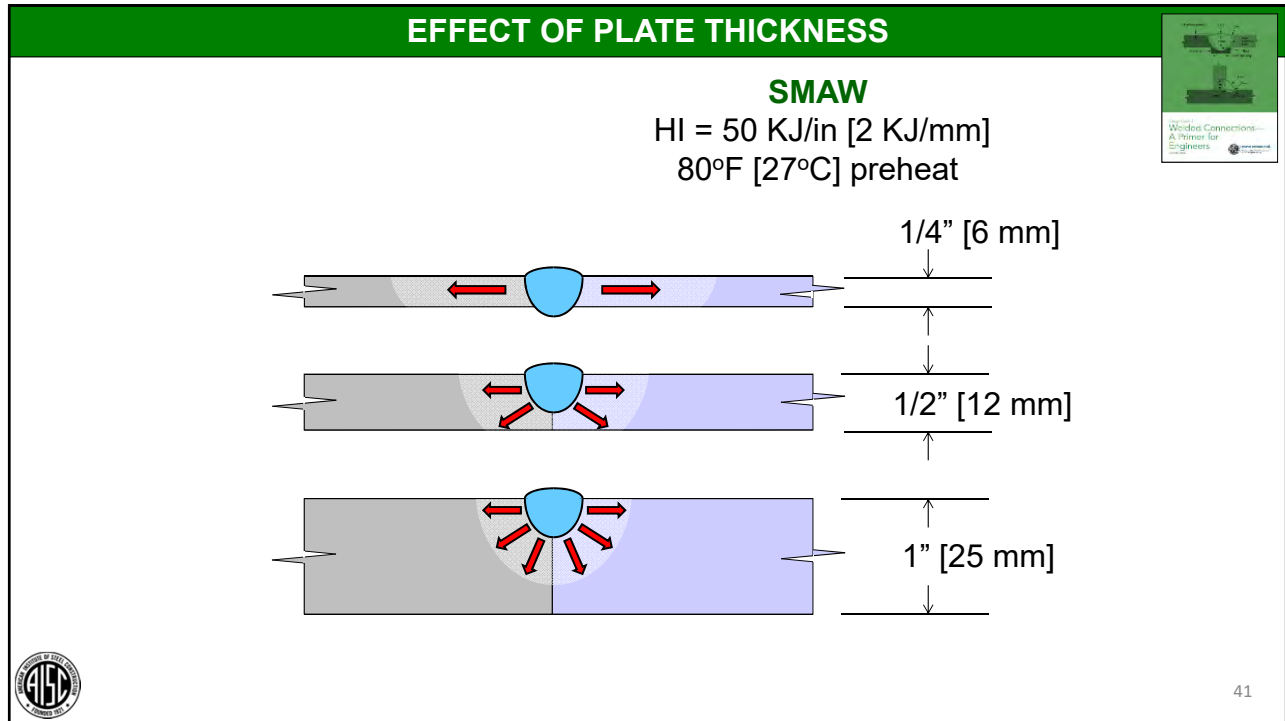
**E = Electromotive force (potential, voltage)**

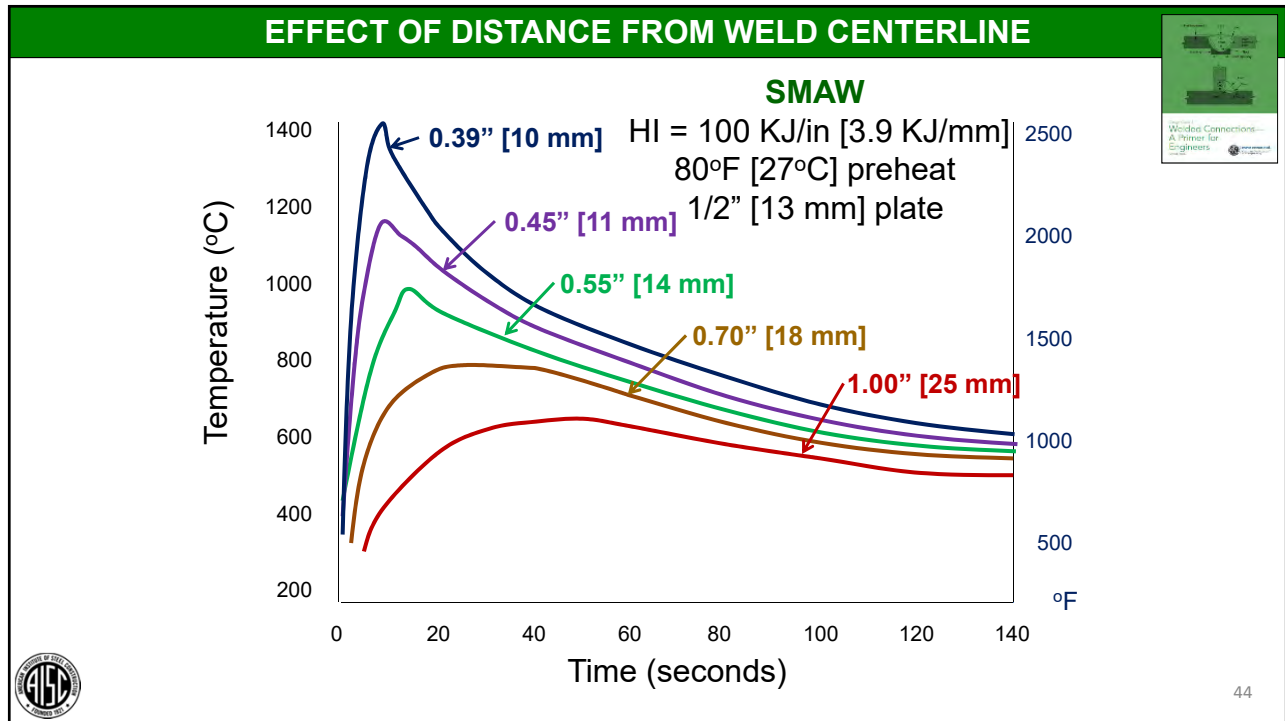
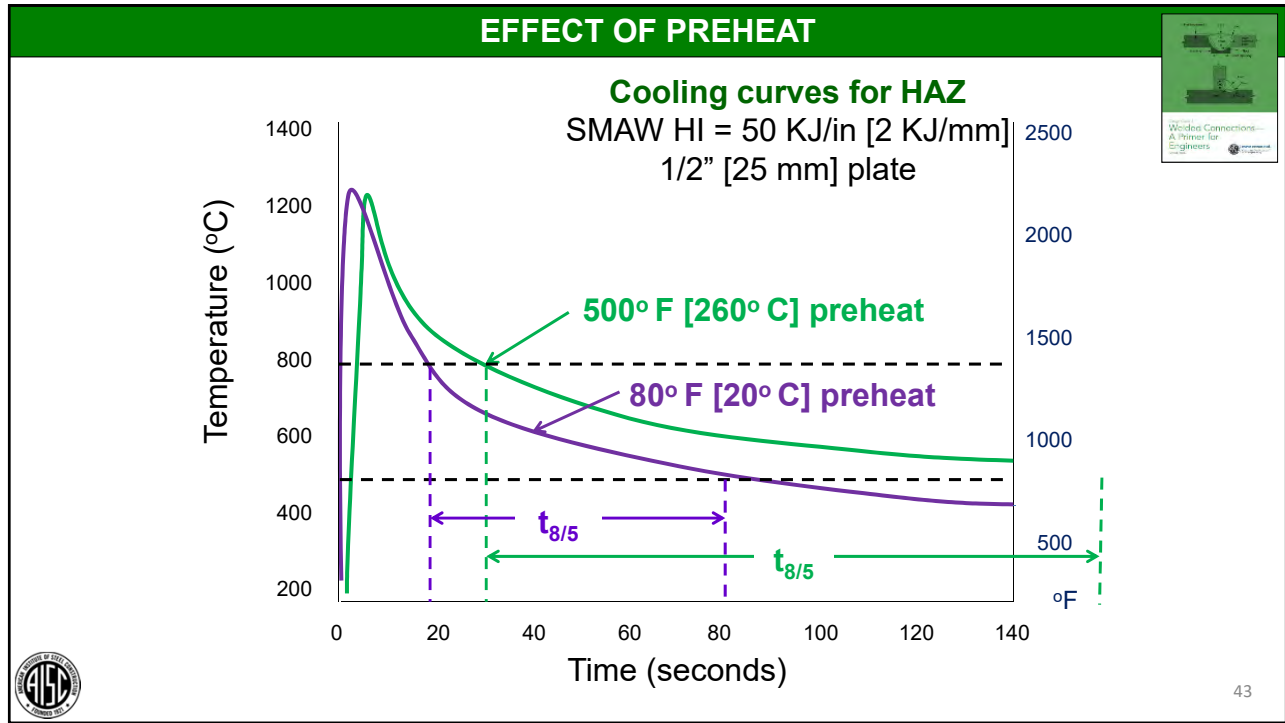
**S = Travel speed**

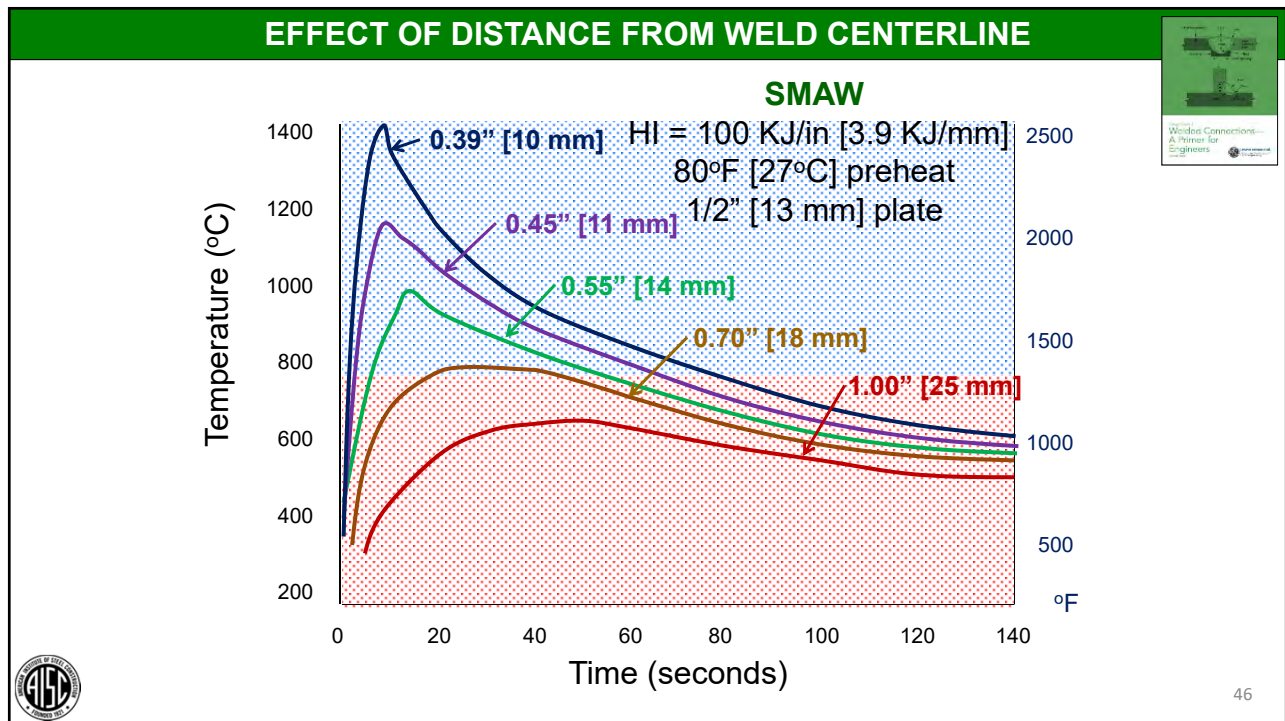
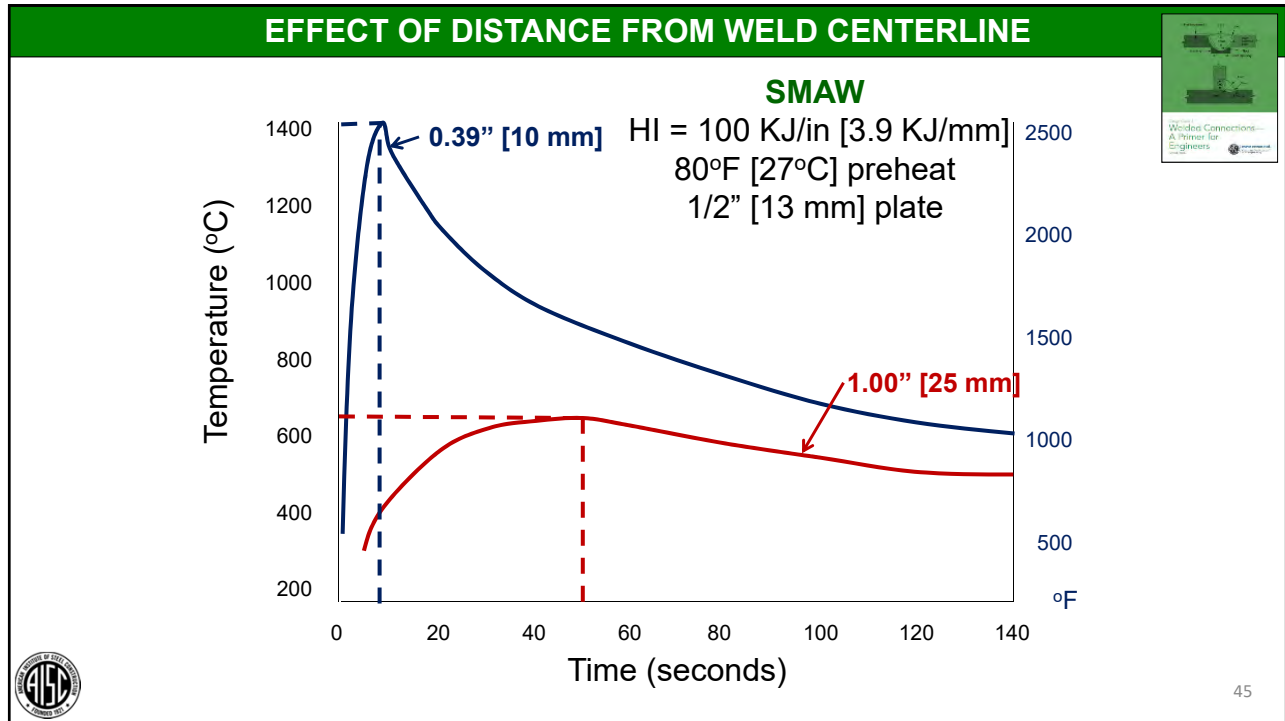


$$HI = \frac{60 E I}{1000 S} \text{ KJ/in [KJ/mm]}$$



40







**HEAT INPUT (ENERGY INPUT)**




**D1.1 does not directly deal with heat input, except:**


- For quenched and tempered steels
- For WPSs required to deliver minimum CVN properties

**D1.5 and D1.8 both address heat input directly.**

**D1.1 does deal with heat input indirectly.**



47

**AISC 360-16 Specification for Structural Steel Buildings**



**Table J2.4: Minimum Fillet Weld Sizes**



Material Thickness of Thinner Part Joined	Minimum Size of Fillet Weld
To 1/4", inclusive	1/8"
Over 1/4" to 1/2"	3/16"
Over 1/2" to 3/4"	1/4"
Over 3/4"	5/16"


48

**AWS D1.1: 2015 Structural Welding Code – Steel**

**Table 5.7: Minimum Fillet Weld Sizes**

Base-Metal Thickness (T) <sup>a</sup>	Minimum Size of Fillet Weld <sup>b</sup>	Approximate Minimum Heat Input
$T \leq 1/4"$	1/8"	7 kJ/in.
$1/4" < T \leq 1/2"$	3/16"	16 kJ/in.
$1/2" < T \leq 3/4"$	1/4"	30 kJ/in.
$3/4" < T$	5/16"	43 kJ/in.





49

**METALLURGY AND CRACKING**


**Metallurgy in a nutshell....**

- Composition (alloys and carbon)
- Cooling Rate

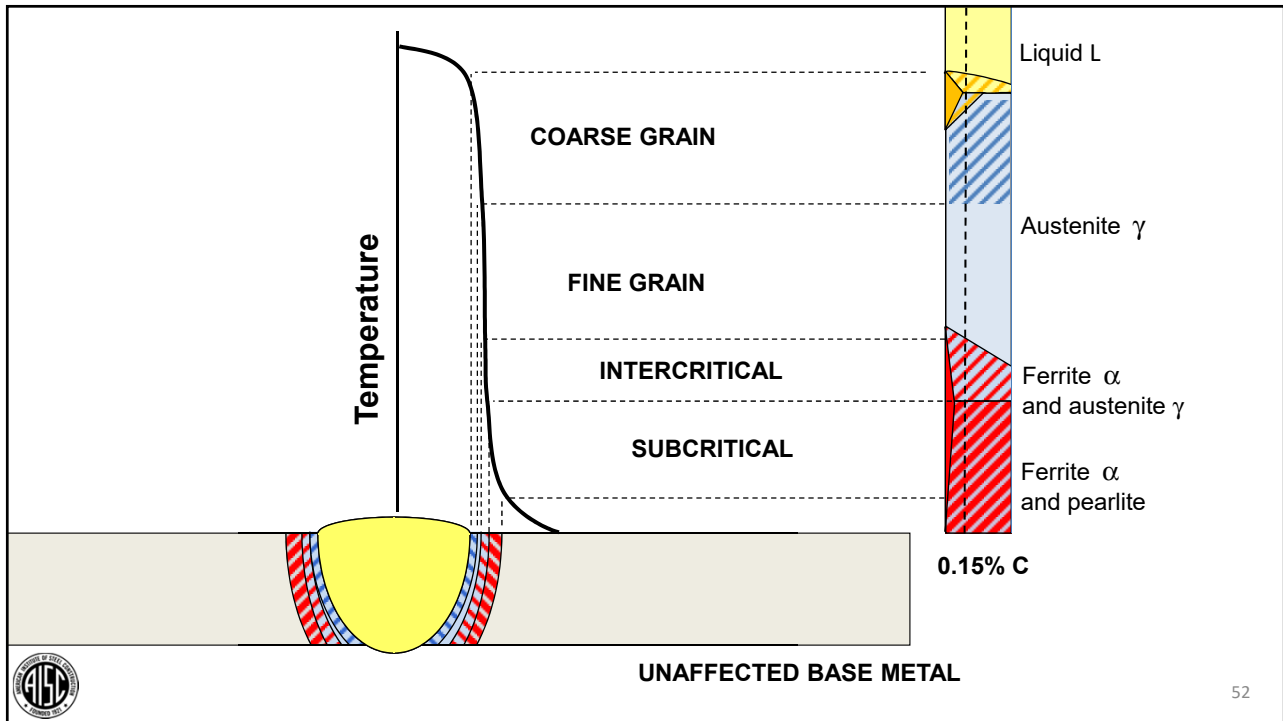
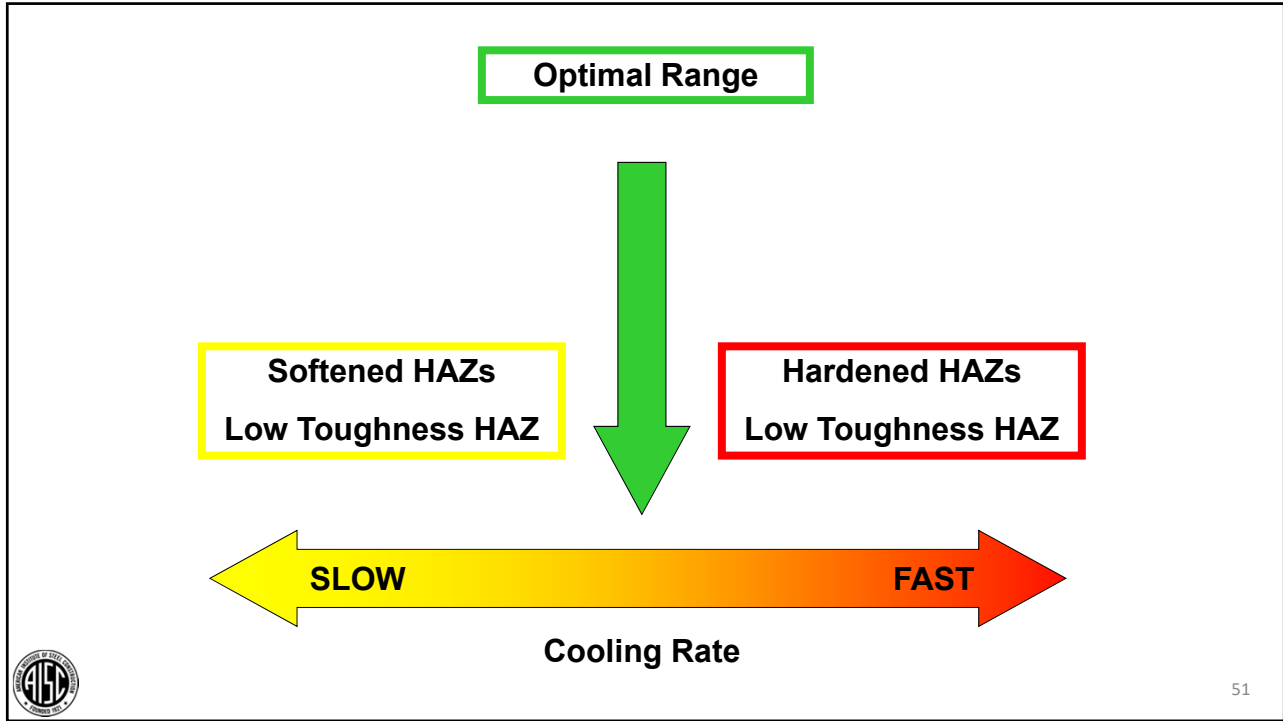


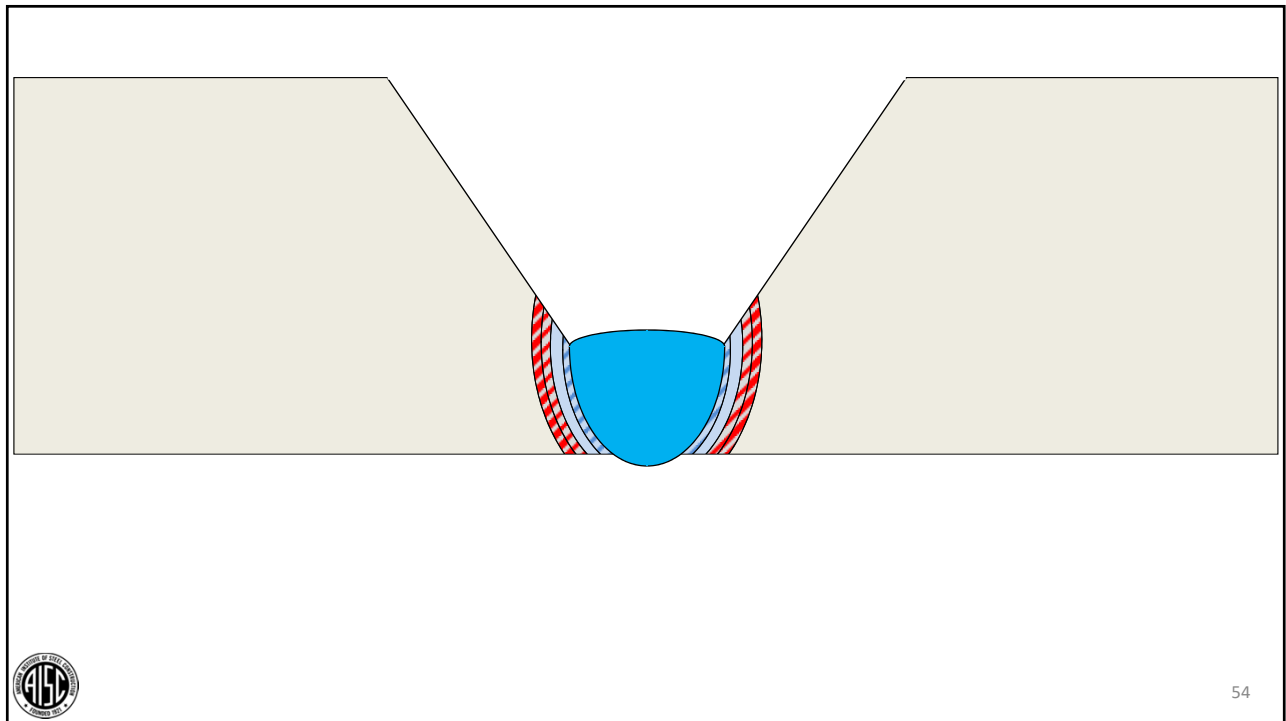
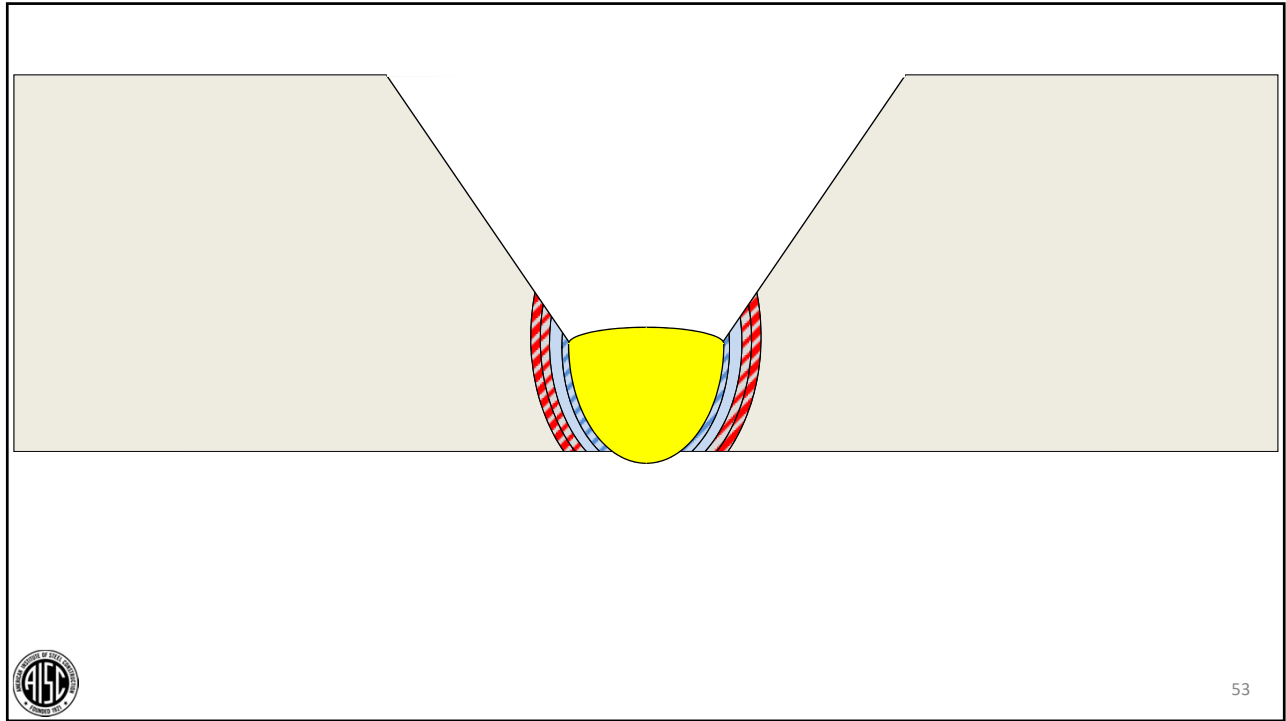
**In the HAZ...**

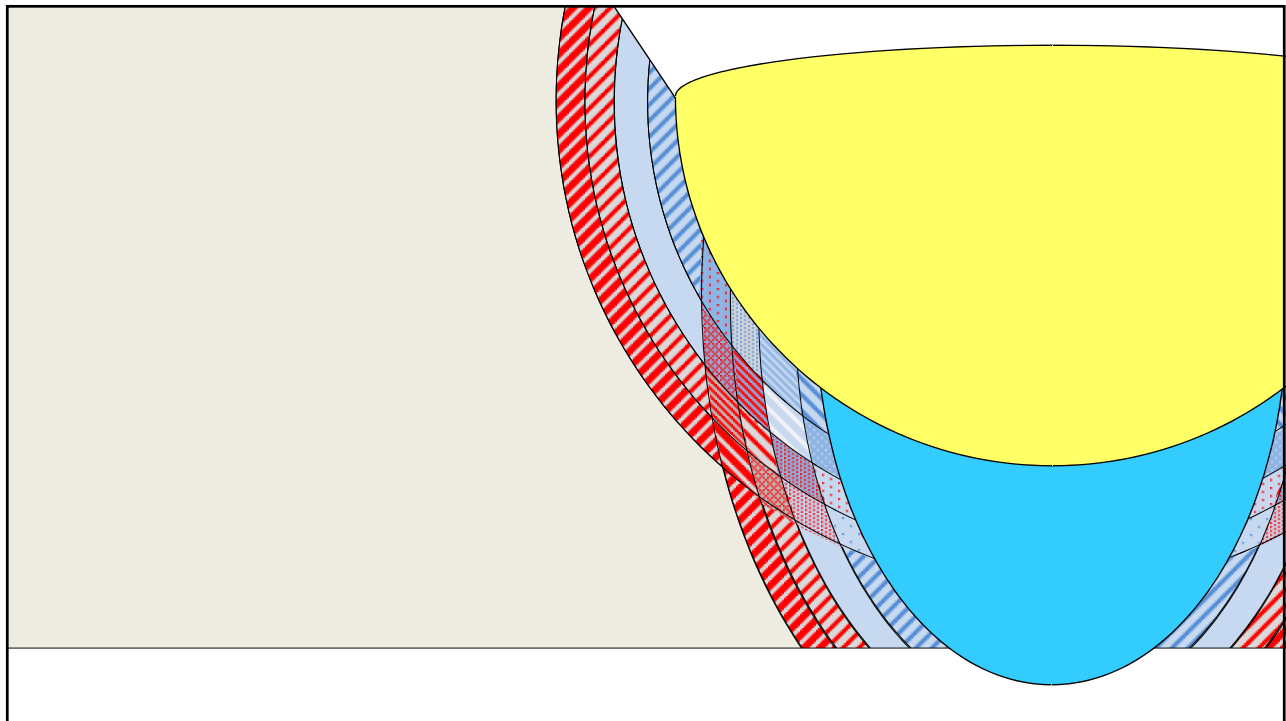
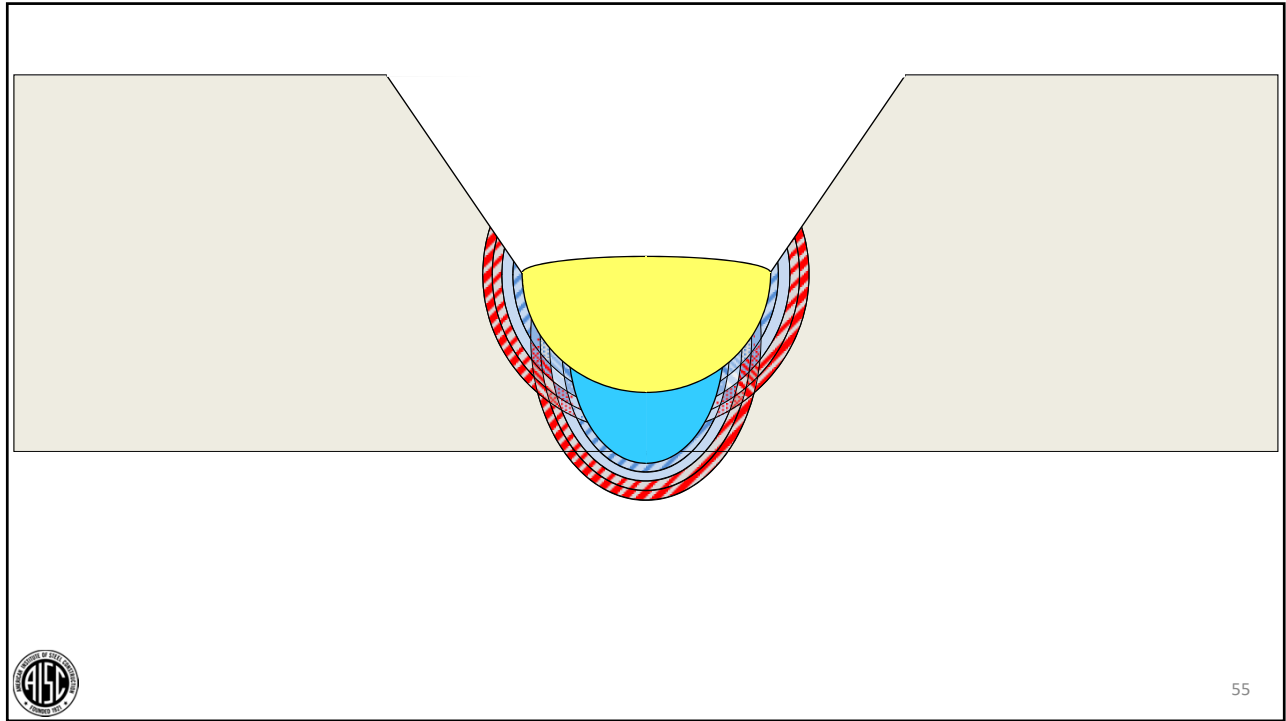
- The composition is that of the base metal
- Heating and cooling rates vary, depending on welding conditions
- Codes and practical welding limits extremes on high and low cooling rates
- Preheat is the primary means by which cooling rates are controlled

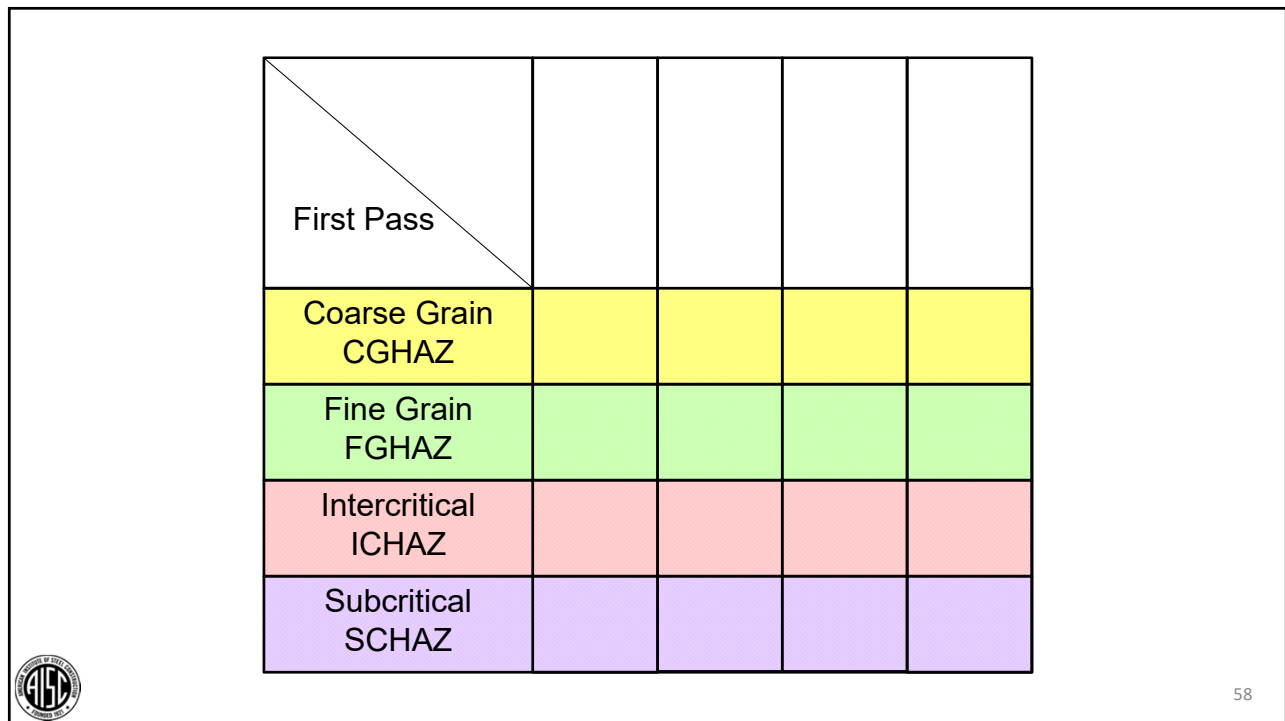
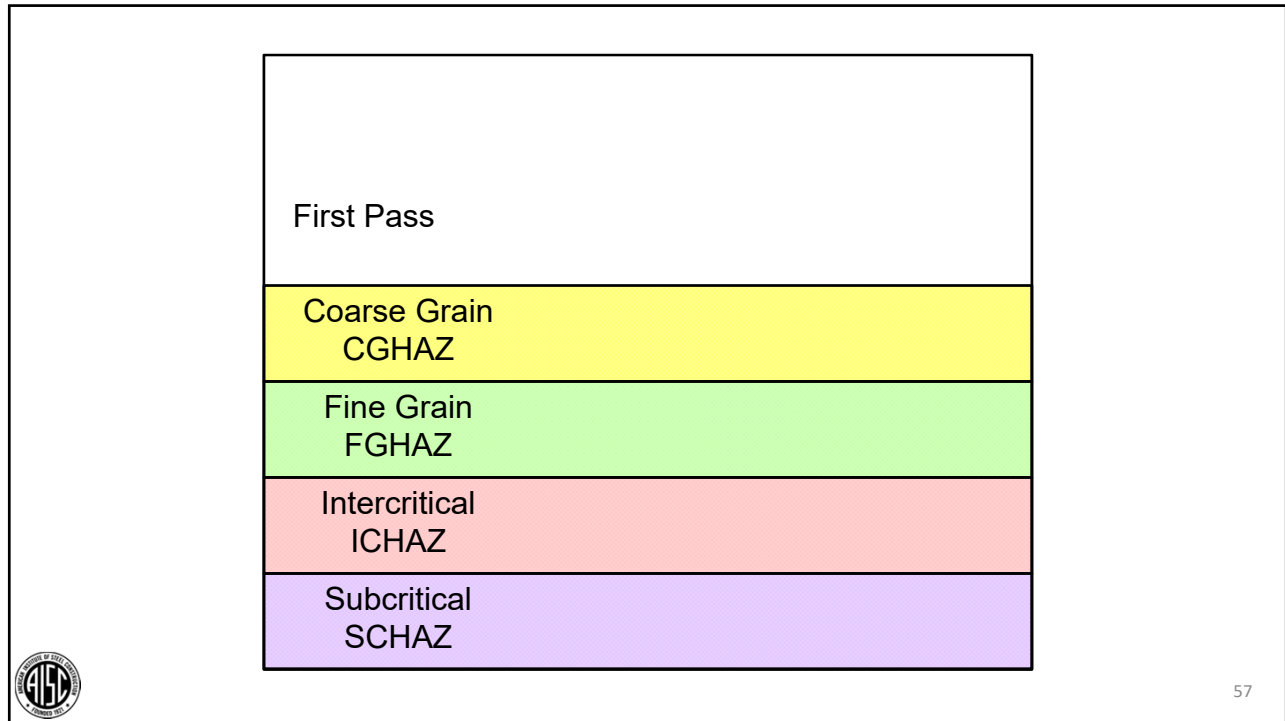


50











Second Pass / First Pass	Coarse Grain CGHAZ	Fine Grain FGHAZ	Intercritical ICHAZ	Subcritical SCHAZ
Coarse Grain CGHAZ	CGHAZ + CGHAZ	CGHAZ + FGHAZ	CGHAZ + ICHAZ	CGHAZ + SCHAZ
Fine Grain FGHAZ	FGHAZ + CGHAZ	FGHAZ + FGHAZ	FGHAZ + ICHAZ	FGHAZ + SCHAZ
Intercritical ICHAZ	ICHAZ + CGHAZ	ICHAZ + FGHAZ	ICHAZ + ICHAZ	ICHAZ + SCHAZ
Subcritical SCHAZ	SCHAZ + CGHAZ	SCHAZ + FGHAZ	SCHAZ + ICHAZ	SCHAZ + SCHAZ

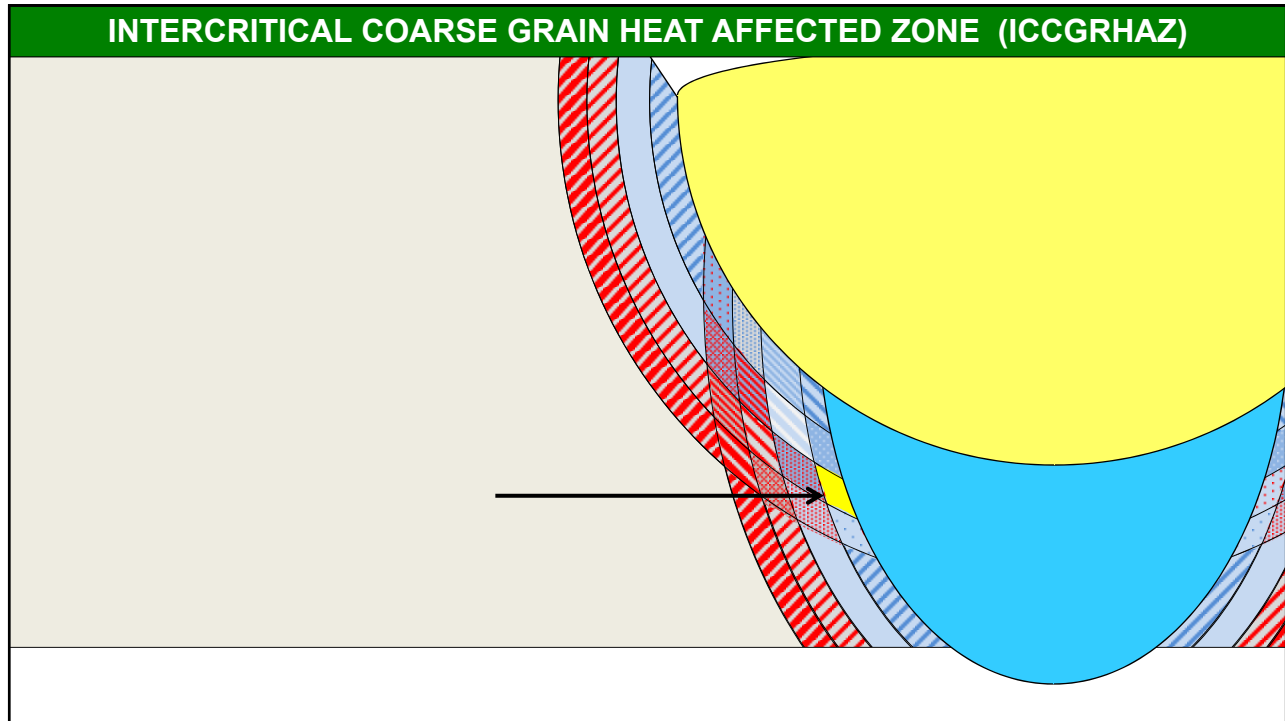


59


Second Pass / First Pass	Coarse Grain CGHAZ	Fine Grain FGHAZ	Intercritical ICHAZ	Subcritical SCHAZ
Coarse Grain CGHAZ	CGHAZ + CGHAZ	CGHAZ + FGHAZ	<b>ICCGHAZ</b>	<b>SCCGHAZ</b>
Fine Grain FGHAZ	FGHAZ + CGHAZ	FGHAZ + FGHAZ	FGHAZ + ICHAZ	FGHAZ + SCHAZ
Intercritical ICHAZ	ICHAZ + CGHAZ	ICHAZ + FGHAZ	ICHAZ + ICHAZ	ICHAZ + SCHAZ
Subcritical SCHAZ	SCHAZ + CGHAZ	SCHAZ + FGHAZ	SCHAZ + ICHAZ	SCHAZ + SCHAZ



60



**SAC PROJECT**




**SAC**  
Steel Project


Report No. SAC/BD-00/13

**Preliminary Evaluation of Heat Affected Zone  
Toughness in Structural Shapes used in the  
Construction of Seismic Moment Frames**

Johnson



“Based on review of the available literature and the information gathered as part of the SAC program, it is expected that HAZ toughness of hot rolled and QST steel shapes is often expected to be higher than that of the as - received base metal.”

62

## SAC PROJECT



Report No. SAC/BD-00/13

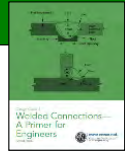
Johnson

### Preliminary Evaluation of Heat Affected Zone Toughness in Structural Shapes used in the Construction of Seismic Moment Frames

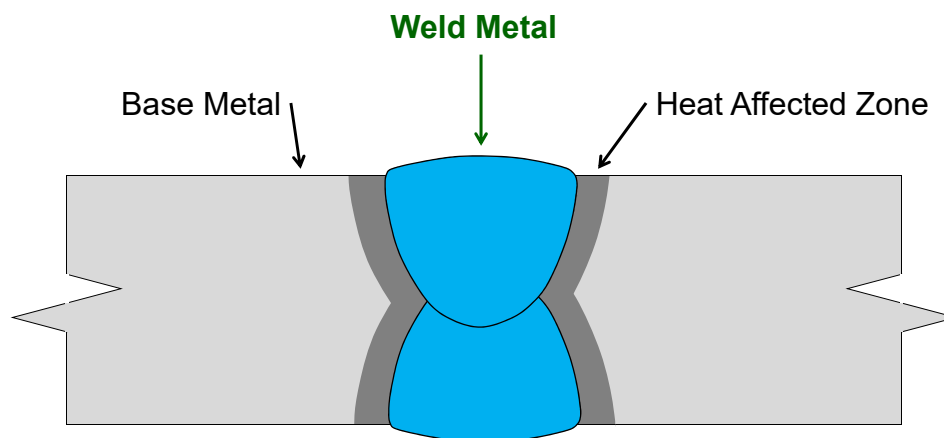
For multipass welds, the two additional regions are as follows: intercritically reheated CGHAZ (ICGCHAZ), and subcritically reheated CGHAZ (SCCGHAZ). In particular, the ICGHAZ region has been identified as a region that can often experience a substantial reduction in CTOD toughness.”



63



## WELD METAL





64



### METALLURGY AND CRACKING



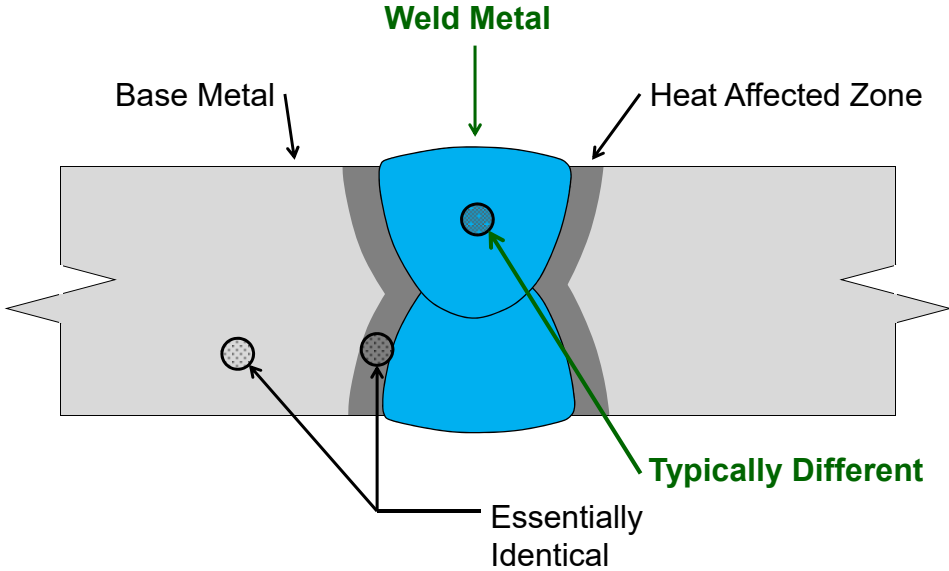
**Metallurgy in a nutshell....**

- **Composition** (alloys and carbon)
- Cooling Rate

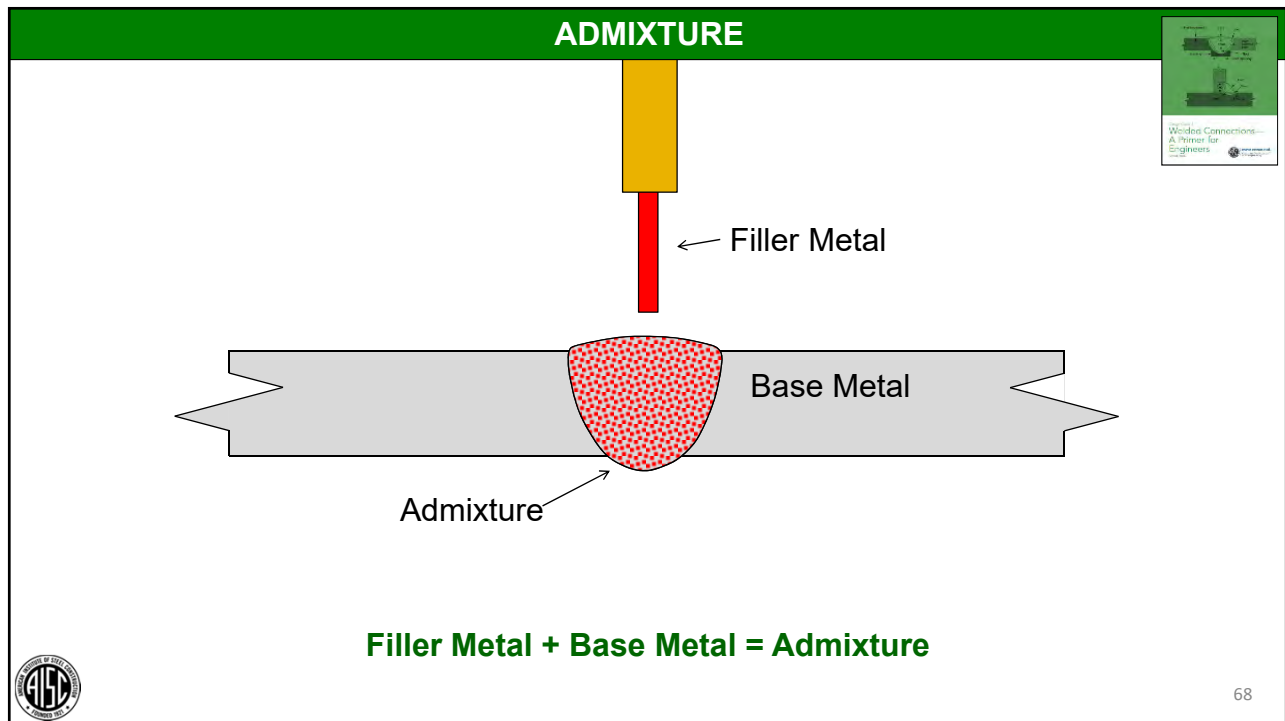
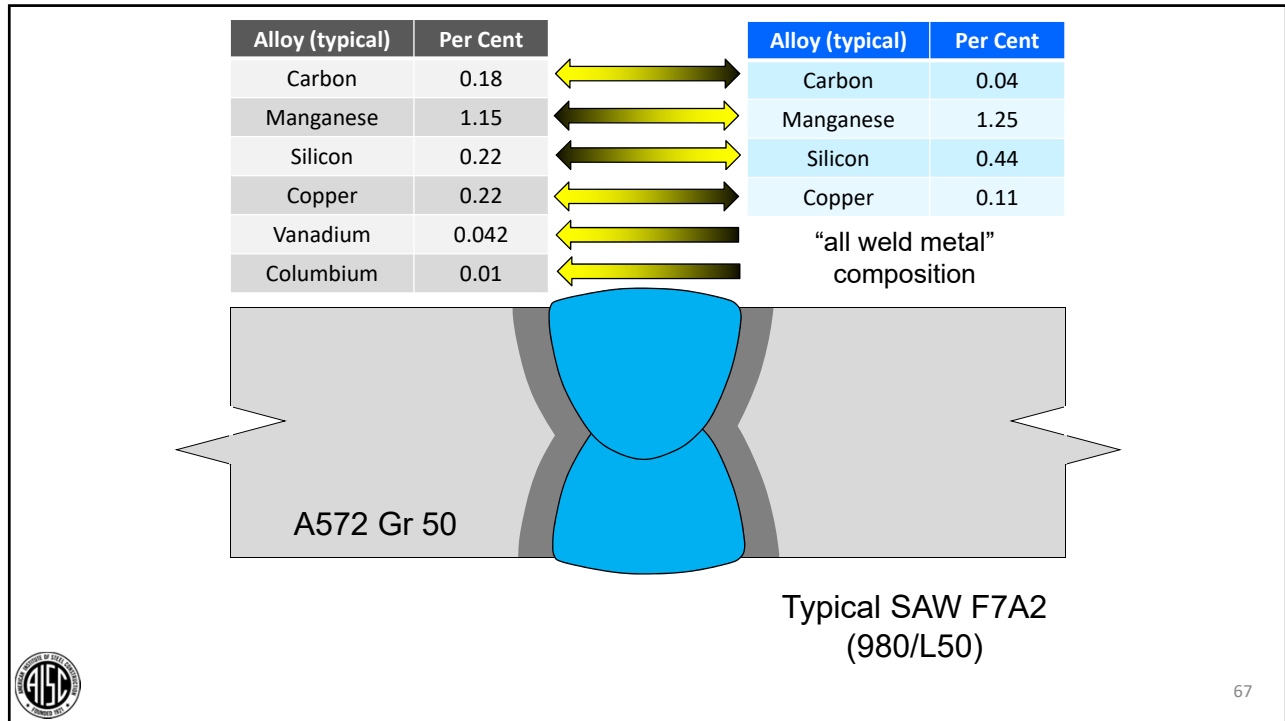


65

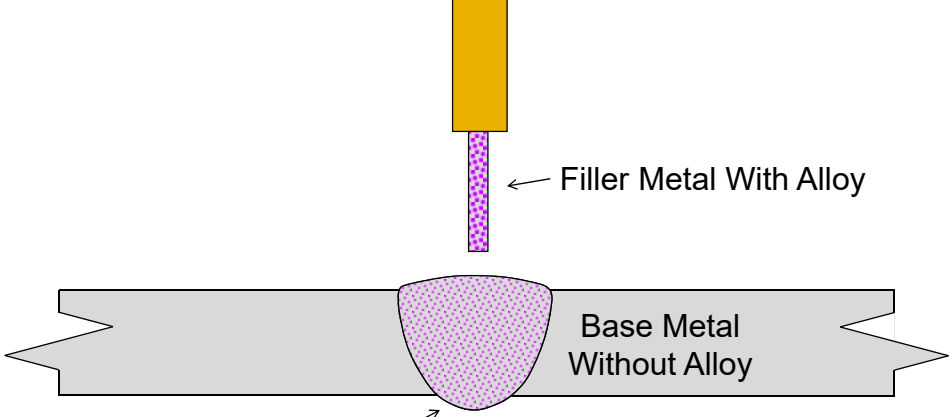
### WELD METAL: CHEMISTRY



66





### DILUTION



The diagram illustrates the process of dilution. A yellow electrode is positioned above a weld pool. The weld pool is shown as a purple dotted area. The filler metal being added is also purple dotted and labeled "Filler Metal With Alloy". The base metal being melted is grey and labeled "Base Metal Without Alloy". The resulting weld metal is a mixture of the filler metal and the base metal, labeled "Alloy in Admixture".

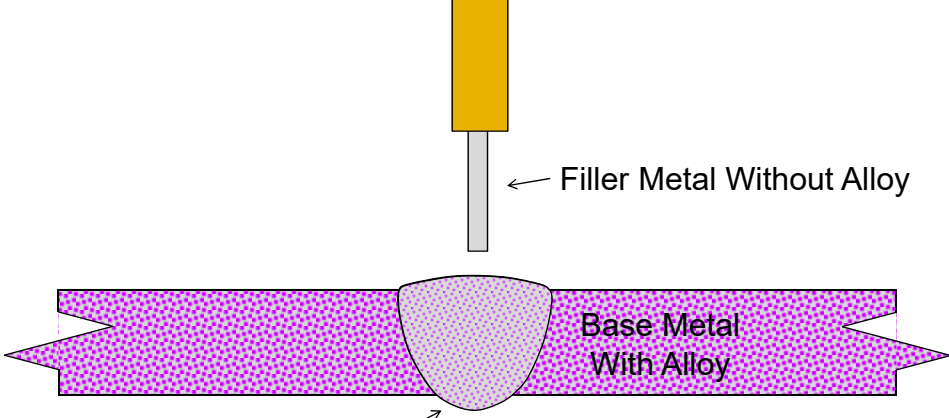
**Alloy in Filler Metal > Alloy in Base Metal → Dilution**

  
Welded Connections—  
A Primer for  
Engineers




69


### PICKUP



The diagram illustrates the process of pickup. A yellow electrode is positioned above a weld pool. The weld pool is shown as a purple dotted area. The filler metal being added is grey and labeled "Filler Metal Without Alloy". The base metal being melted is purple dotted and labeled "Base Metal With Alloy". The resulting weld metal is a mixture of the filler metal and the base metal, labeled "Alloy in Admixture".

**Alloy in Filler Metal < Alloy in Base Metal → Pickup**

  
Welded Connections—  
A Primer for  
Engineers



70



### PICKUP

Example: using carbon steel electrode on weathering steel

Filler Metal Without Alloy



Base Metal With Alloy

Alloy in Admixture

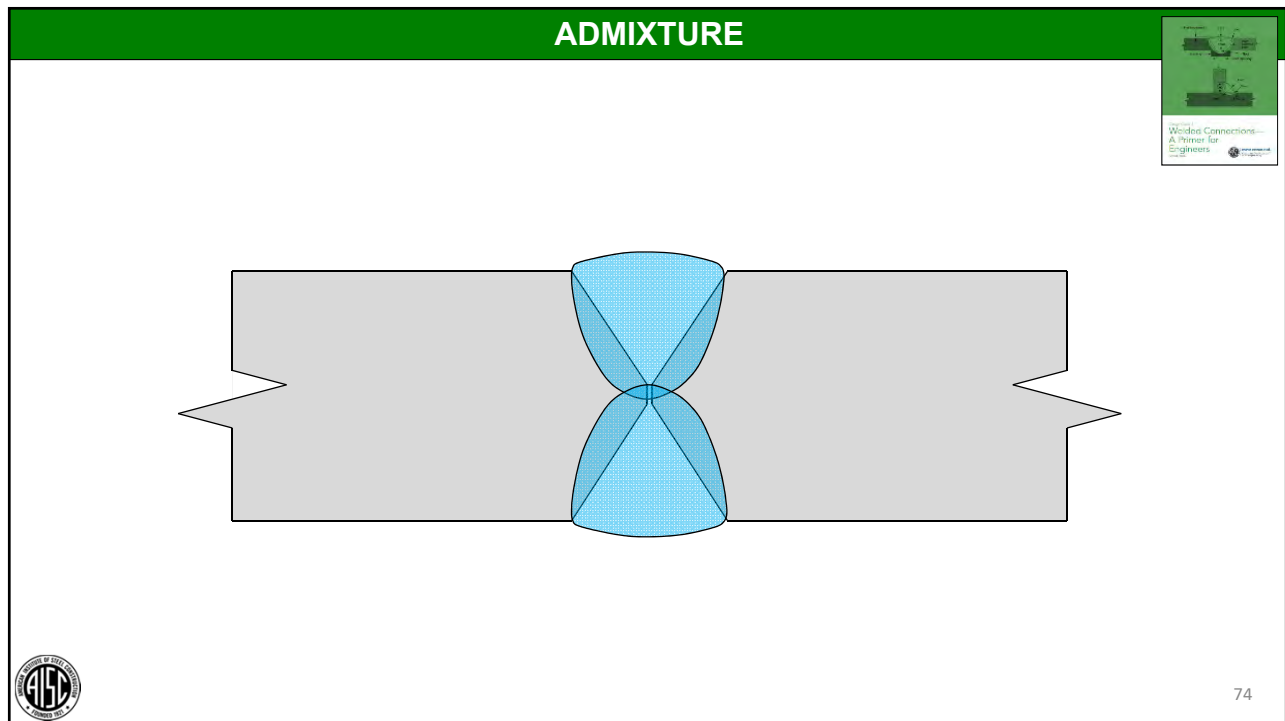
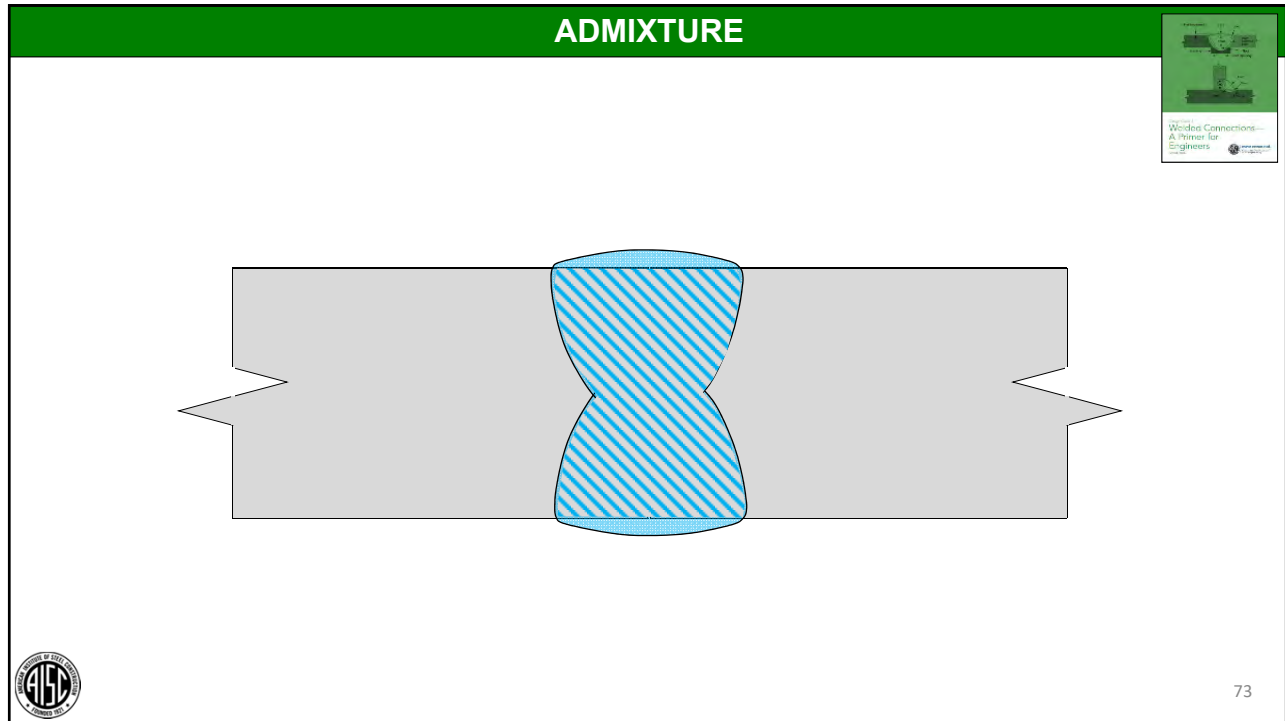


71

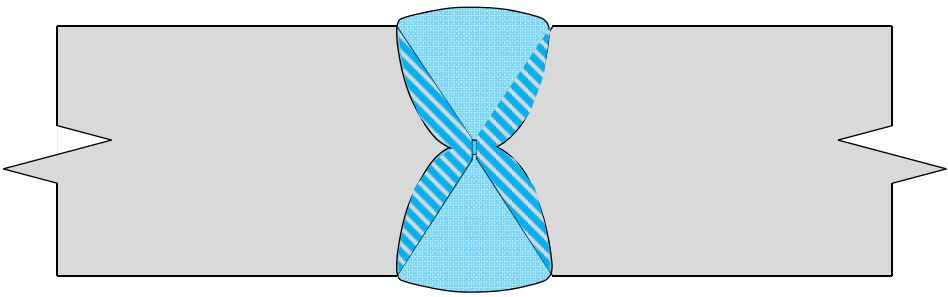
### ADMIXTURE





72



### ADMIXTURE

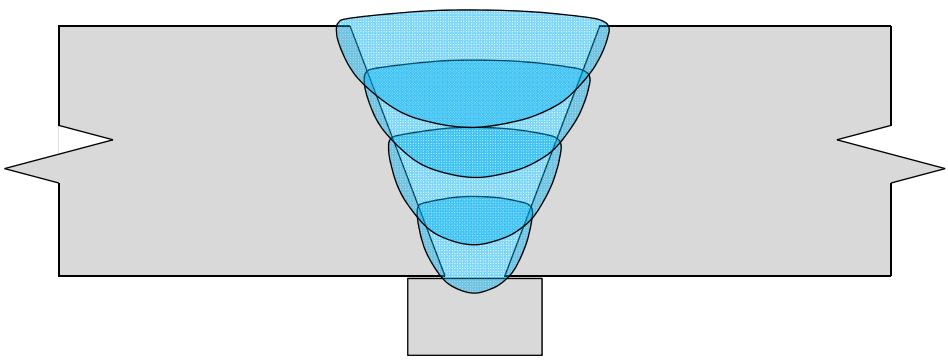


The diagram illustrates a butt joint weld. Two gray rectangular plates are joined at their center by a weld. The weld is shown in a cross-section with a blue, textured, hourglass-like shape representing the weld metal. The weld metal is shown mixing with the base metal of the plates, creating a transition zone. The weld metal is shaded with a blue and white striped pattern, while the base metal is a solid gray. The plates have jagged ends on the left and right sides, indicating they are part of a larger structure.





75

### ADMIXTURE

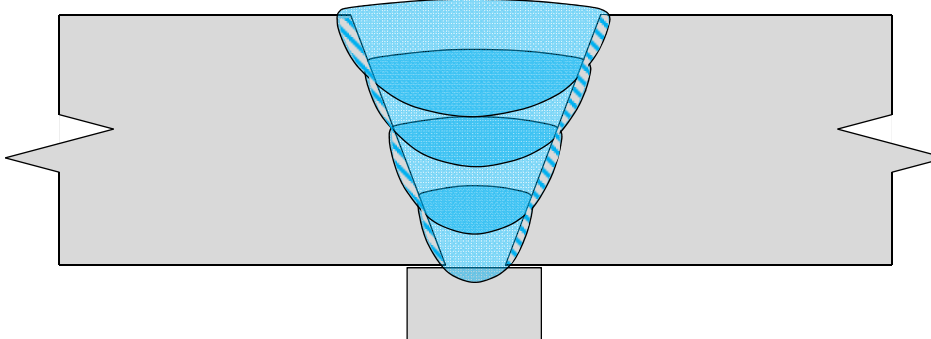


The diagram illustrates a fillet weld. Two gray rectangular plates are joined at their center by a weld. The weld is shown in a cross-section with a blue, textured, funnel-like shape representing the weld metal. The weld metal is shown mixing with the base metal of the plates, creating a transition zone. The weld metal is shaded with a blue and white striped pattern, while the base metal is a solid gray. The plates have jagged ends on the left and right sides, indicating they are part of a larger structure.





76

### ADMIXTURE

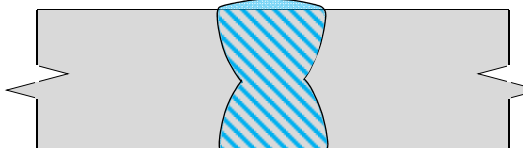


The diagram shows a cross-section of a butt joint between two steel plates. A central weld is shown with a blue, funnel-shaped admixture pattern. The admixture is concentrated in the center of the weld and tapers towards the edges, indicating a low level of admixture.

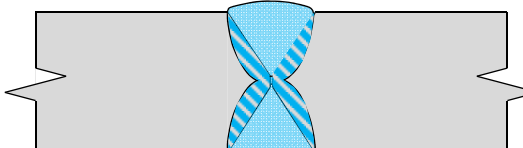


77

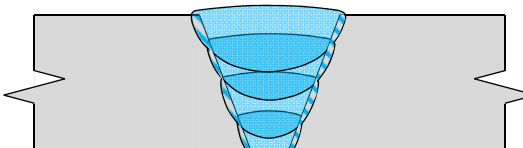
### ADMIXTURE





**High Admixture**



**Medium Admixture**



**Low Admixture**





78

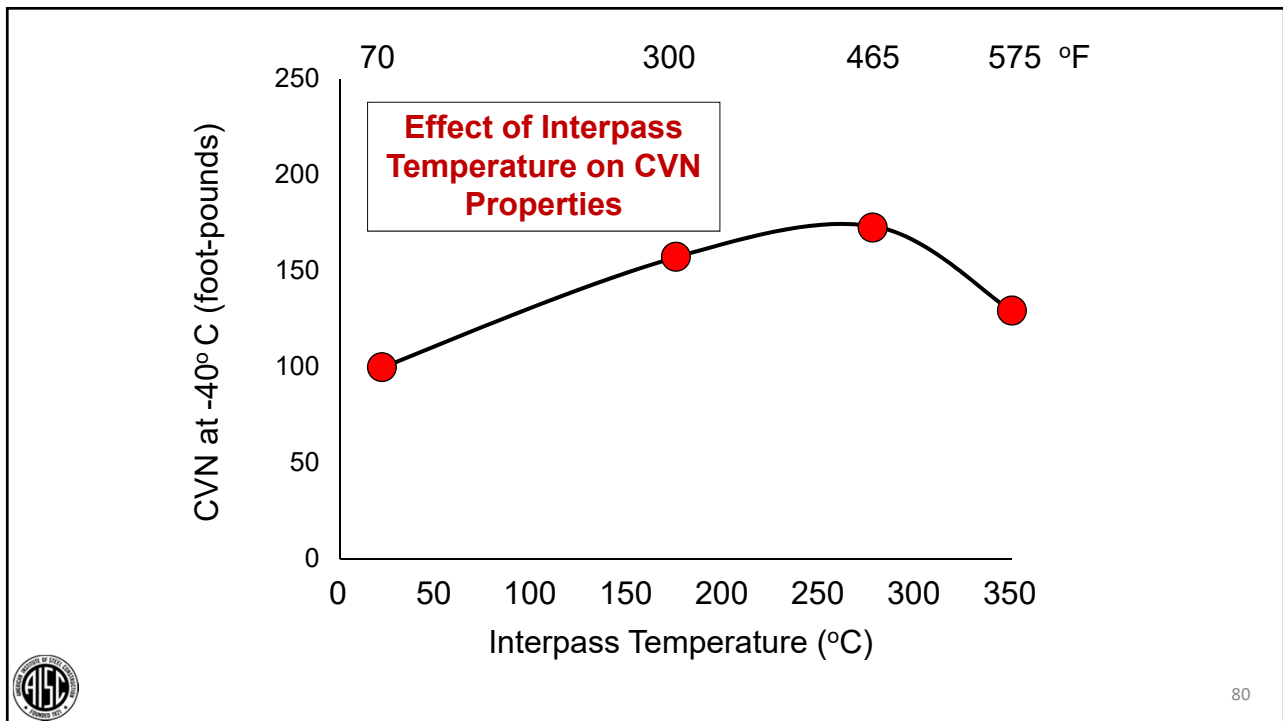
### METALLURGY AND CRACKING

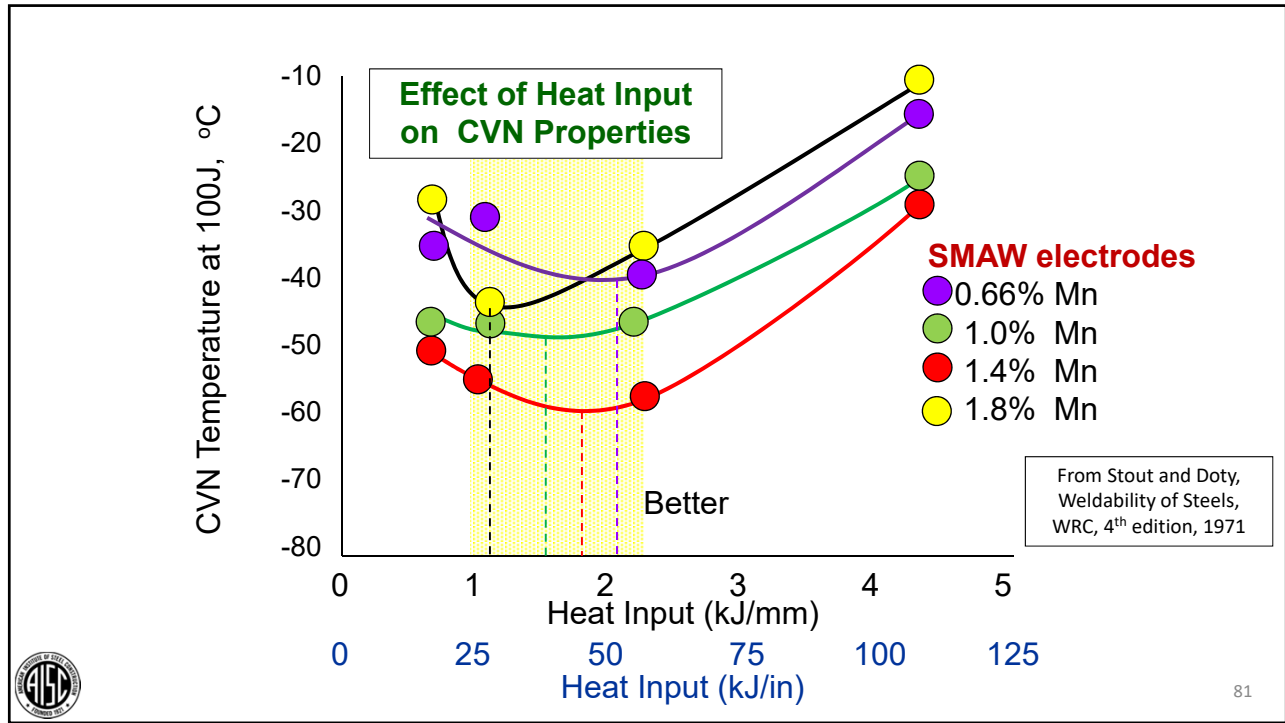
Metallurgy in a nutshell....

- Composition (alloys and carbon)
- **Cooling Rate**



79







## UNIFIED DESIGN OF STEEL STRUCTURES

“Most structural steel used today accept welding without the occurrences of unwanted defects.”

Louis F. Geschwindner





## METALLURGY AND CRACKING

### Outline

- Welding and Metallurgy
- ➔ • Steel Categories
- Cracking
- Special Steels



83

## STEEL GROUPS


### Steel Categories:

- AWS D1.1 Prequalified Steels
- AWS D1.1 Approved Steels
- AWS D1.1 Unlisted Steels
- Unidentified Steels




84

STEEL GROUPS




**AWS D1.1 Prequalified Steels:**

- Steels that may be used with prequalified welding procedure specifications (WPS) without WPS qualification testing (Table 3.1)
- Includes steels with a history of satisfactory service and with known, good weldability
- Includes newer steels that have undergone testing and analysis
- All prequalified steels have  $F_y \leq 90$  ksi [620 MPa]
- All prequalified steels have mechanical property controls / compositional limits appropriate for welding processes / conditions within the code
- Listed in AWS D1.1, Table 3.1



85

AWS D1.1: 2015 Structural Welding Code – Steel




**Table 3.1**  
**Approved Base Metals for Prequalified WPSs (see 3.3)**

Group	Steel Specification Requirements					
	Steel Specification	Minimum Yield Point/Strength		Tensile Range		
			ksi	MPa	ksi	MPa
	ASTM A36	( $\leq 3/4$ in [20 mm])	36	250	58–80	400–550
	ASTM A53	Grade B	35	240	60 min.	415 min.
	ASTM A106	Grade B	35	240	60 min.	415 min.
	ASTM A131	Grades A, B, CS, D, DS, E	34	235	58–75	400–520
	ASTM A139	Grade B	35	240	60 min.	415 min.
	ASTM A381	Grade Y35	35	240	60 min.	415 min.
	ASTM A500	Grade A	33	230	45 min.	310 min.
		Grade B	42	290	58 min.	400 min.
		Grade C	46	315	62 min.	425 min.
	ASTM A501	Grade A	36	250	58 min.	400 min.
	ASTM A516	Grade 55	30	205	55–75	380–515
		Grade 60	32	220	60–80	415–550



86

STEEL GROUPS




**AWS D1.1 Approved Steels:**

- Code-approved base metals, which require WPS qualification testing
- Includes high-strength steels (i.e., those with  $F_y > 90$  ksi [620 MPa])
- Includes newer steels that do not have a sufficient history of satisfactory usage to be considered prequalified
- Listed in AWS D1.1, Table 4.9, along with matching strength filler metals and preheat values



87

AWS D1.1: 2015 Structural Welding Code – Steel

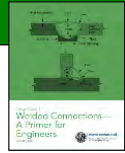


**Table 4.9**  
**Code-Approved Base Metals and Filler Metals Requiring Qualification per Clause 4**

Specification	Base Metal				Matching Strength Filler Metal			Base Metal Thickness, T		Minimum Preheat and Interpass Temperature	
	Minimum Yield Point/Strength		Tensile Range		Process	AWS Electrode Specification <sup>2</sup>	Electrode Classification	in	mm	°F	°C
	ksi	MPa	ksi	MPa							
ASTM A871 Grade 60 Grade 65	60	415	75 min.	520 min.	SMAW	A5.5	E8015-X E8016-X E8018-X	Up to 3/4 Over 3/4 thru 1-1/2	Up to 20 Over 20 thru 38	50	10
	65	450	80 min.	550 min.			SAW				
					GMAW	A5.28 A5.36	ER80S-XXX E80C-XXX E8TX-XAX-XXX				
							FCAW				
ASTM A514 (Over 2-1/2 in [65 mm])	90	620	100–130	690–895	SMAW	A5.5	E10015-X E10016-X E10018-X E10018M	Over 1-1/2 thru 2-1/2	Over 38 thru 65	175	80
ASTM A709 Grade HPS 100W [HPS 690W] (Over 2-1/2 in to 4 in)	90	620	100–130	690–895			SAW	A5.23	F10XX-EXXX-XX F10XX-ECXXX-XX	Over 2-1/2	Over 65


88

## STEEL GROUPS



### AWS D1.1 Unlisted Steels:

- Steels not listed in AWS D1.1, Table 3.1 or Table 4.9
- Includes steels with poor weldability, which are intentionally omitted
- Includes new steels that have good weldability, but not yet incorporated into the code
- Includes steels with mechanical properties not sufficiently defined (e.g., only chemical compositions are specified for AISI/SAE grades of steels)
- Includes steels that are not classified in U.S. standards (e.g., ASTM or API), some of which might have good weldability



89

## STEEL GROUPS



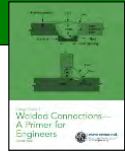
### AWS D1.1 Unlisted Steels (continued):

- Welding on unlisted steels requires WPS qualification testing
- Only exception is given in AWS D1.1, clause 3.4; the unlisted steel must:
  - be used for an auxiliary attachment.
  - be approved by the engineer.
  - have a chemical composition that falls within the limits of a prequalified steel grade
  - follow the preheat requirements for prequalified WPS



90

## STEEL GROUPS



### AWS D1.1 Unlisted Steels (continued):

- Passing a WPS qualification test satisfies AWS D1.1 requirements for welding on unlisted steels...
- ...but it is not a weldability test per se.
  - WPS qualification test plates do not sufficiently replicate actual fabrication conditions
  - A number of weldability tests have been developed (e.g., Lehigh Restraint Test, Tekken Test, CTS Test, Gapped-Bead-on-Plate Test)
- When using unlisted steels, investigate other data, beyond WPS qualification tests, to support the decision (e.g., mill data, past projects)



91

## AISC 360-16 Specification for Structural Steel Buildings



### A3.1 Structural Steel Materials

#### 1b. Unidentified Steel

Unidentified steel, free of injurious defects, is permitted to be used only for members or details whose failure will not reduce the strength of the structure, either locally or overall. Such use shall be subject to the approval of the engineer of record.

**User Note:** Unidentified steel may be used for details where the precise mechanical properties and weldability are not of concern. These are commonly curb plates, shims and other similar pieces.



92

## METALLURGY AND CRACKING

### Outline

- Welding and Metallurgy
- Steel Categories
- • Cracking
- Special Steels



93

## AWS D1.1: 2015 Structural Welding Code – Steel



### 5.25.3 Engineer's Approval.

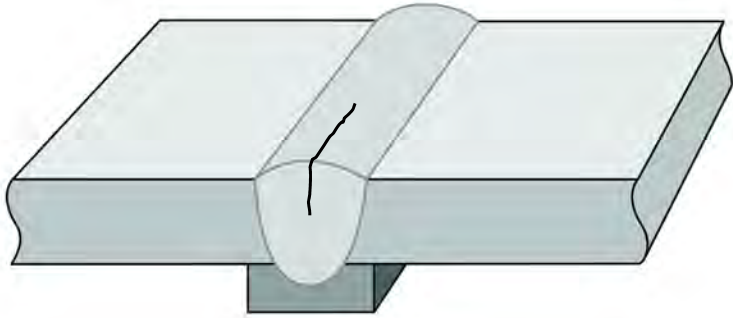
Prior approval of the Engineer shall be obtained for repairs to base metal (other than those required by 5.14), **repair of major or delayed cracks,** repairs to ESW and EGW with internal defects, or for a revised design to compensate for deficiencies. The Engineer shall be notified before welded members are cut apart.





94

### TYPES OF WELD CRACKS

#### Centerline Cracking



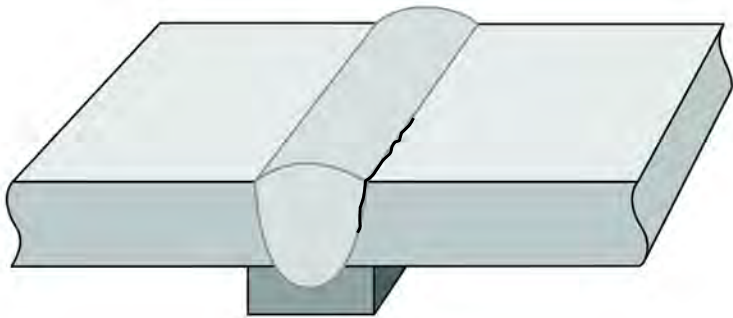
The diagram shows a 3D perspective of a butt-welded joint between two steel plates. A vertical crack is shown running along the centerline of the weld, extending from the top surface down to the root of the joint.





95

### TYPES OF WELD CRACKS

#### Underbead Cracking



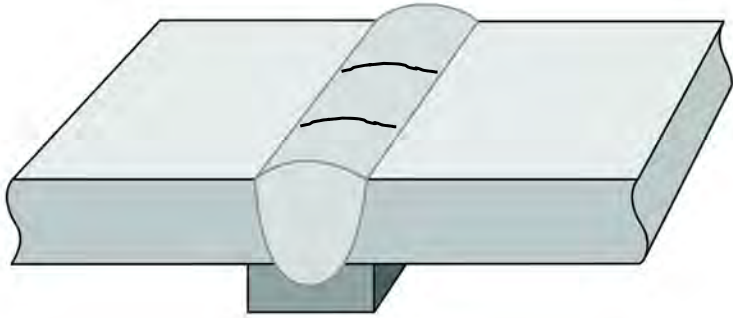
The diagram shows a 3D perspective of a butt-welded joint between two steel plates. A crack is shown running along the bottom surface of the weld, just above the root of the joint.





96

### TYPES OF WELD CRACKS

#### Transverse Cracking



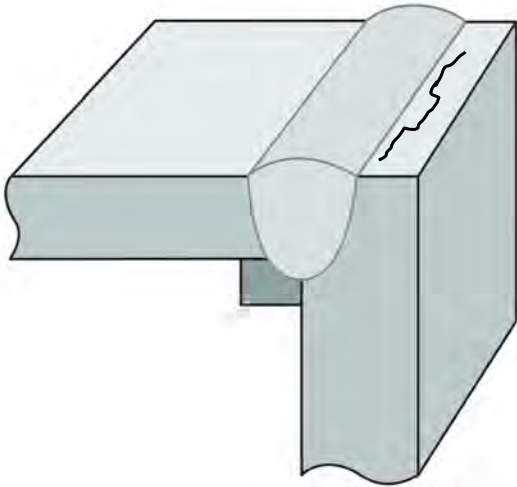
The diagram shows a 3D perspective of a butt-welded joint between two steel plates. A vertical crack is shown running through the weld metal, perpendicular to the longitudinal axis of the joint. The crack is depicted as a jagged line within the weld metal.





97

### TYPES OF WELD CRACKS

#### Lamellar Tearing

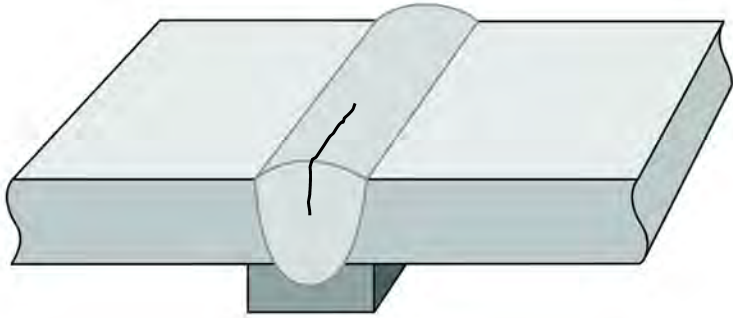


The diagram shows a 3D perspective of a T-joint weld. A crack is shown running parallel to the longitudinal axis of the joint, along the interface between the weld metal and the base metal. The crack is depicted as a jagged line that follows the boundary between the weld and the base metal.





98

### CENTERLINE CRACKING



A 3D perspective diagram of a fillet weld joint. A crack is shown running along the centerline of the weld bead, extending from the root of the weld towards the surface. The crack is highlighted with a black line.





99

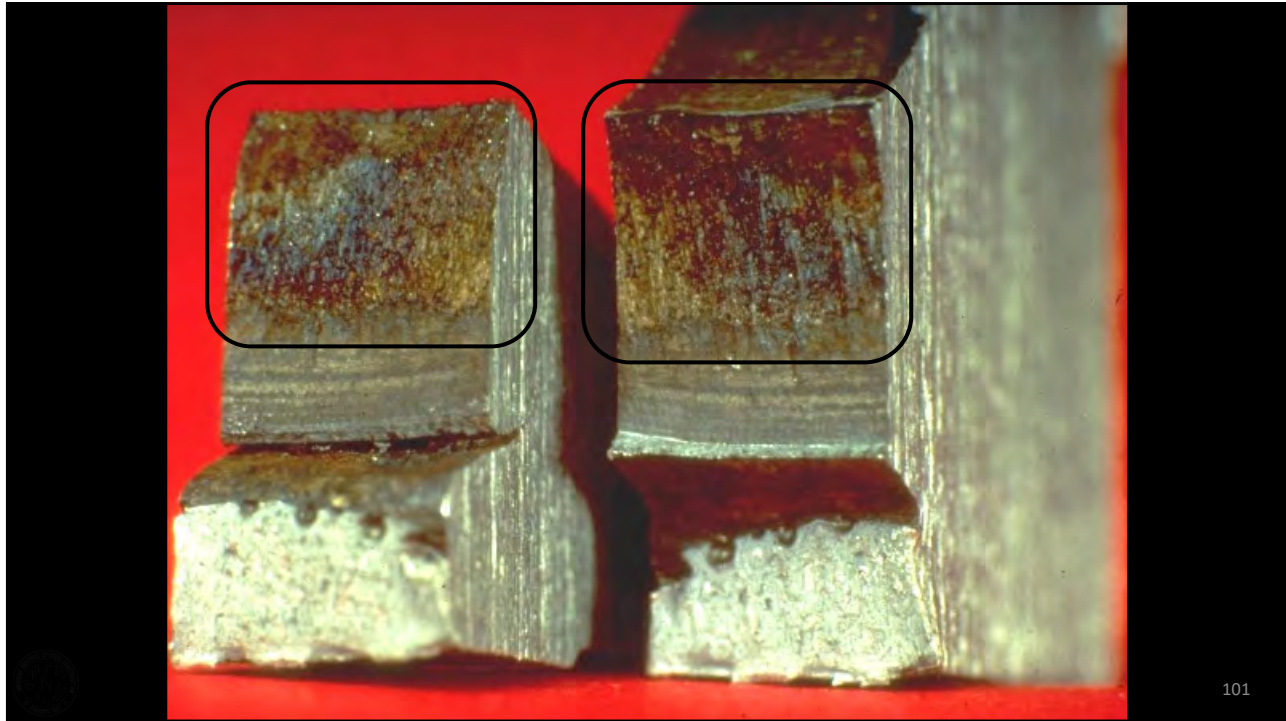
### CENTERLINE CRACKING

**Characteristics:**

- Near the center of a welded bead
- Is present as weld cools — is not delayed
- Occurs at high temperatures — the crack surface may exhibit “temper colors)
- Cracks may extend from one weld layer into the next, but are more commonly isolated to one layer
- Overloaded fillet welds often fail through the weld throat and may look like centerline cracks



100



101


### CENTERLINE CRACKING

The diagram shows a cross-section of a weld joint between two metal plates. A vertical dashed line represents the weld bead centerline, labeled with the Greek letter  $\zeta$ . A green arrow points downwards from the centerline to a blue, semi-circular area representing the weld metal. Within this blue area, several curved lines indicate the presence of centerline cracks. The metal plates are shaded in light gray and light purple.

A small 3D perspective drawing of a weld joint, showing two plates meeting at a central point.

A small thumbnail version of the current slide, showing the title and some text.

Centerline cracks are near the weld bead centerline; may not be in the center of the joint.






102

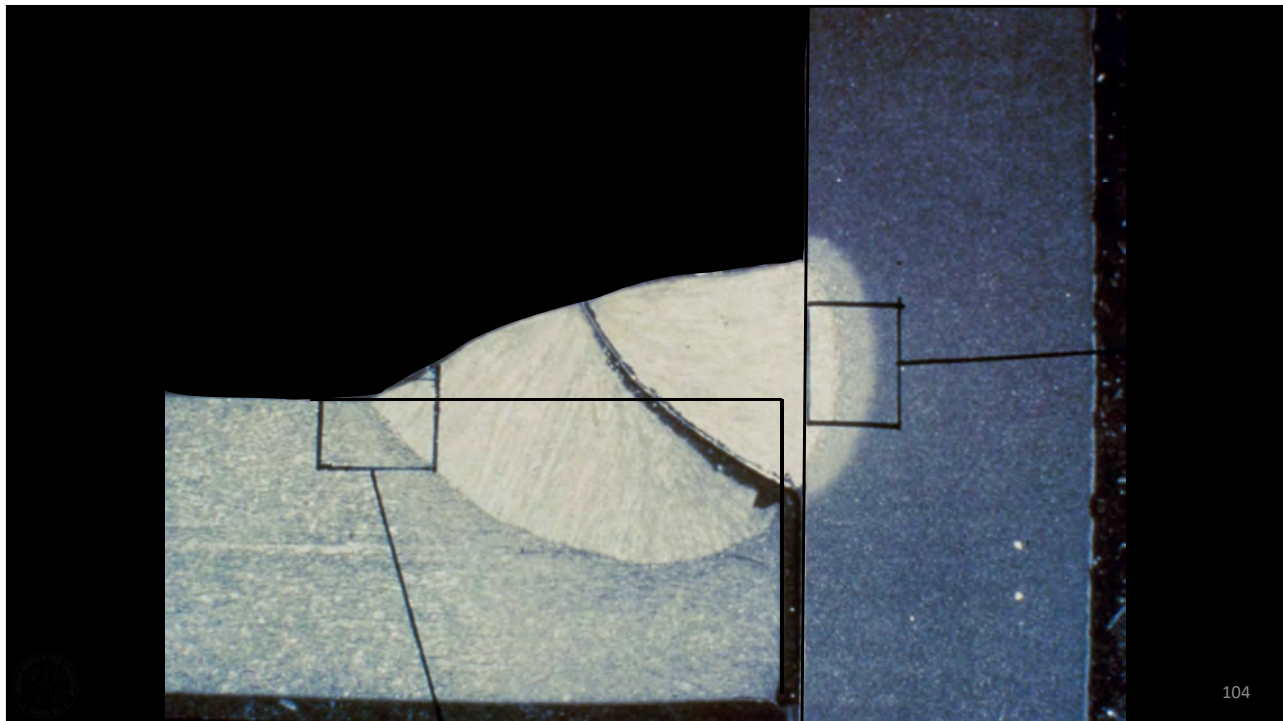
## CENTERLINE CRACKING

**Cause 1: Segregation Cracking**


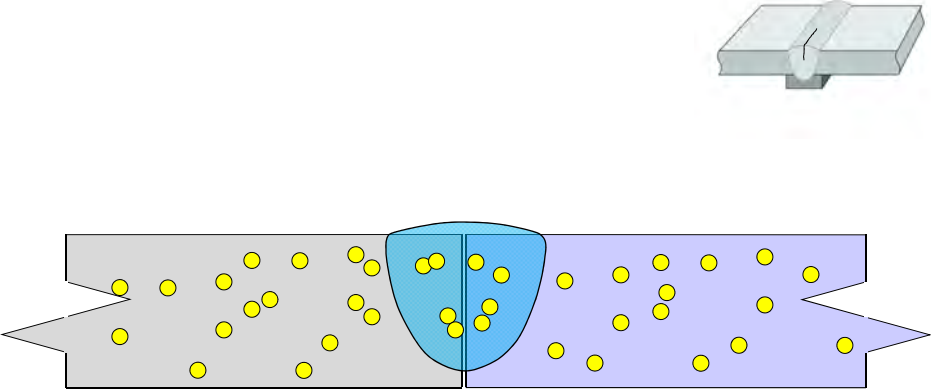
**Low melting point ingredients segregate to the center during solidification**



103




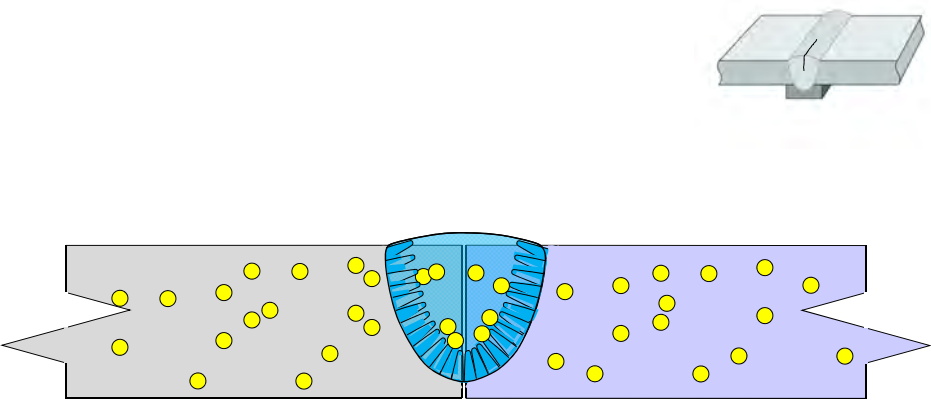
### CENTERLINE CRACKING



105

Welded Connections—  
A Primer for  
Engineers

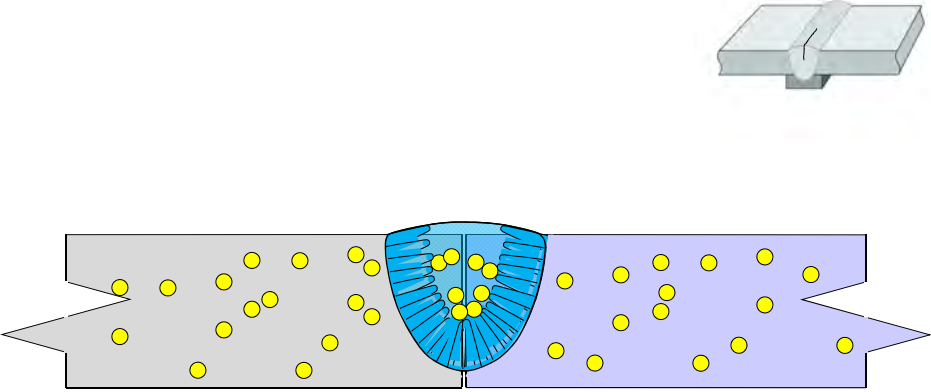
### CENTERLINE CRACKING





106

Welded Connections—  
A Primer for  
Engineers

### CENTERLINE CRACKING

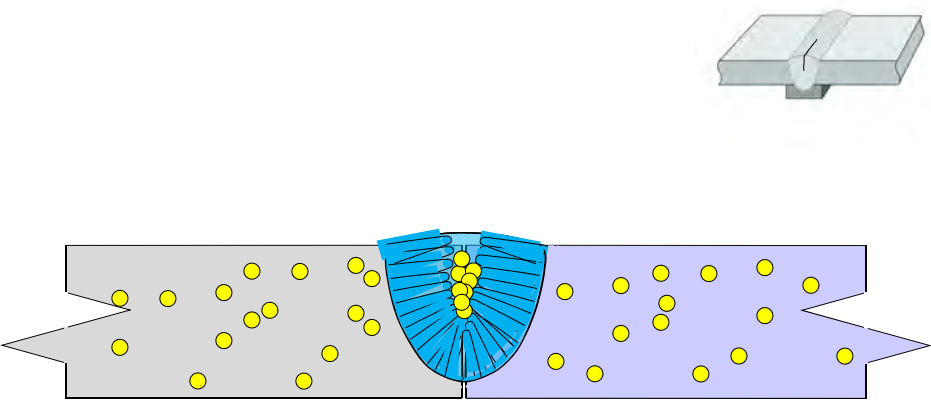


The diagram illustrates centerline cracking in a weld joint. At the top right, a 3D perspective view shows two steel plates joined by a weld. Below it, a 2D cross-sectional view shows the weld metal (shaded blue) between two base metal plates (shaded grey and purple). Yellow dots representing impurities are scattered throughout the base metal. A blue, semi-circular crack pattern is shown originating from the centerline of the weld and extending into the base metal on both sides.





107

### CENTERLINE CRACKING



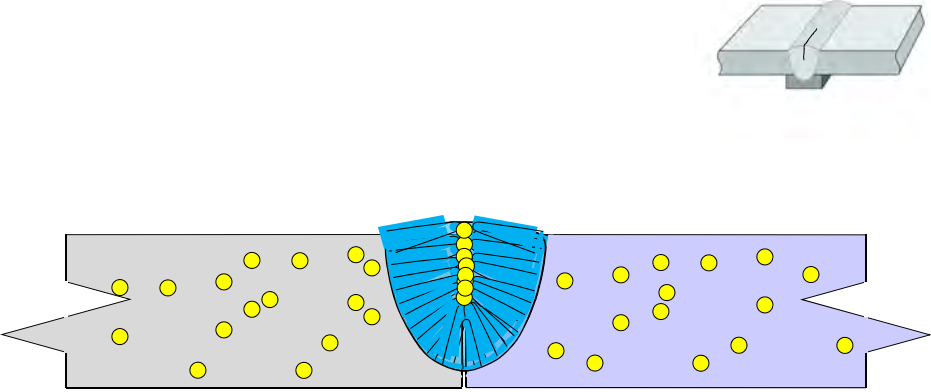


The diagram illustrates centerline cracking in a weld joint. At the top right, a 3D perspective view shows two steel plates joined by a weld. Below it, a 2D cross-sectional view shows the weld metal (shaded blue) between two base metal plates (shaded grey and purple). Yellow dots representing impurities are scattered throughout the base metal. A blue, semi-circular crack pattern is shown originating from the centerline of the weld and extending into the base metal on both sides.





108

### CENTERLINE CRACKING



109

### CENTERLINE CRACKING




**Cause 1: Segregation Cracking**

**Low melting point ingredients segregate to the center during solidification**

**Solution: Minimize low melting point ingredients in the molten weld metal**

- Use “good” steel
  - Low levels of:
    - Phosphorous (P)    – Tin (Sn)
    - **Sulfur (S)**        – Copper (Cu)
    - Zinc (Zn)            – Carbon (C)



110

## CENTERLINE CRACKING

### Cause 1: Segregation Cracking

**TWI Hot Cracking Susceptibility**  
(Universal Crack Sensitivity)



**$UCS = 230 C + 190 S + 75 P + 45 Nb - 12.3 Si - 5.4 Mn - 1$**


UCS  $\leq$  10 “High Resistance to Cracking”

UCS  $>$  30 “Strong Susceptibility to Cracking”

Based on WELD METAL Composition

From Welding Metallurgy by Linnert, 4<sup>th</sup> Edition, Volume 1



111



## CENTERLINE CRACKING


### Cause 1: Segregation Cracking

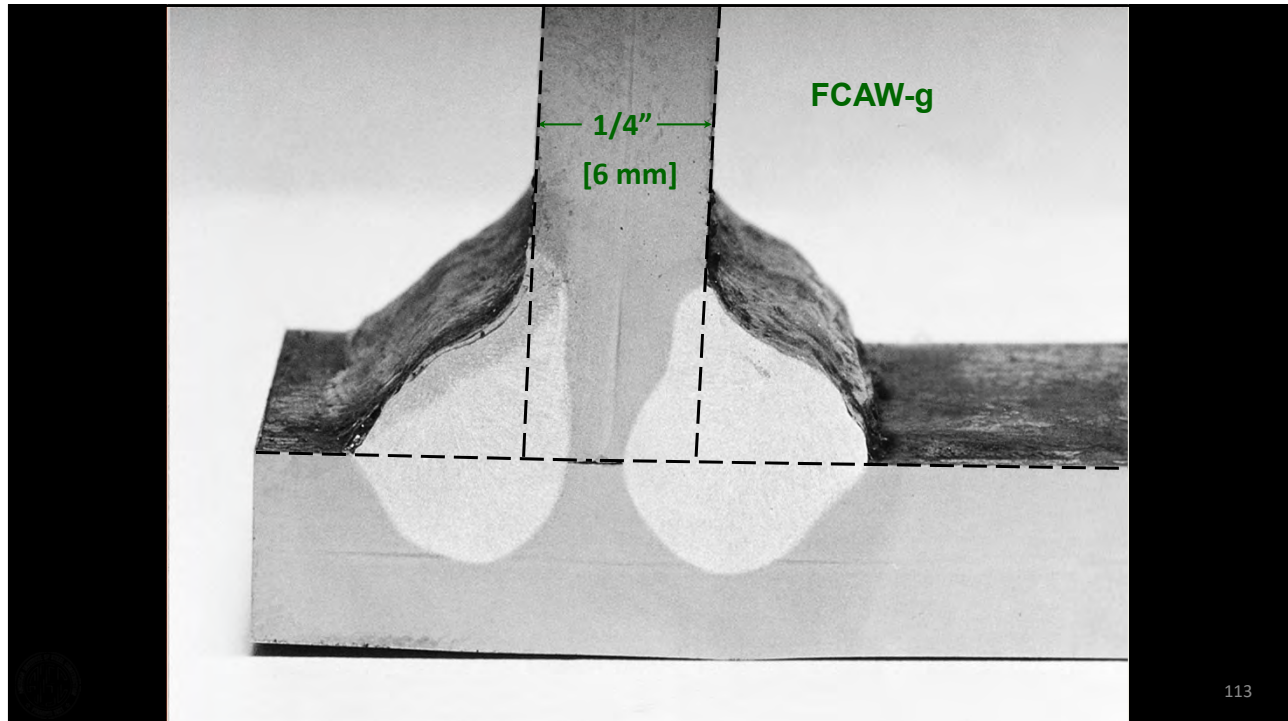
**Low melting point ingredients segregate to the center during solidification**

**Solution: Minimize low melting point ingredients in the molten weld metal**

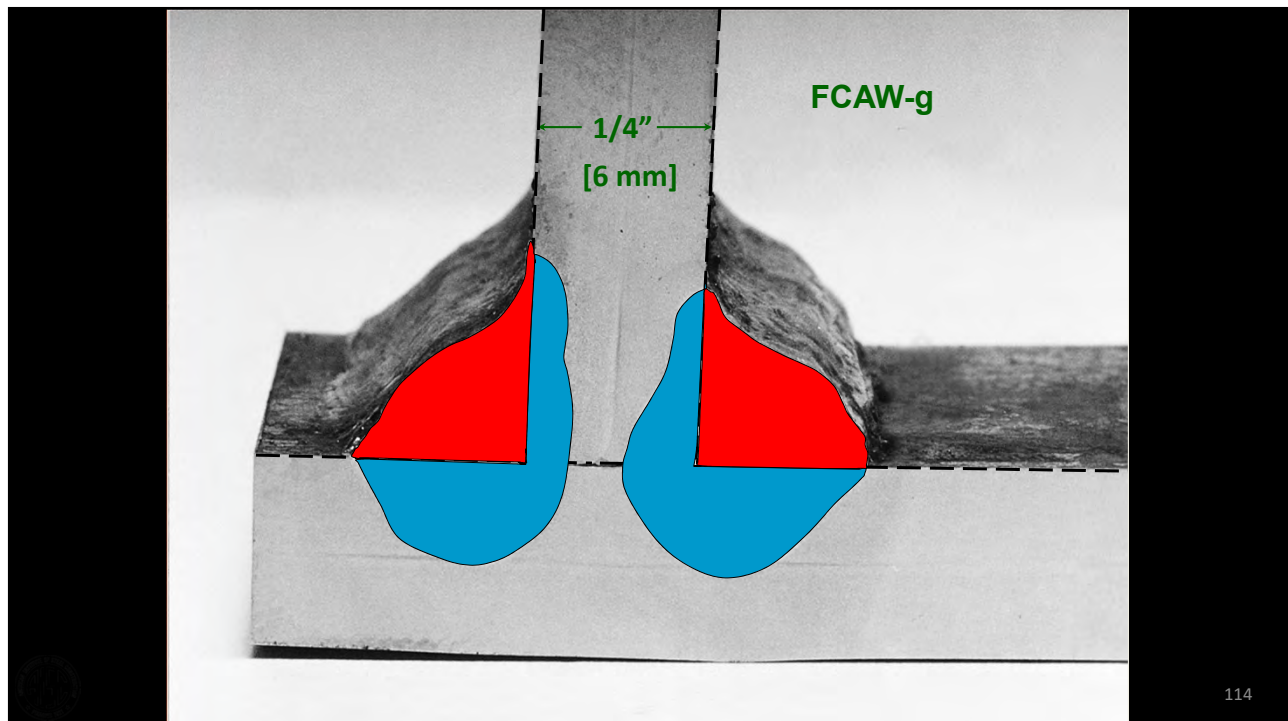
- Use “good” steel
- Minimize admixture



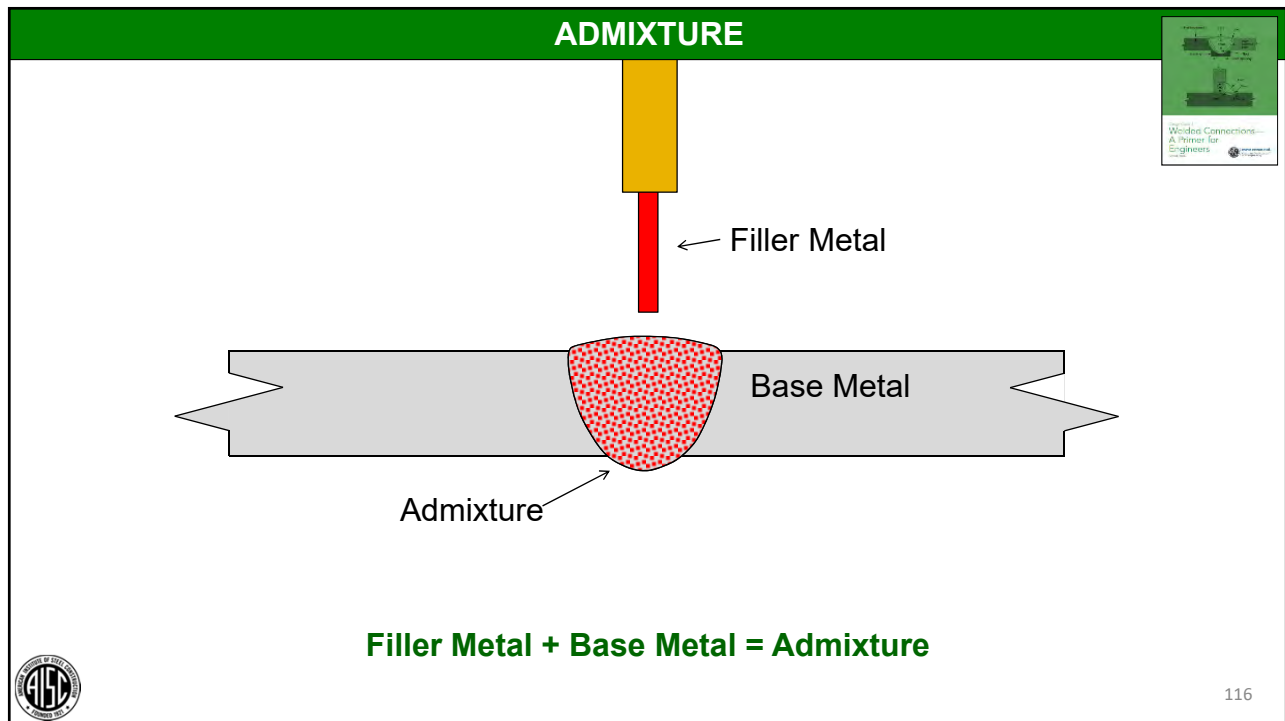
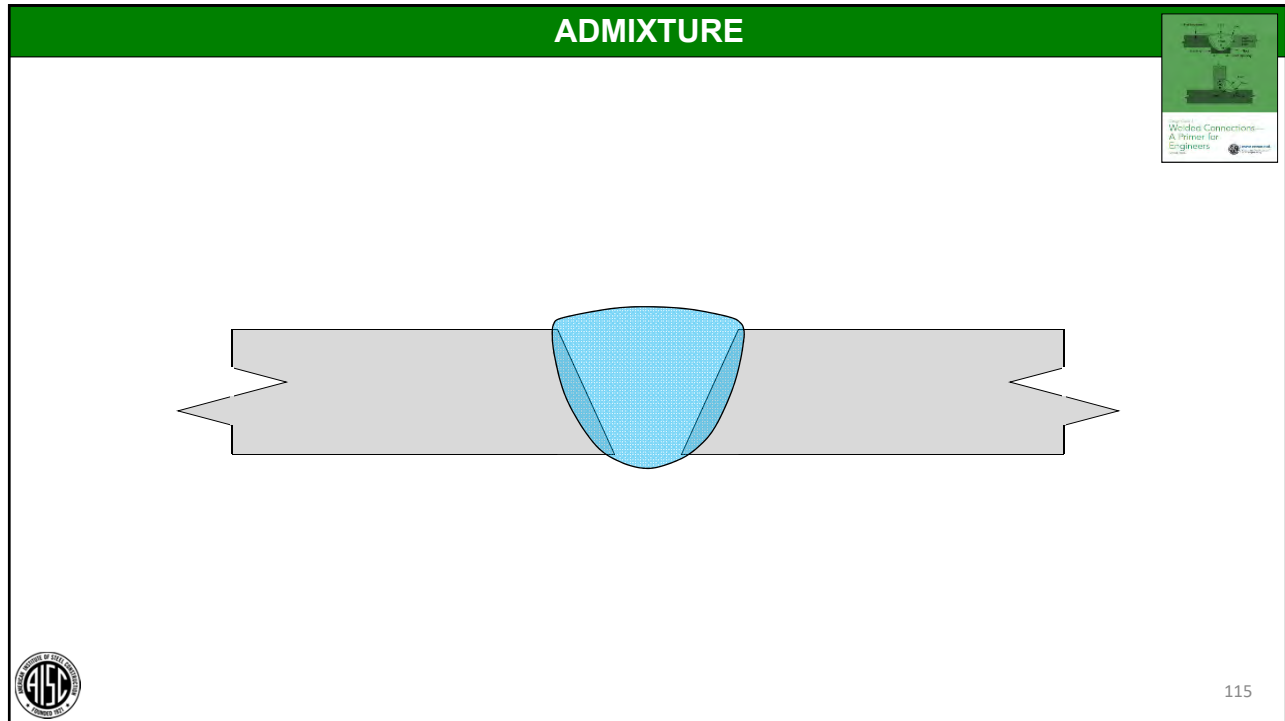
112



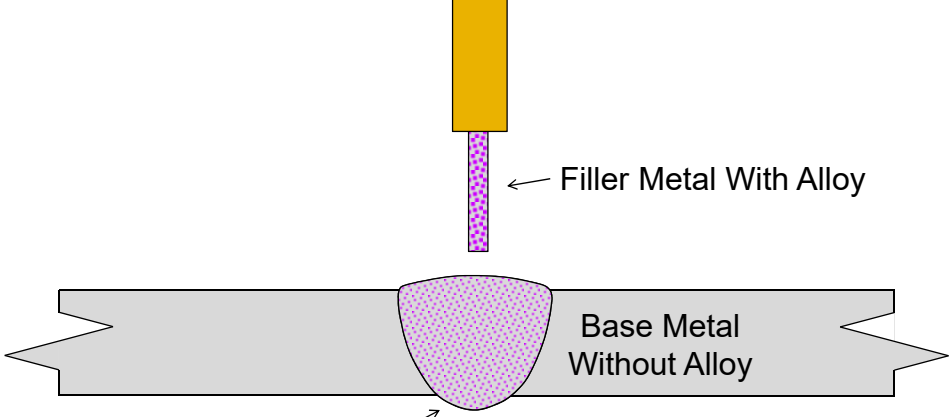
113



114




### DILUTION




The diagram shows a cross-section of a weld joint. A yellow electrode is positioned above a purple filler metal. The filler metal is being deposited into a groove in a grey base metal. The resulting weld metal is a mixture of the filler metal and the base metal. Labels include: 'Filler Metal With Alloy' pointing to the purple filler metal, 'Base Metal Without Alloy' pointing to the grey base metal, and 'Alloy in Admixture' pointing to the purple weld metal.

**Alloy in Filler Metal > Alloy in Base Metal → Dilution**

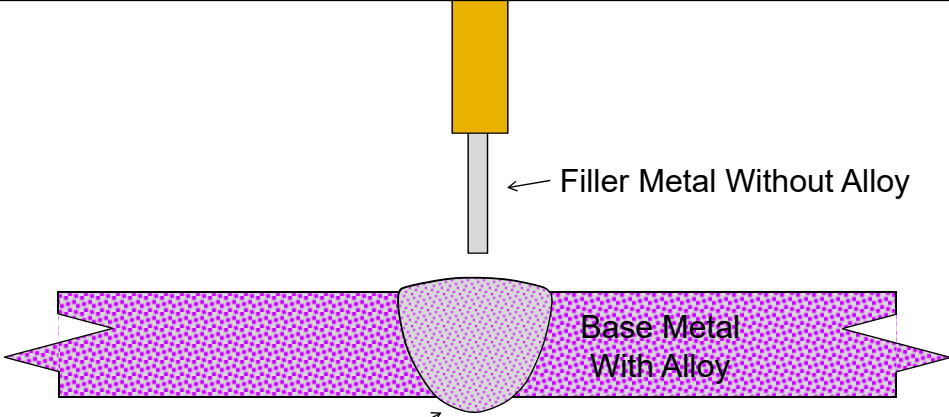


Welded Connections—  
A Primer for  
Engineers



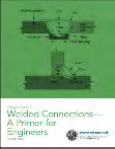
117

### PICKUP




The diagram shows a cross-section of a weld joint. A yellow electrode is positioned above a grey filler metal. The filler metal is being deposited into a groove in a purple base metal. The resulting weld metal is a mixture of the filler metal and the base metal. Labels include: 'Filler Metal Without Alloy' pointing to the grey filler metal, 'Base Metal With Alloy' pointing to the purple base metal, and 'Alloy in Admixture' pointing to the purple weld metal.

**Alloy in Filler Metal < Alloy in Base Metal → Pickup**



Welded Connections—  
A Primer for  
Engineers



118

### PICKUP

Welded Connections—  
A Primer for  
Engineers

119

### CENTERLINE CRACKING

**Cause 1: Segregation Cracking**

**Low melting point ingredients segregate to the center during solidification**

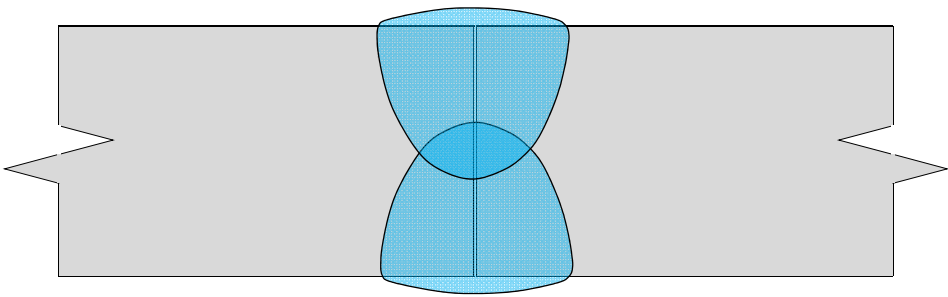
**Solution: Minimize low melting point ingredients in the molten weld metal**

- Use “good” steel
- Minimize admixture
  - Change joint detail


Welded Connections—  
A Primer for  
Engineers

120


**ADMIXTURE: HIGH**



The diagram shows a cross-section of a butt-welded joint between two gray steel plates. The weld metal is shaded in light blue with a fine, uniform stippled texture, indicating a high level of admixture. The weld metal is wider than the plates and has a convex shape on both the top and bottom surfaces. The plates have jagged ends on the left and right sides.

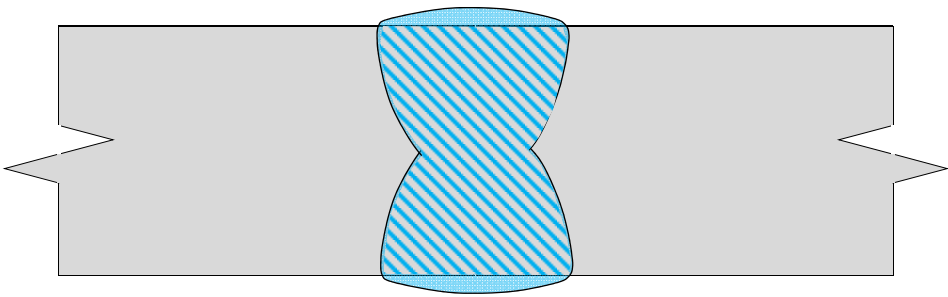


Welded Connections—  
A Primer for  
Engineers




121


**ADMIXTURE: HIGH**



The diagram shows a cross-section of a butt-welded joint between two gray steel plates. The weld metal is shaded in light blue with a diagonal hatched texture, indicating a high level of admixture. The weld metal is wider than the plates and has a convex shape on both the top and bottom surfaces. The plates have jagged ends on the left and right sides.

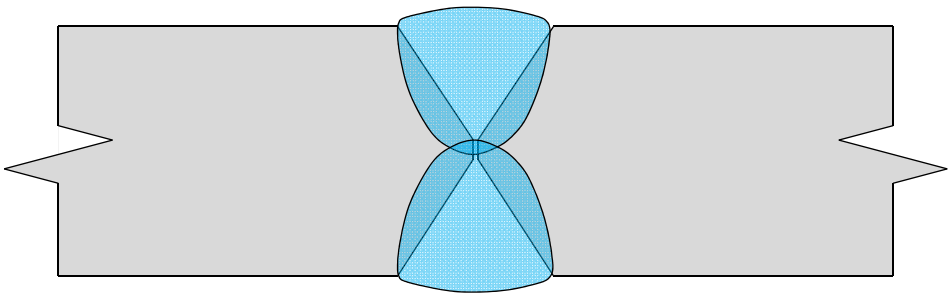


Welded Connections—  
A Primer for  
Engineers




122


**ADMIXTURE: MEDIUM**



The diagram shows a butt joint between two gray steel plates. The weld metal is represented by a blue, textured, hourglass-shaped area in the center. The weld metal is wider at the top and bottom surfaces and tapers towards the root. The root is a narrow V-shape. The plates have jagged ends on the left and right sides.

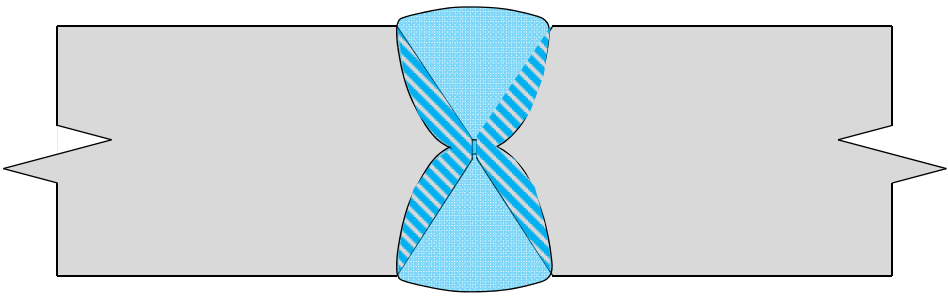


Welded Connections—  
A Primer for  
Engineers




123


**ADMIXTURE: MEDIUM**



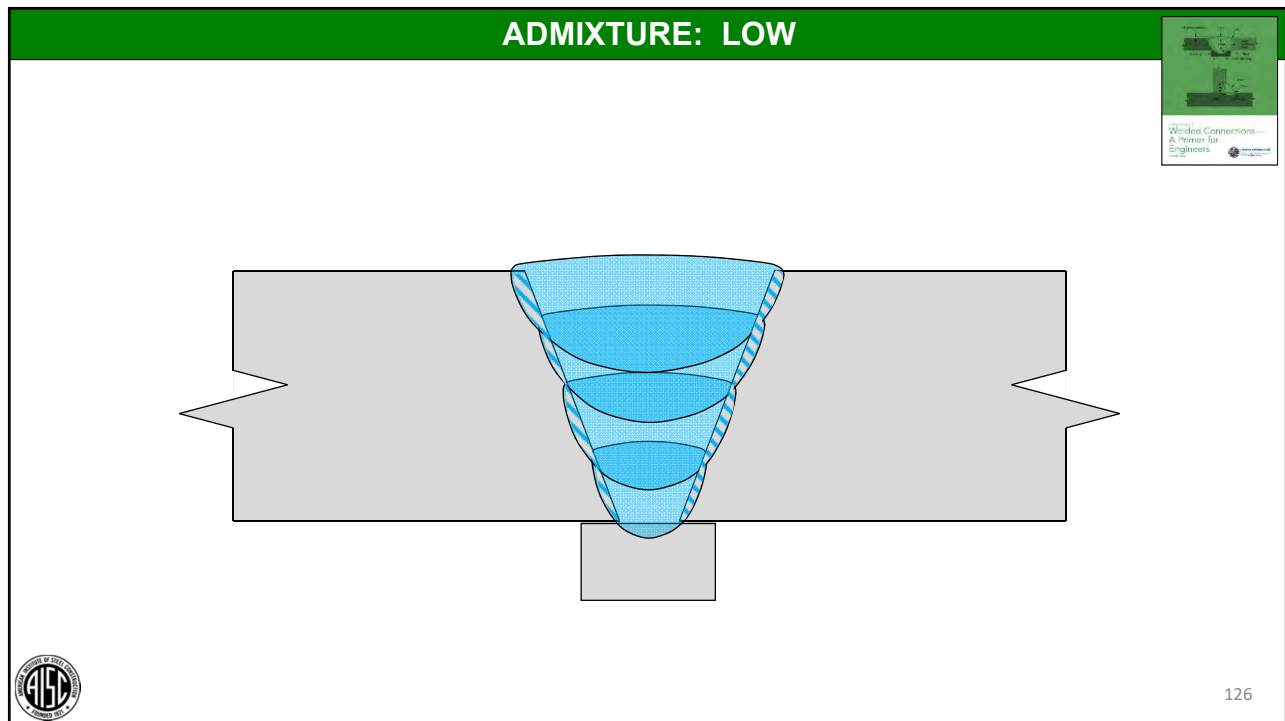
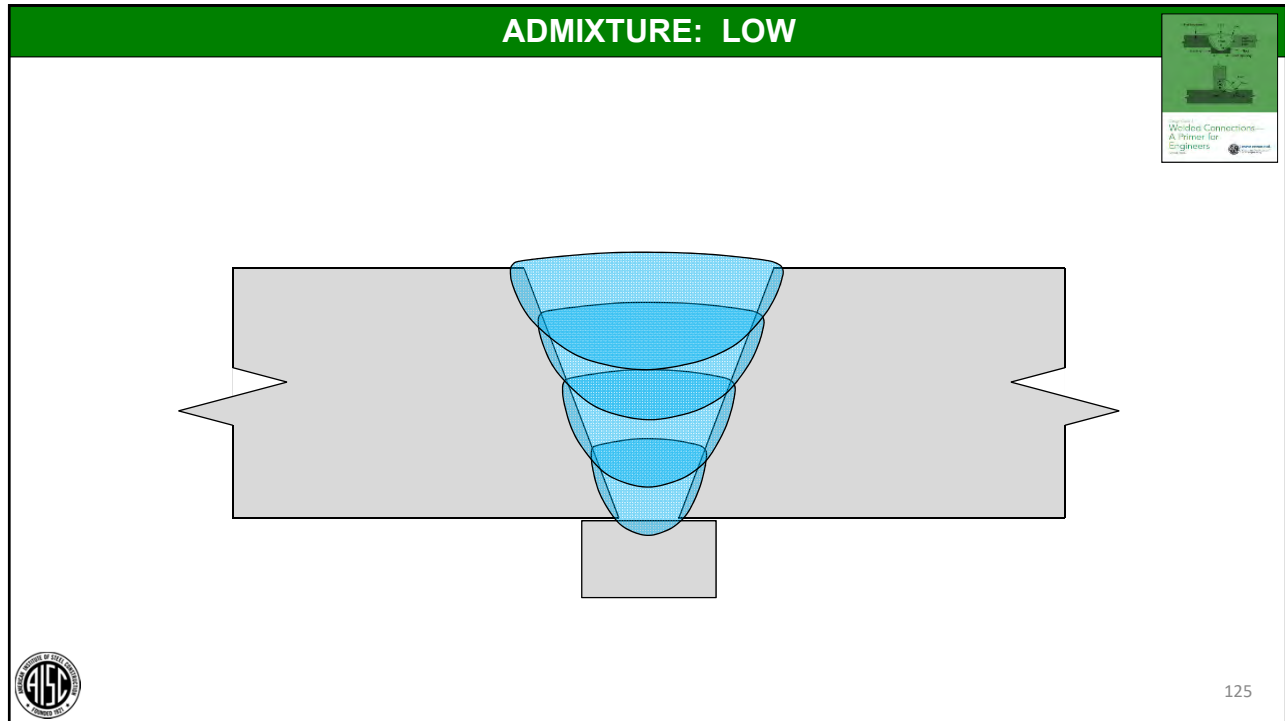
The diagram shows a butt joint between two gray steel plates, identical to the one above. The weld metal is represented by a blue, textured, hourglass-shaped area in the center. The weld metal is wider at the top and bottom surfaces and tapers towards the root. The root is a narrow V-shape. The plates have jagged ends on the left and right sides. A diagonal crack is shown in the weld metal, starting from the root and extending outwards towards the top and bottom surfaces.



Welded Connections—  
A Primer for  
Engineers



124




## CENTERLINE CRACKING


**Cause 1: Segregation Cracking**


**Low melting point ingredients segregate to the center during solidification**

**Solution: Minimize low melting point ingredients in the molten weld metal**

- Use “good” steel
- Minimize admixture
  - Change joint detail
  - Minimize penetration (unless needed for joint strength)

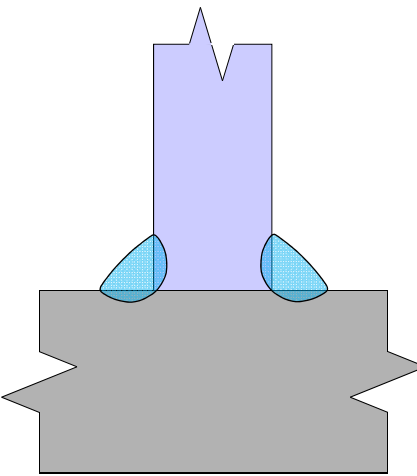




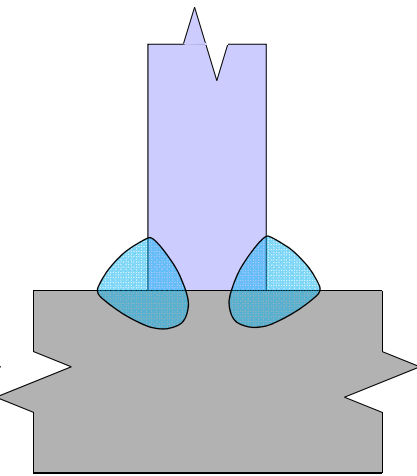
127

## ADMIXTURE


Acceptable fillet welds per AISC, AWS D1.1



**Minimal Admixture**



**Significant Admixture**

128

## CENTERLINE CRACKING


**Cause 1: Segregation Cracking**


**Low melting point ingredients segregate to the center during solidification**

**Solution: Minimize low melting point ingredients in the molten weld metal**

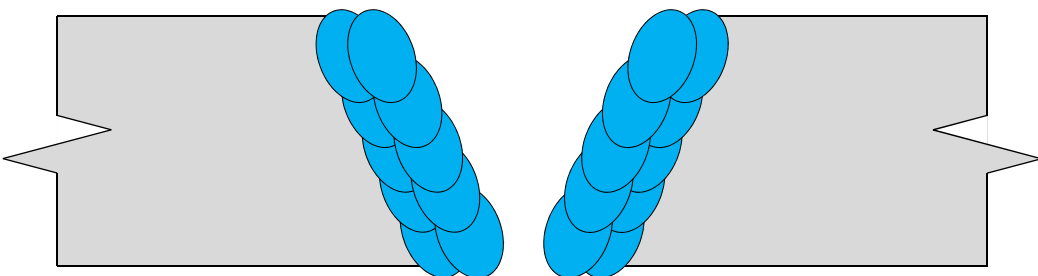
- Use “good” steel
- Minimize admixture
  - Change joint detail
  - Minimize penetration (unless needed for joint strength)
  - Use “buttering” (overlay) technique








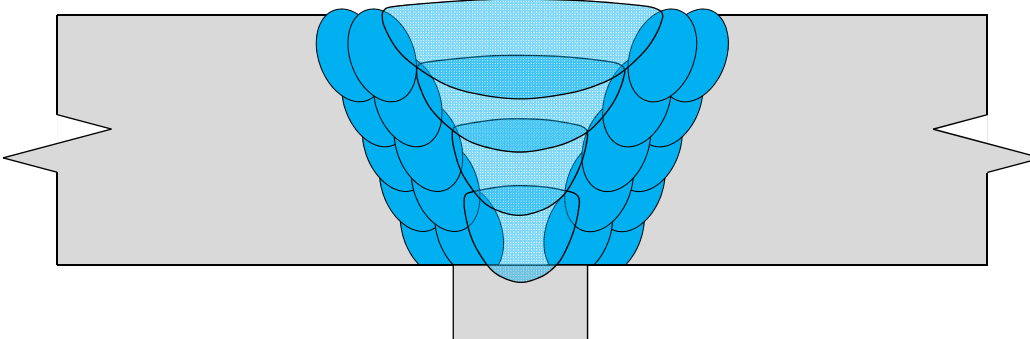
129

## BUTTERING





130

### BUTTERING



131

### CENTERLINE CRACKING




**Cause 1: Segregation Cracking**

**Low melting point ingredients segregate to the center during solidification**

**Solution: Minimize low melting point ingredients in the molten weld metal**

- Use “good” steel
- Minimize admixture
- For sulfur, use higher manganese (Mn) filler metal

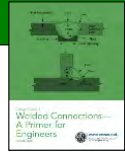
Sulfur is not present as an element, but as a compound; either FeS or MnS.



132

## CENTERLINE CRACKING

### Cause 2: Width-to-Depth Ratio Cracking

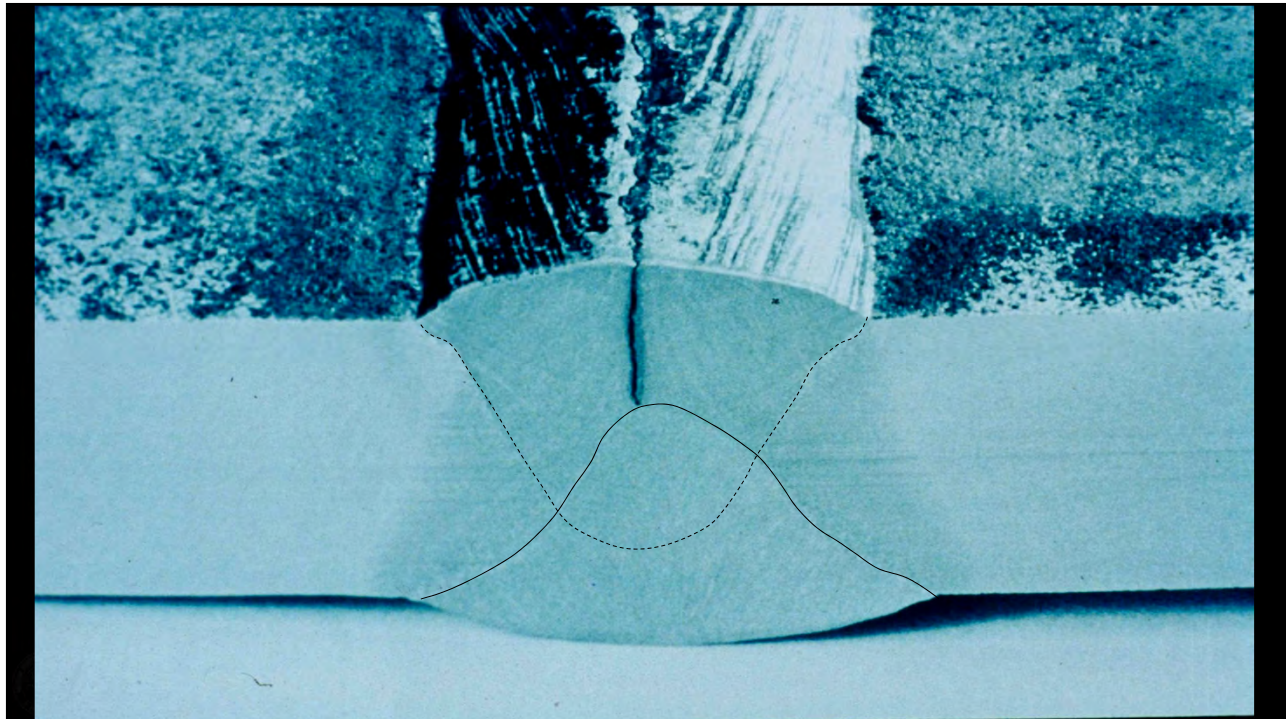


The cross-sectional width of the bead is less than the depth of the bead.

**Solution: Make sure each bead is wider than it is deep.**

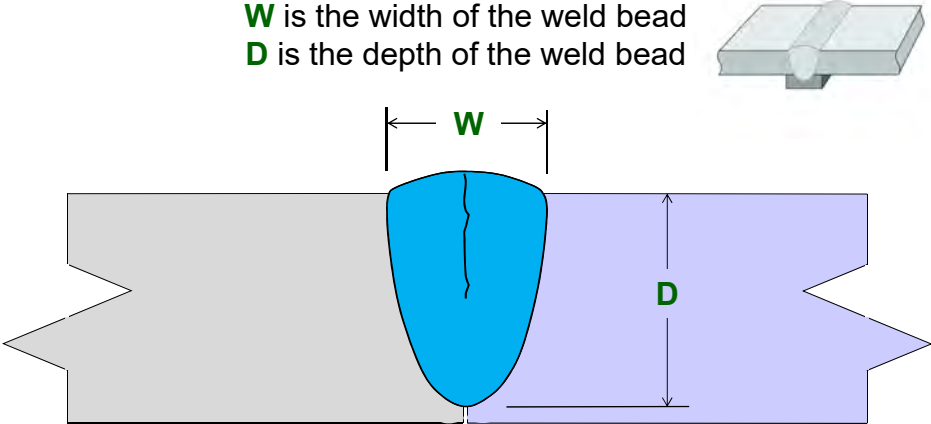


133





### CENTERLINE CRACKING

**W** is the width of the weld bead  
**D** is the depth of the weld bead



When **W < D**, the weld tends to crack






135

### CENTERLINE CRACKING

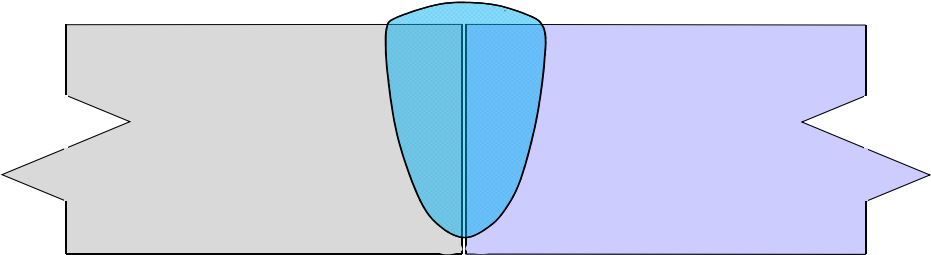
**Cause 2: Width-to-Depth Ratio Cracking**

**The cross-sectional width of the bead is less than the depth of the bead.**






136

### CENTERLINE CRACKING

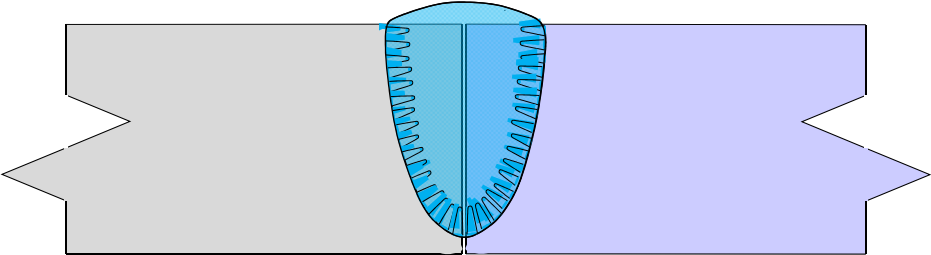


The diagram shows a cross-section of a weld joint between two plates. The weld metal is shaded in light blue. A vertical crack is shown running through the center of the weld metal, extending from the top surface down to the root. The heat-affected zone (HAZ) is shown in a lighter shade of blue, and the base metal is in grey and purple.



  



137

### CENTERLINE CRACKING

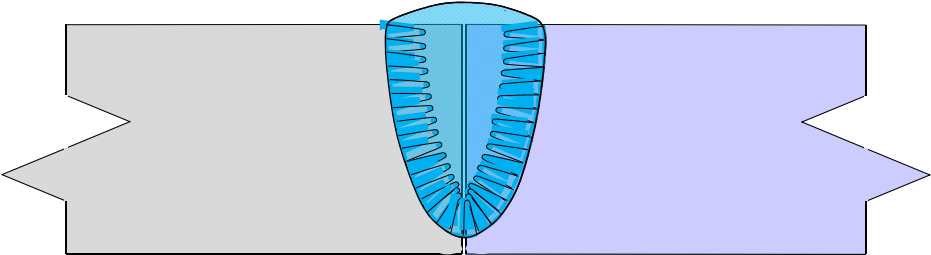


The diagram is identical to the one on slide 137, but the crack in the weld metal is now filled with a zig-zag pattern, representing a crack that has formed and filled with a substance, possibly a repair or a byproduct of the cracking process.


  


138

### CENTERLINE CRACKING

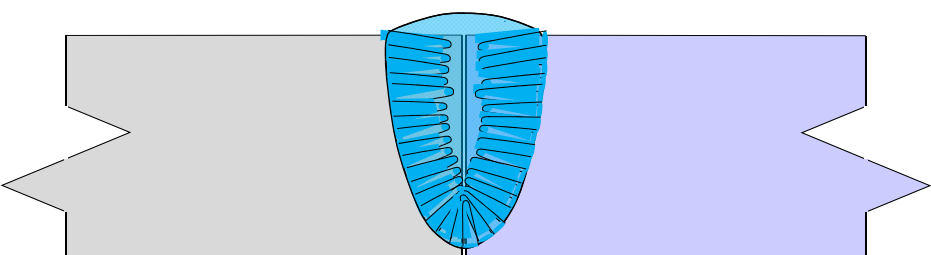


The diagram shows a cross-section of a butt-welded joint between two plates. The weld metal is shaded in blue. A vertical crack is shown running through the center of the weld metal, extending from the root to the surface. The plates are shaded in grey and purple. A small 3D perspective view of the joint is shown in the top right corner. A small inset image in the top right corner shows a book cover titled "Welded Connections—A Primer for Engineers".




139

### CENTERLINE CRACKING

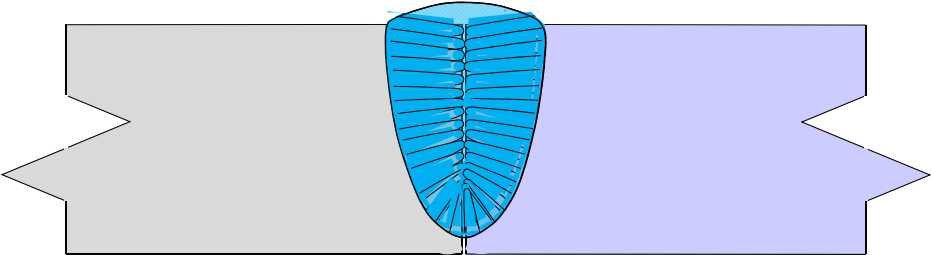




The diagram shows a cross-section of a butt-welded joint between two plates. The weld metal is shaded in blue. A vertical crack is shown running through the center of the weld metal, extending from the root to the surface. The plates are shaded in grey and purple. A small 3D perspective view of the joint is shown in the top right corner. A small inset image in the top right corner shows a book cover titled "Welded Connections—A Primer for Engineers".




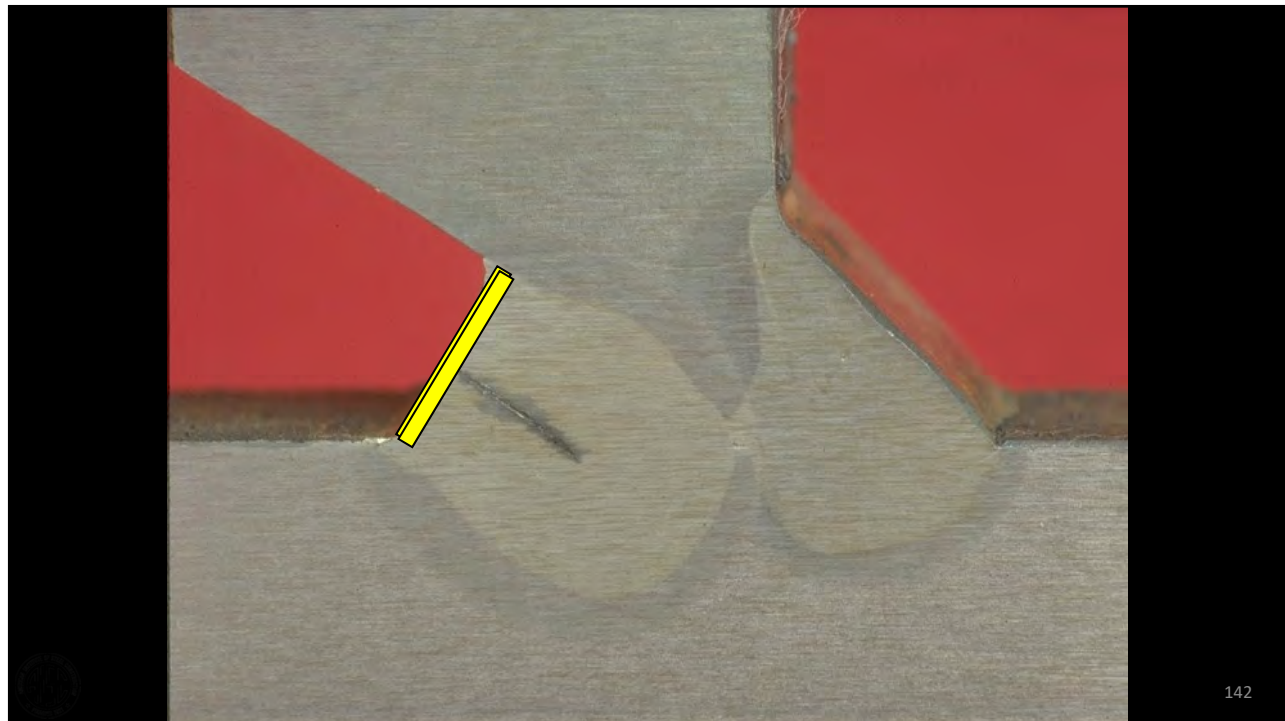
140

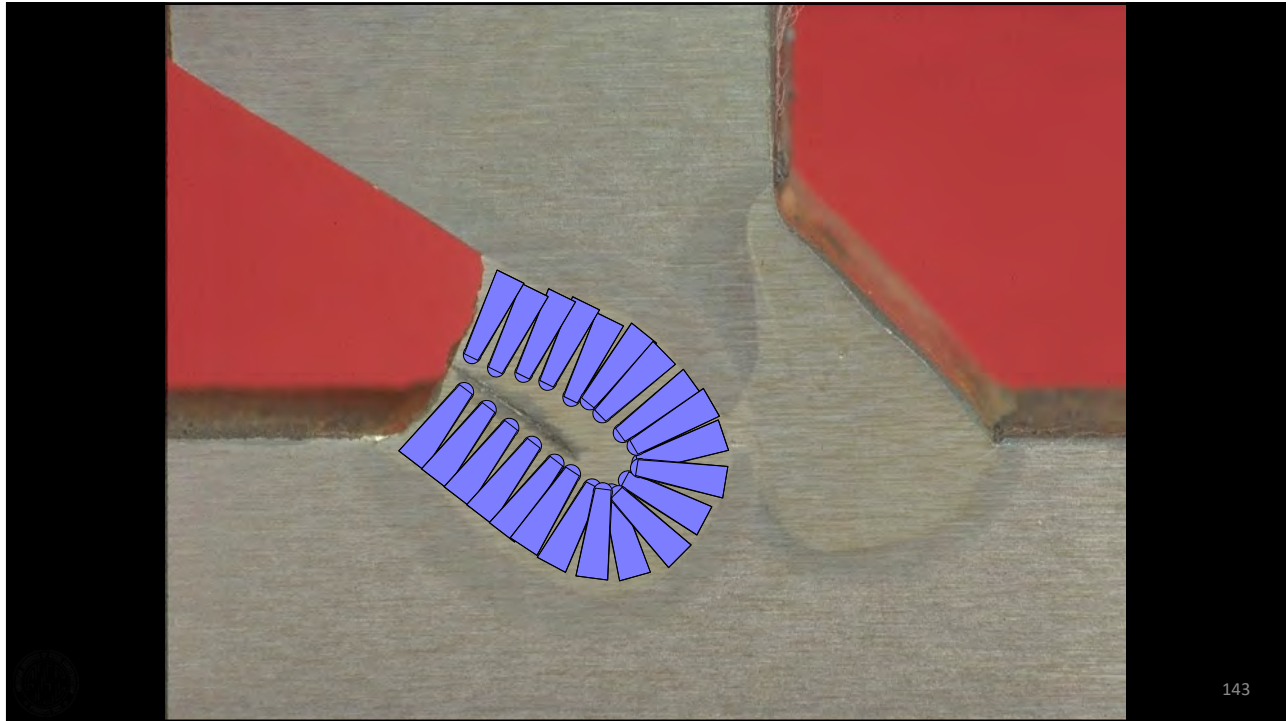
### CENTERLINE CRACKING



  
  
Welded Connections—  
A Primer for  
Engineers

141





143

## CENTERLINE CRACKING

### Cause 2: Width-to-Depth Ratio Cracking



The cross-sectional width of the bead is less than the depth of the bead.

**Solution: Make sure each bead is wider than it is deep.**

Width-to-Depth Ratio (W/D) should be:

**1:1 minimum**

**1.2:1 preferred**

**1.4:1 is ideal**



144

**CENTERLINE CRACKING**



**Cause 2: Width-to-Depth Ratio Cracking**

The cross-sectional width of the bead is less than the depth of the bead.

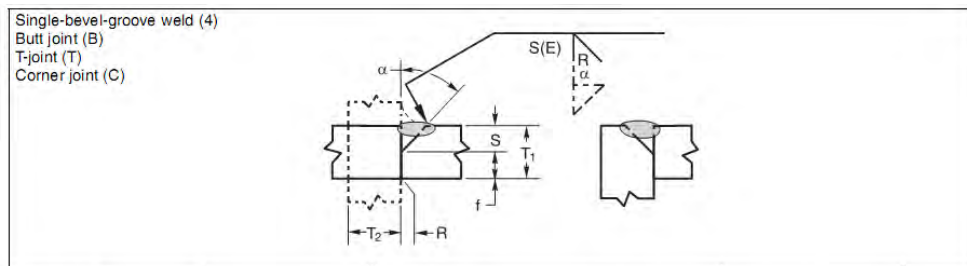
**Solution: Make sure each bead is wider than it is deep.**

- Use a proper joint detail



**AWS D1.1: 2015 Structural Welding Code – Steel**

**Figure 3.2: Prequalified PJP Groove Welded Joint Details**



Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Weld Size (E)	Notes
		T <sub>1</sub>	T <sub>2</sub>	Root Opening Root Face Groove Angle	Tolerances				
					As Detailed (see 3.12.3)	As Fit-Up (see 3.12.3)			
SMAW	BTC-P4	U	U	R = 0 f = 1/8 min. α = 45°	+1/16, -0 +U -0 +10°, -0°	+1/8, -1/16 ±1/16 +10°, -5°	All	S-1/8	b, e, f, g, i, k
GMAW FCAW	BTC-P4-GF	1/4 min.	U	R = 0 f = 1/8 min. α = 45°	+1/16, -0 +U -0 +10°, -0°	+1/8, -1/16 ±1/16 +10°, -5°	F, H V, OH	S S-1/8	a, b, f, g, i, k
SAW	TC-P4-S	7/16 min.	U	R = 0 f = 1/4 min. α = 60°	±0 +U, -0 +10°, -0°	+1/16, -0 ±1/16 +10°, -5°	F	S	b, f, g, j, k



**AWS D1.1: 2015 Structural Welding Code – Steel**

Welding Process	Root Opening Root Face Groove Angle
SMAW	R = 0 f = 1/8" min. <b><math>\alpha = 45^\circ</math></b>
GMAW FCAW	R = 0 f = 1/8" min. <b><math>\alpha = 45^\circ</math></b>
SAW	R = 0 f = 1/4" min. <b><math>\alpha = 60^\circ</math></b>

The diagram illustrates a groove weld joint between two steel plates. Key features and dimensions are labeled:  $\alpha$  is the groove angle; S(E) is the root opening; R is the root face radius; S is the groove depth; T1 and T2 are the thicknesses of the plates; and f is the groove face width. A secondary diagram shows a cross-section of the weld metal.

147

BTC-P4, BTC-P4-GF

45°

TC-P4-S

60°

The diagrams show the groove profiles for two different welding processes. The BTC-P4, BTC-P4-GF process uses a 45-degree groove angle, while the TC-P4-S process uses a 60-degree groove angle. The groove faces are shaded in blue.

148

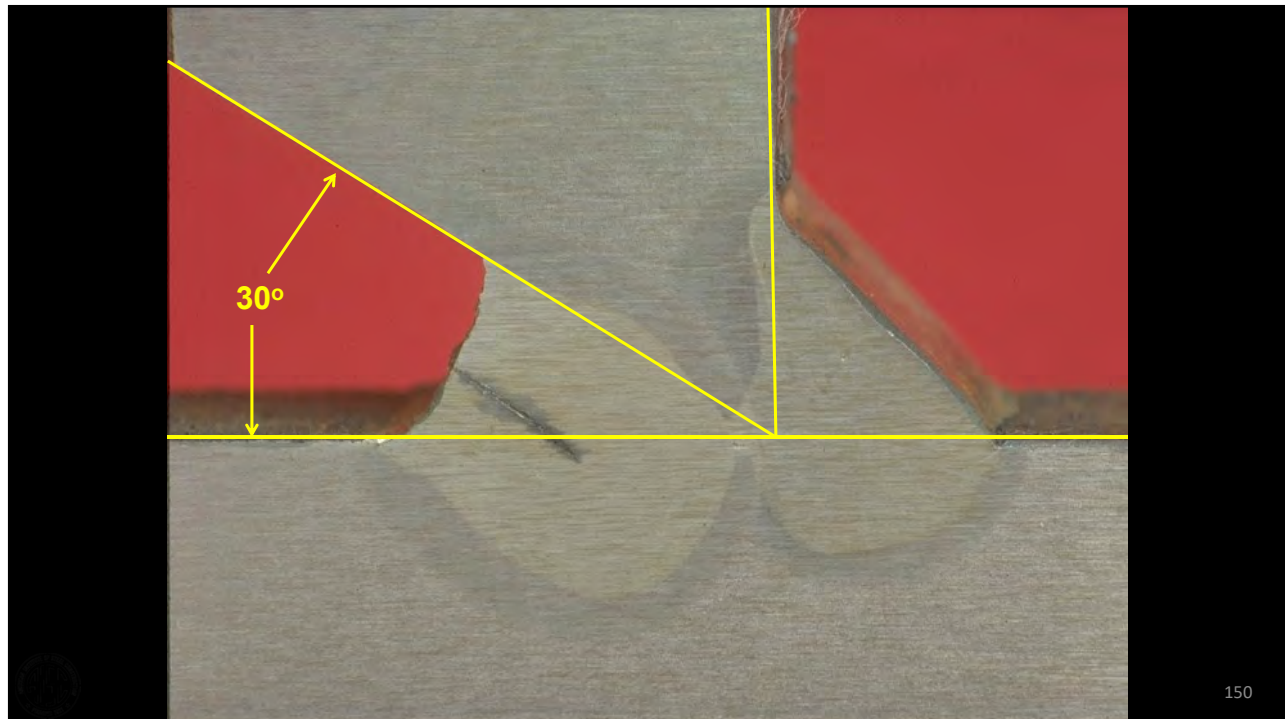
**AWS D1.1: 2015 Structural Welding Code – Steel**

45°  
1/4" [6 mm]

30°  
3/8" [9 mm]

**TC-U4**

149





### CENTERLINE CRACKING


**Cause 2: Width-to-Depth Ratio Cracking**

The cross-sectional width of the bead is less than the depth of the bead.

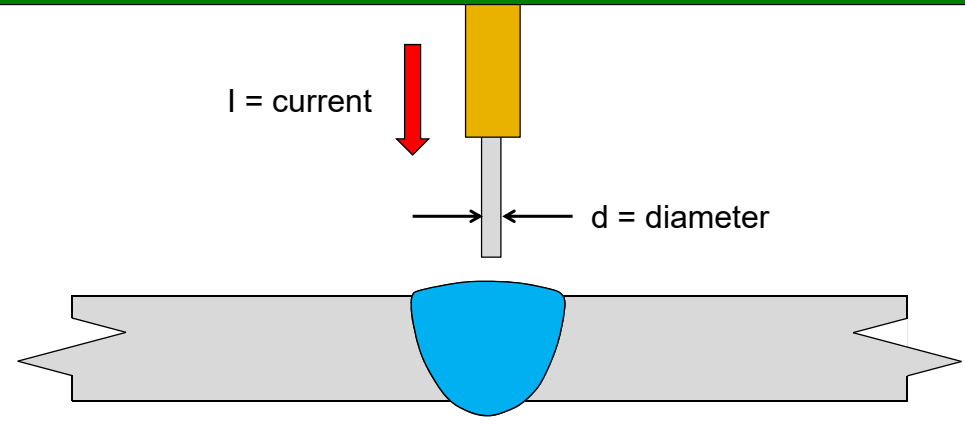
**Solution: Make sure each bead is wider than it is deep.**

- Use a proper joint detail
- Control current density ( $\delta$ )



151

### CURRENT DENSITY ( $\delta$ )




$$\delta = \left( \frac{I}{A} \right) \propto \left( \frac{I}{d^2} \right)$$

where

I = current (amps)

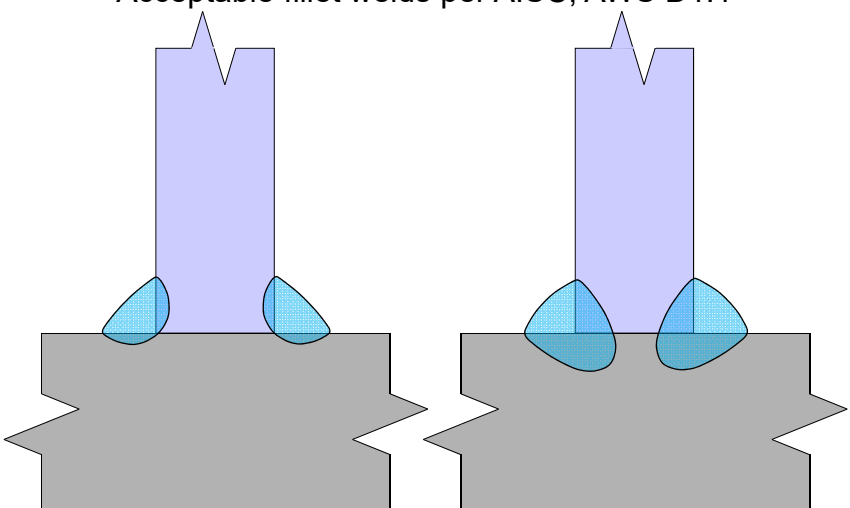
A = cross sectional area of filler metal

d = diameter of filler metal

152

**CURRENT DENSITY ( $\delta$ )**

Acceptable fillet welds per AISC, AWS D1.1

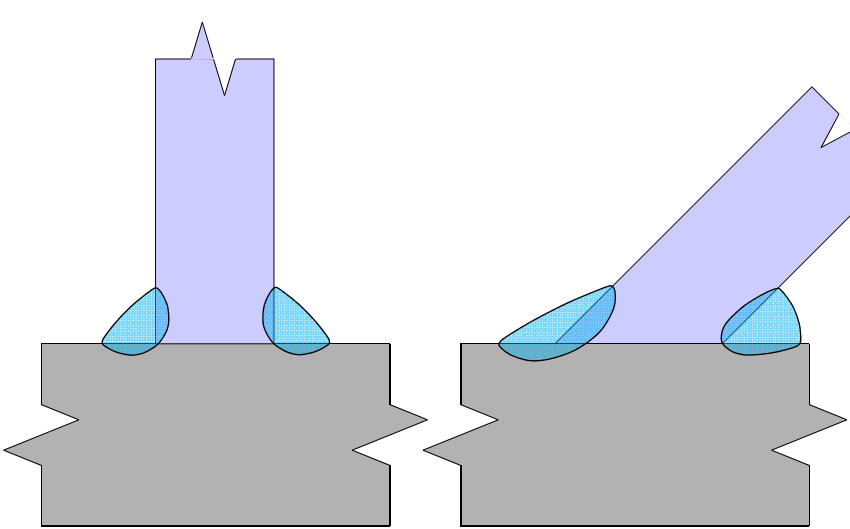


The diagram shows two cross-sections of a fillet weld. The left one, labeled 'Normal Current Density', shows a weld with a smooth, rounded toe. The right one, labeled 'Excessive Current Density', shows a weld with a sharp, pointed toe and a concave root, indicating a lack of fusion.

**Normal Current Density**      **Excessive Current Density**

153

**CURRENT DENSITY ( $\delta$ )**



The diagram shows two cross-sections of fillet welds. The left one, labeled 'In 90° joint, W/D = 2:1', shows a weld with a smooth, rounded toe. The right one, labeled 'In 45° joint, acute side is problematic', shows a weld with a sharp, pointed toe on the acute side of the joint.

**In 90° joint, W/D = 2:1**      **In 45° joint, acute side is problematic**

154


### CENTERLINE CRACKING


**Cause 2: Width-to-Depth Ratio Cracking**


The cross-sectional width of the bead is less than the depth of the bead.

**Solution: Make sure each bead is wider than it is deep.**

- Use a proper joint detail
- Control current density ( $\delta$ )







155


### CENTERLINE CRACKING

**Cause 3: Surface Profile Cracking**

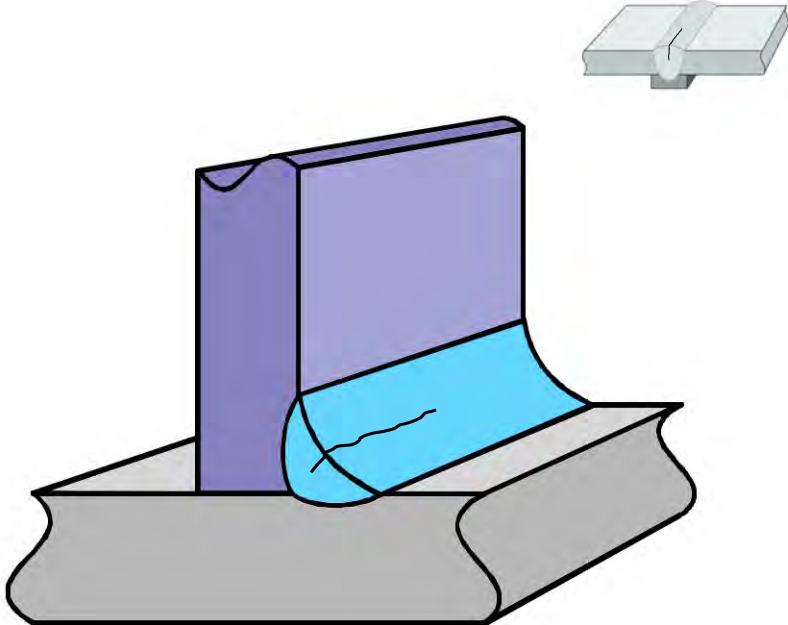
The surface of the weld is concave






156

### CENTERLINE CRACKING

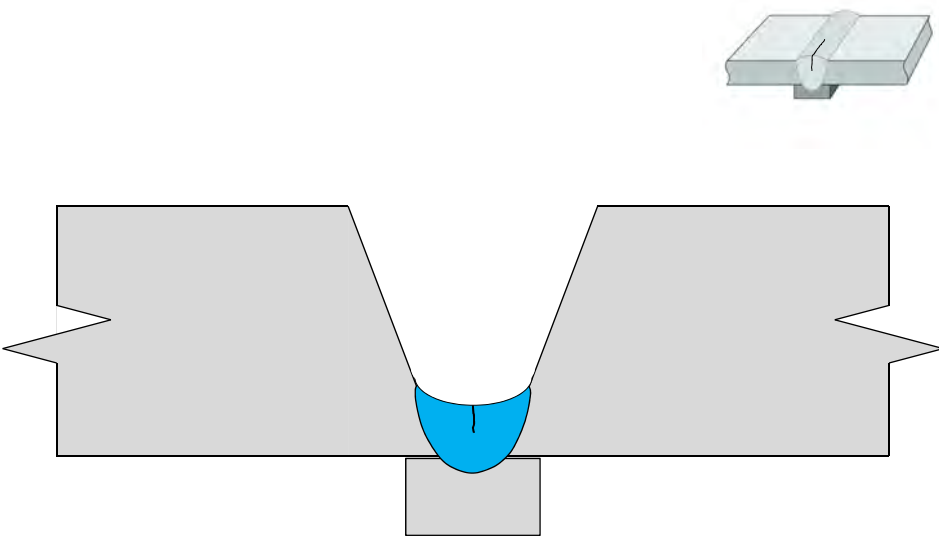


The diagram shows a 3D perspective of a T-joint weld. A vertical purple plate is welded to a horizontal grey plate. The weld metal is highlighted in light blue. A crack is shown running along the centerline of the weld. A small inset in the top right shows a similar joint with a crack. A small thumbnail of the book cover is in the top right corner.




157

### CENTERLINE CRACKING

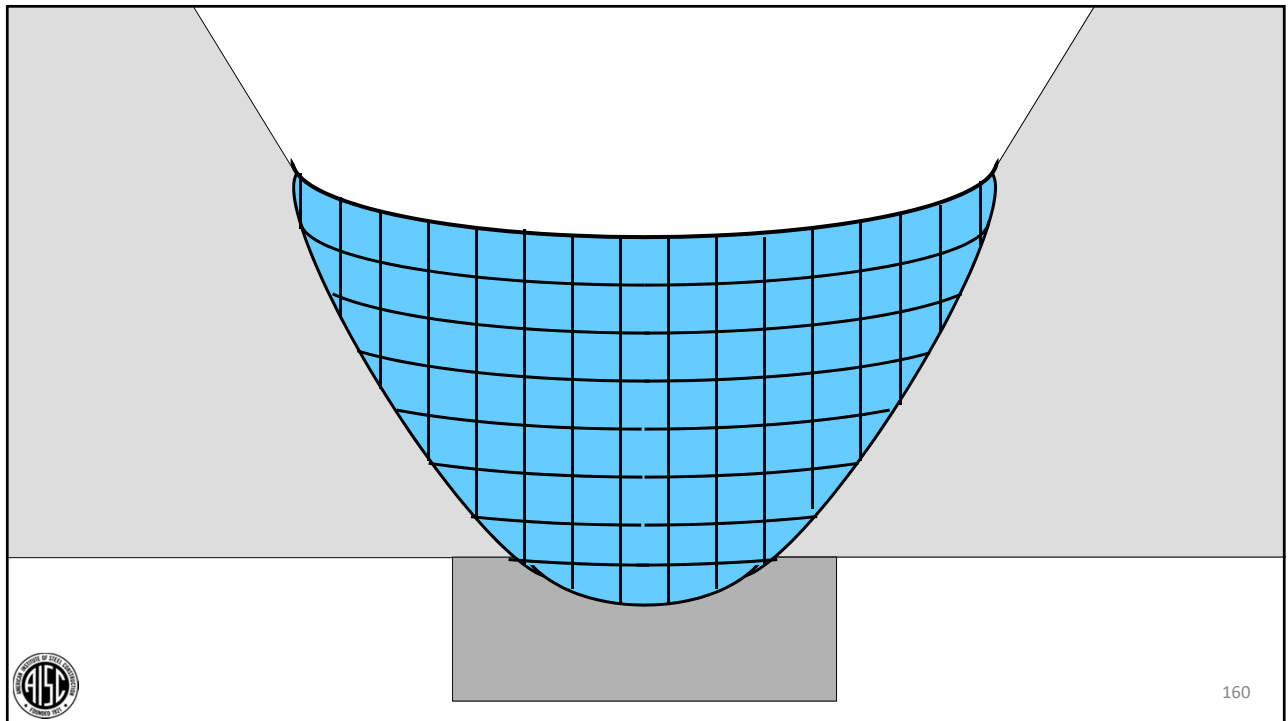
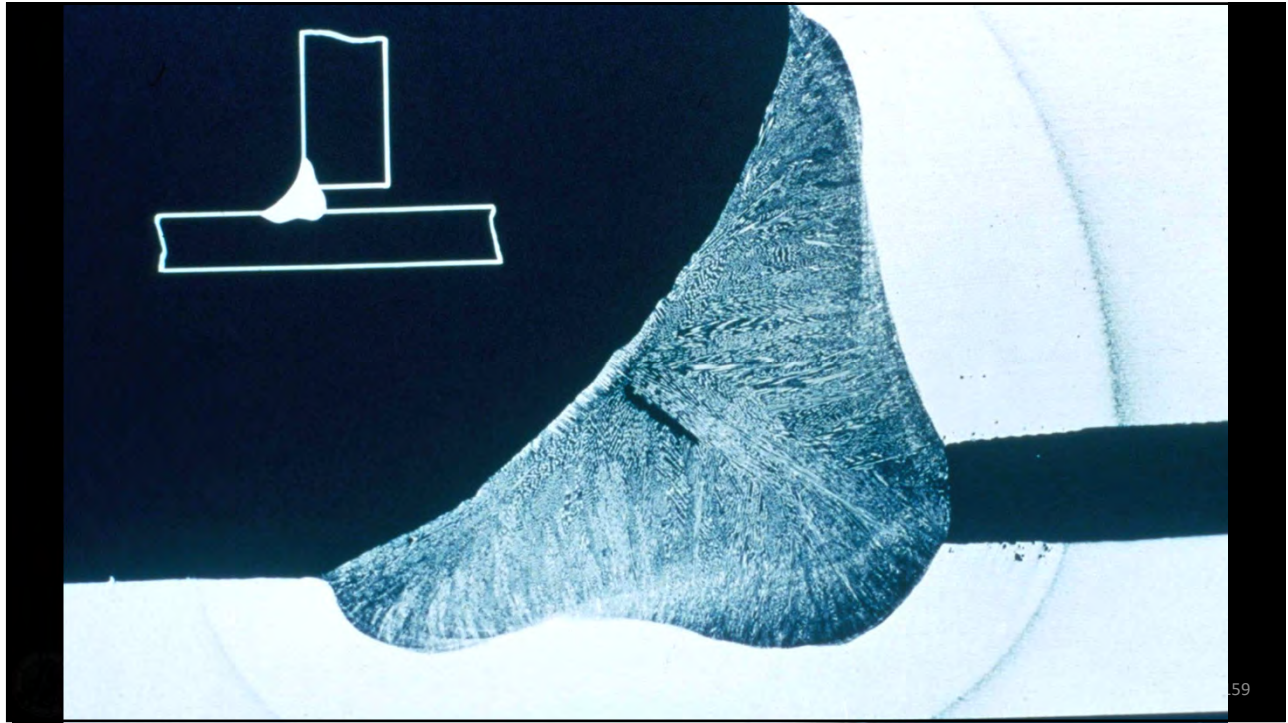


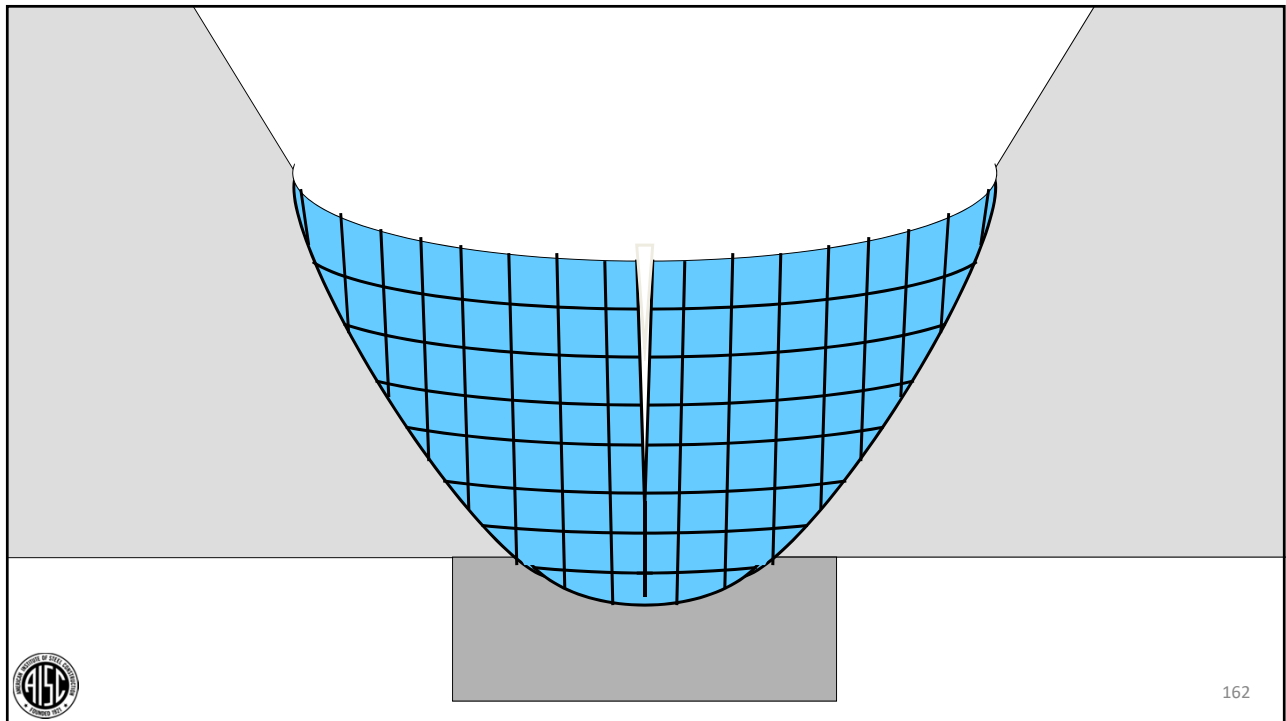
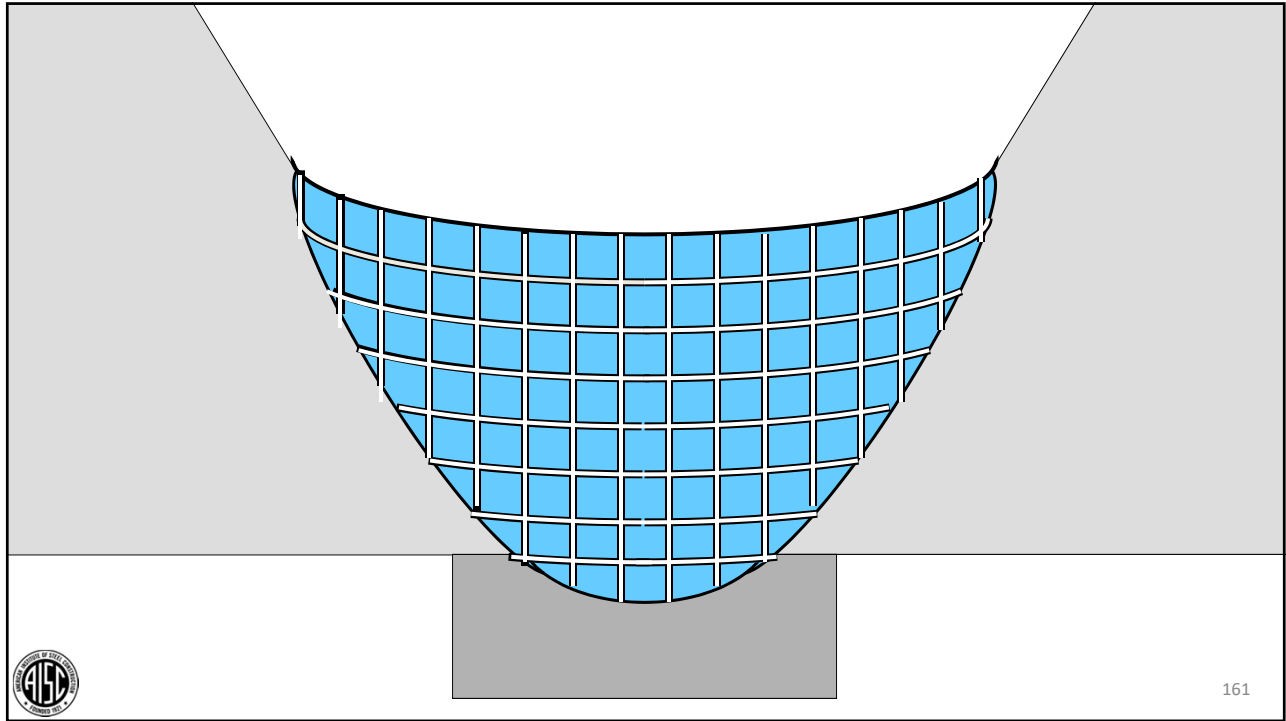
The diagram shows a cross-section of a V-groove weld joint. The root pass is highlighted in light blue and is concave. A crack is shown running along the centerline of this root pass. A small inset in the top right shows a similar joint with a crack. A small thumbnail of the book cover is in the top right corner.

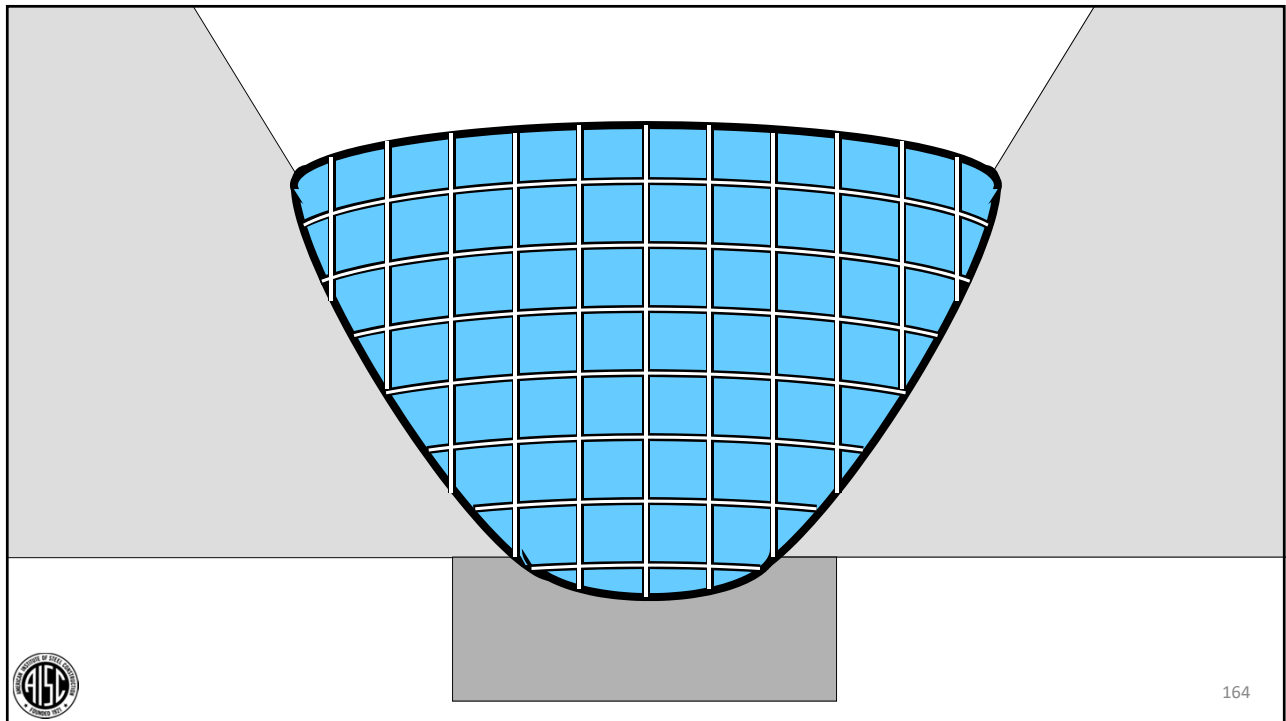
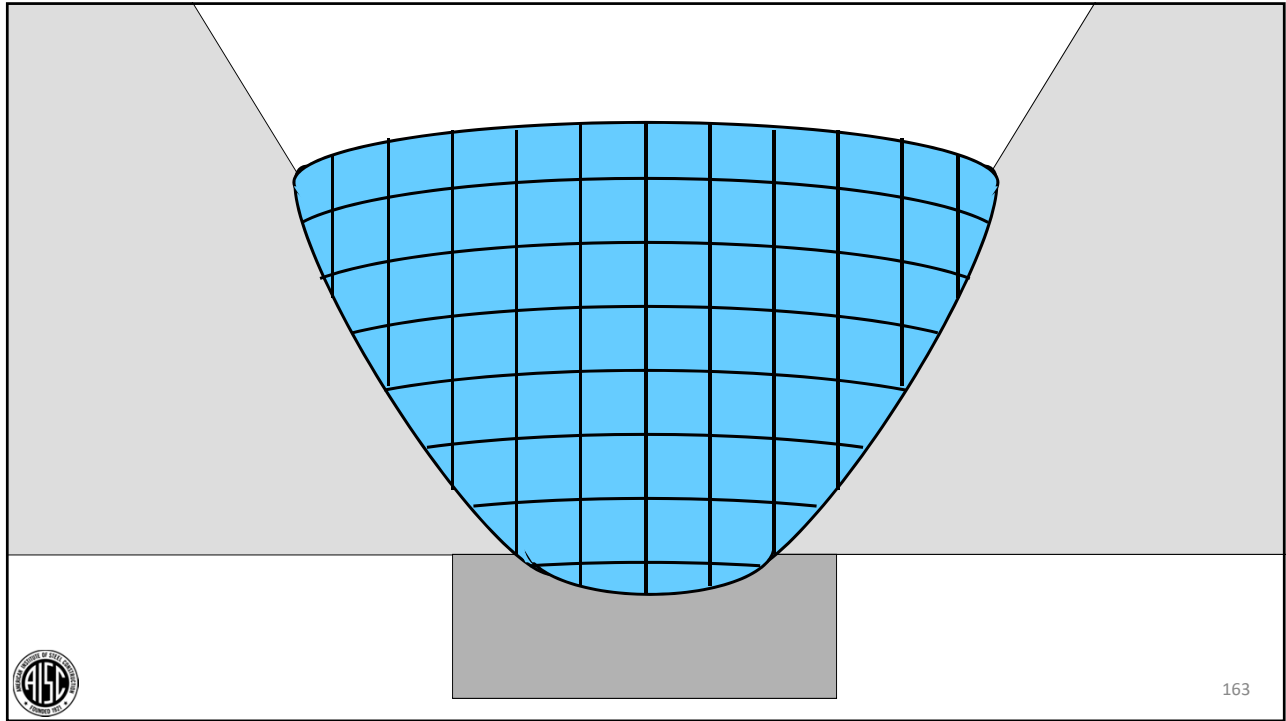
Any concave pass, especially root passes

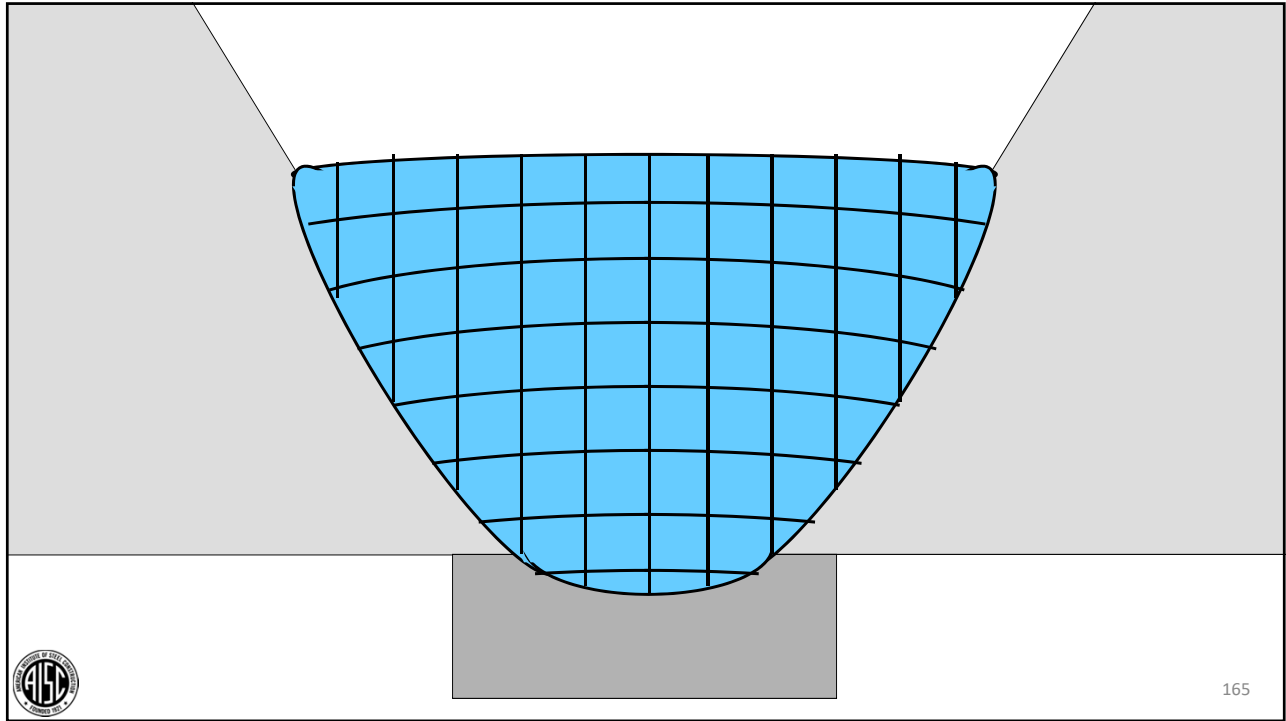


158











### CENTERLINE CRACKING


**Cause 3: Surface Profile Cracking**

**The surface of the weld is concave**

**Solution: Make sure the bead surface is convex**

- Use a proper welding procedure
  - Shielding gas
    - Argon/oxygen combinations tend to give concave beads
    - Argon/CO<sub>2</sub> combinations tend to give flatter/more convex beads
    - Vertical up (convex) versus vertical down (concave)
    - Lower voltage, amperage (“colder”)



167



### CENTERLINE CRACKING


**Cause 3: Surface Profile Cracking**

**The surface of the weld is concave**

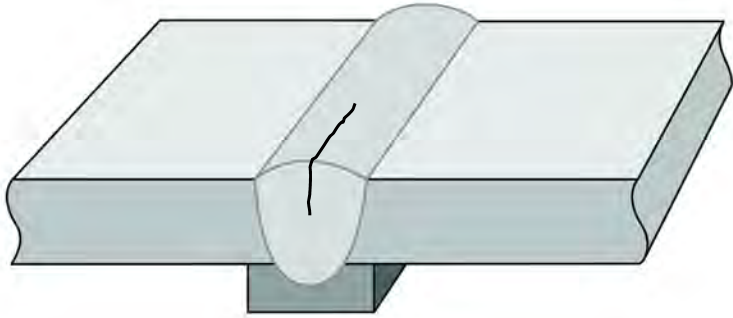
**Solution: Make sure the bead surface is convex**

- Use a proper welding procedure





168

### CENTERLINE CRACKING




A 3D perspective view of a butt-welded joint. A vertical crack is shown running along the centerline of the weld bead, extending from the surface into the root of the joint.



169



### CENTERLINE CRACKING



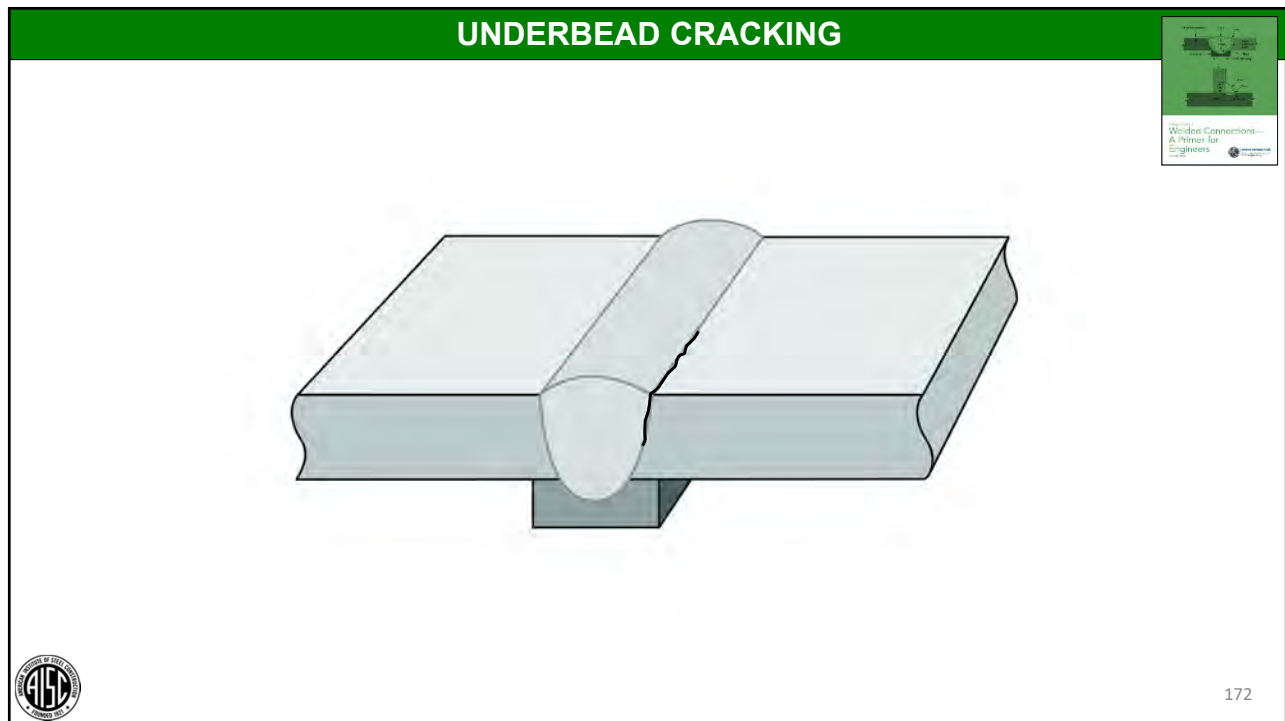
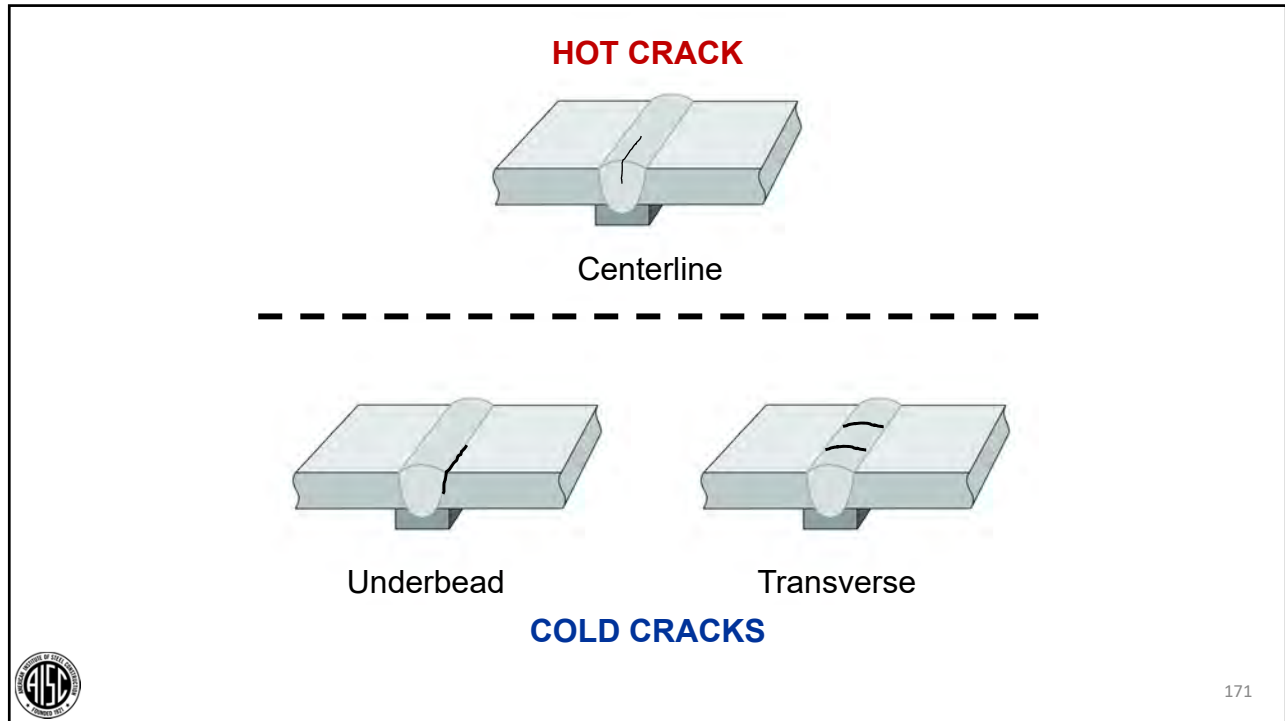
**Cause 1: Segregation Cracking**  
**Cause 2: Width-to-Depth Ratio Cracking**  
**Cause 3: Surface Profile Cracking**

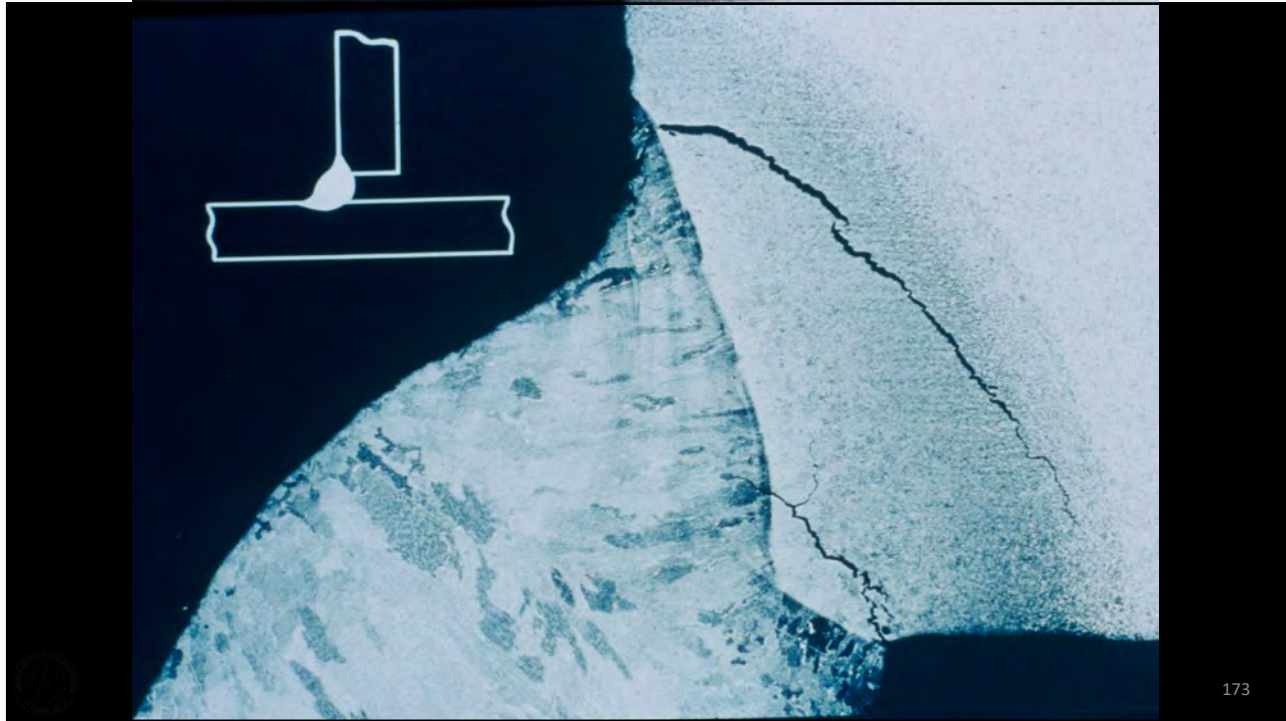
**To troubleshoot, use a countdown.**

- Surface profile: Is it concave?
- If not, check the cross section: Is the bead deeper than it is wide?
- If not, check the weld deposit chemistry.



170





## UNDERBEAD CRACKING

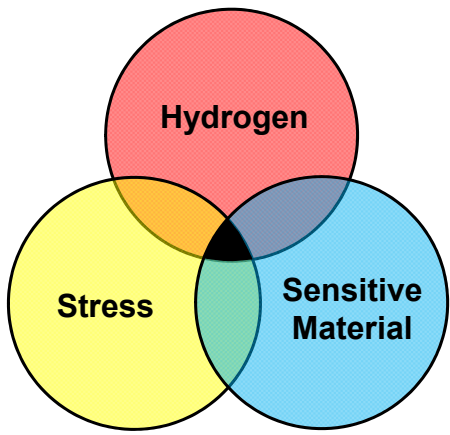
### Characteristics:

- Located at weld toe or in heat affected zone (HAZ)
- Occurs at lower temperatures
- May be delayed—occurring up to 72 hours (or more) after welding
- May occur immediately after the weldment cools sufficiently
- Is driven by the transverse shrinkage stress
- Can be confused with in-service fatigue cracks which often occur at weld toes




### UNDERBEAD CRACKING

**Cause:** Excessive hydrogen AND a sensitive material AND an applied or residual stress

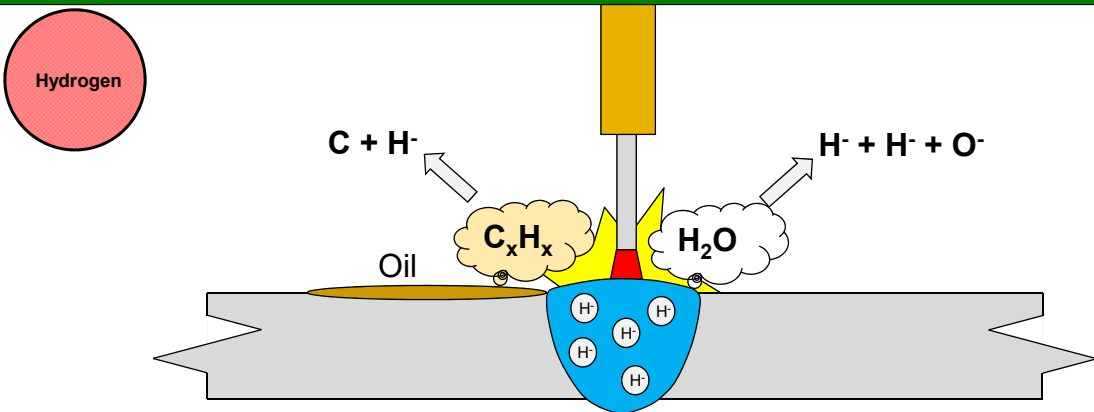


The diagram consists of three overlapping circles: a red circle labeled "Hydrogen", a yellow circle labeled "Stress", and a blue circle labeled "Sensitive Material". The central area where all three circles overlap is shaded black, representing the condition for underbead cracking. To the right of the text is a 3D perspective drawing of a welded joint with a crack visible in the underbead area. In the top right corner, there is a small thumbnail of the presentation slide.




175

### DEVELOPMENT OF ATOMIC HYDROGEN

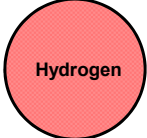


The diagram shows a cross-section of a metal workpiece being welded. A welding torch is positioned above the workpiece, with a blue shield containing several "H" atoms (atomic hydrogen) positioned directly in front of the weld. To the left, a cloud labeled "Oil" is shown with an arrow pointing to the chemical formula  $C_xH_x$ . An arrow points from this cloud to the left, labeled  $C + H^{\cdot}$ . To the right, a cloud labeled "H<sub>2</sub>O" is shown with an arrow pointing to the right, labeled  $H^{\cdot} + H^{\cdot} + O^{\cdot}$ . In the top left corner, there is a red circle labeled "Hydrogen". In the top right corner, there is a small thumbnail of the presentation slide.

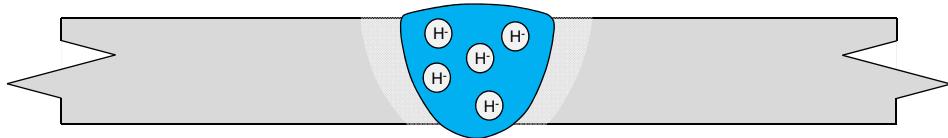



176

### MIGRATION OF ATOMIC HYDROGEN




Hydrogen

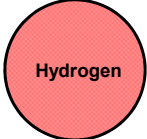




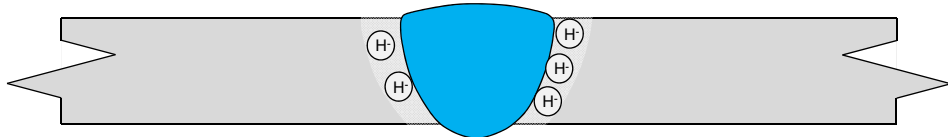
Welded Connections—  
A Primer for  
Engineers


177

### MIGRATION OF ATOMIC HYDROGEN




Hydrogen





Welded Connections—  
A Primer for  
Engineers

178

### SHRINKAGE STRESSES

**Stress**

179

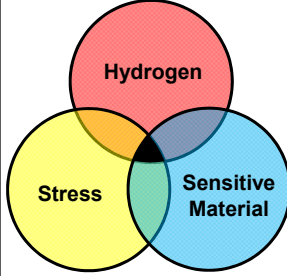
### SENSITIVE MATERIAL

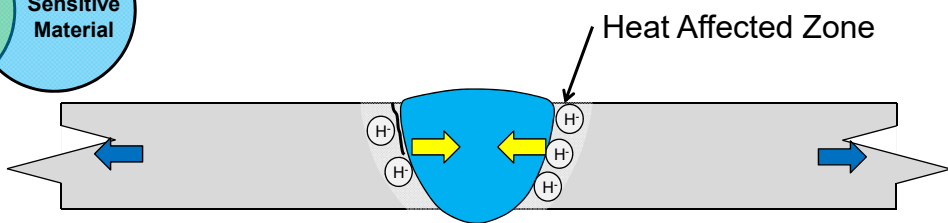
**Sensitive  
Material**


  

180

### COMBINING ALL THREE








Welded Connections—  
A Primer for  
Engineers

Heat Affected Zone

Because it takes time for hydrogen to diffuse, and because this cracking only occurs when the steel is cool (< 400°F), it may be “delayed”.


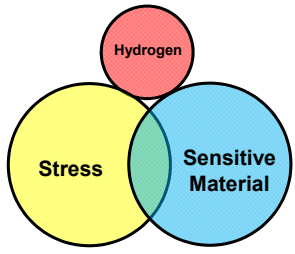
181


### UNDERBEAD CRACKING

**Cause:** Excessive hydrogen AND a sensitive material AND an applied or residual stress


**Solution:**

- Reduce Hydrogen
  - Selection of filler metals
  - Storage and exposure of filler metals
  - Control base metal cleanliness
  - Maximize diffusion of hydrogen



Welded Connections—  
A Primer for  
Engineers

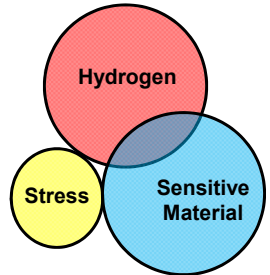

182


### UNDERBEAD CRACKING

**Cause:** Excessive hydrogen AND a sensitive material AND an applied or residual stress


**Solution:**

- Reduce Residual Stress
  - Use matching or undermatching filler metal
  - Control welding sequence
  - Maintain proper preheat and interpass temperatures
  - Peen weld beads





183

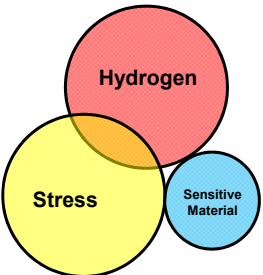




### UNDERBEAD CRACKING

**Cause:** Excessive hydrogen AND a sensitive material AND an applied or residual stress


**Solution:**

- Reduce Material (HAZ) Sensitivity
  - Selection of base metal (low hardenability—low carbon, low alloys)
  - Increased preheat
  - Higher heat input
  - Increased interpass temperature



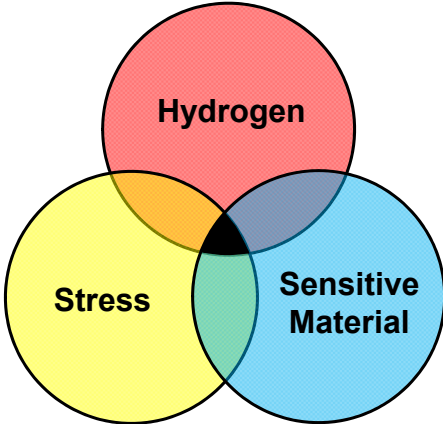


184






### UNDERBEAD CRACKING

**Cause:** Excessive hydrogen AND a sensitive material AND an applied or residual stress



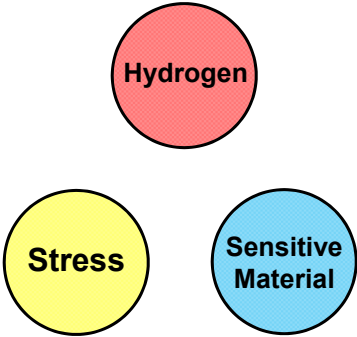


A Venn diagram with three overlapping circles. The top circle is red and labeled "Hydrogen". The bottom-left circle is yellow and labeled "Stress". The bottom-right circle is blue and labeled "Sensitive Material". The intersections between Hydrogen and Stress, Hydrogen and Sensitive Material, and Stress and Sensitive Material are shaded in orange, purple, and green respectively. The central intersection where all three overlap is shaded black.



185


### UNDERBEAD CRACKING

**Cause:** Excessive hydrogen AND a sensitive material AND an applied or residual stress



Three separate circles are shown: a red circle labeled "Hydrogen" at the top, a yellow circle labeled "Stress" at the bottom left, and a blue circle labeled "Sensitive Material" at the bottom right. They do not overlap.



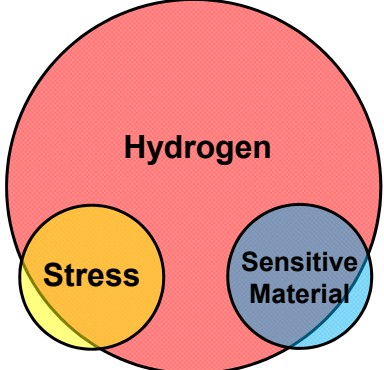
Typically, when an underbead cracking problem is encountered, all three variables are reduced.




186

### UNDERBEAD CRACKING

**Cause:** Excessive hydrogen AND a sensitive material AND an applied or residual stress

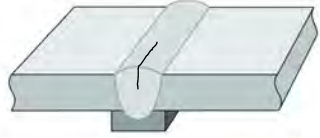


Crack-free welding is possible, even with very high hydrogen levels, if the other factors are small.




187

### HOT CRACK




Centerline

---




Underbead



Transverse



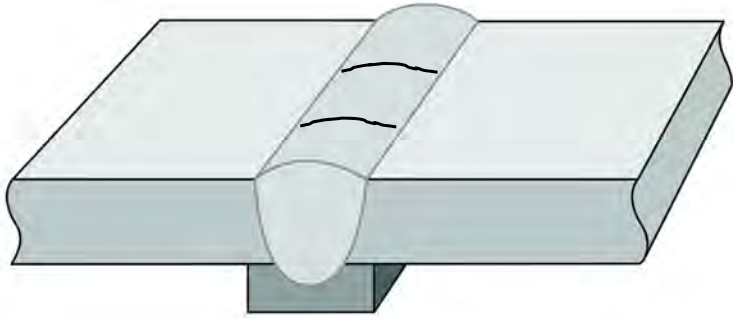
### COLD CRACKS



188

### TYPES OF WELD CRACKS

#### Transverse Cracking

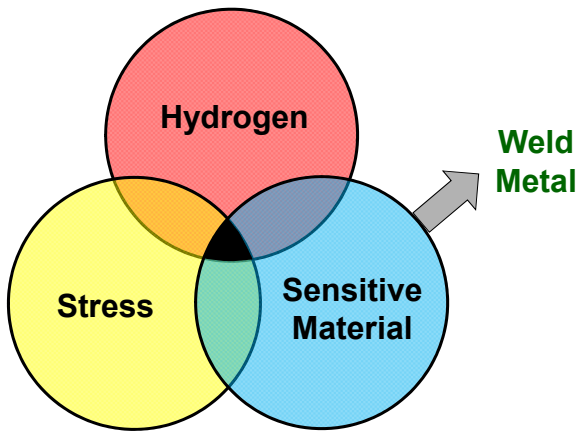


189





### TRANSVERSE CRACKING

**Cause:** Excessive hydrogen AND a sensitive material AND an applied or residual stress



The diagram consists of three overlapping circles: a red circle labeled 'Hydrogen', a yellow circle labeled 'Stress', and a blue circle labeled 'Sensitive Material'. The central area where all three circles overlap is shaded black. An arrow points from this central area to the text 'Weld Metal'. To the right of the diagram is a small 3D illustration of a welded joint with a crack.






191

### TRANSVERSE CRACKING

**Characteristics:**

- May be delayed, just like underbead cracking
- Is caused by longitudinal shrinkage stress (underbead cracking is driven by transverse stress)
- Longitudinal spacing may be very regular
- Must have a sufficiently long weld (typically > 18" long)




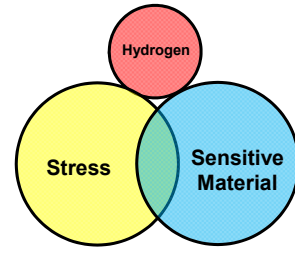

192


### TRANSVERSE CRACKING

**Cause:** Excessive hydrogen AND a sensitive material AND an applied or residual stress

**Solution:**

- Reduce Hydrogen
  - Selection of filler metals
  - Storage and exposure of filler metals
  - Control base metal cleanliness
  - Maximize diffusion of hydrogen



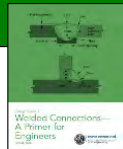
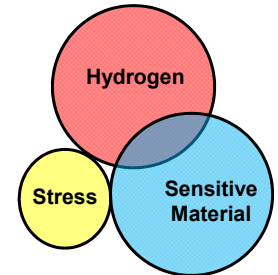

193

### TRANSVERSE CRACKING


**Cause:** Excessive hydrogen AND a sensitive material AND an applied or residual stress

**Solution:**

- Reduce Residual Stress
  - Use **matching** or undermatching filler metal
  - Maintain proper preheat and interpass temperatures



**Transverse cracking nearly always involves weld deposits that are higher in strength than the base metal.**

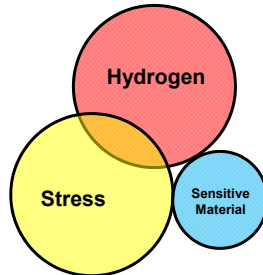

194


### TRANSVERSE CRACKING

**Cause:** Excessive hydrogen AND a sensitive material AND an applied or residual stress


**Solution:**

- Reduce Material (Weld Metal) Sensitivity
  - Selection of filler metal
  - Use undermatching where possible
  - Increased preheat
  - Higher heat input
  - Increased interpass temperature
  - Control admixture (pickup)



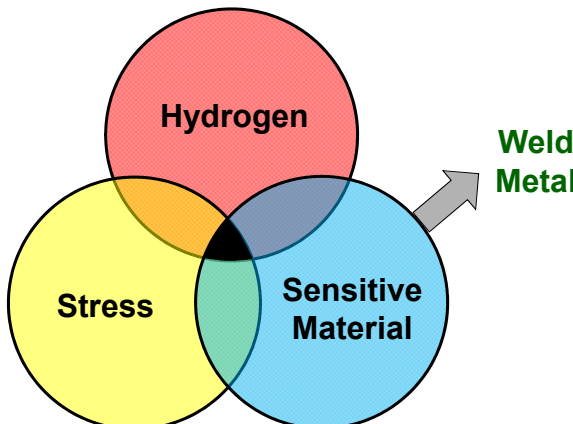




195




### TRANSVERSE CRACKING

**Cause:** Excessive hydrogen AND a sensitive material AND an applied or residual stress



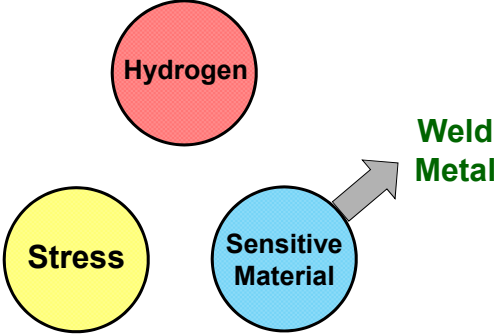


196






### TRANSVERSE CRACKING

**Cause:** Excessive hydrogen AND a sensitive material AND an applied or residual stress



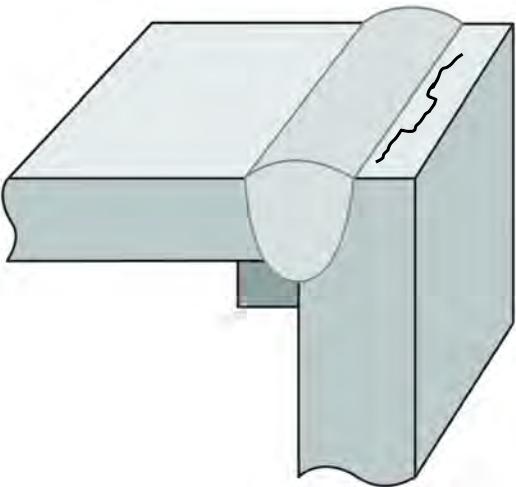


The diagram features three colored circles: a red circle labeled "Hydrogen", a yellow circle labeled "Stress", and a blue circle labeled "Sensitive Material". A grey arrow points from the "Sensitive Material" circle towards the text "Weld Metal".

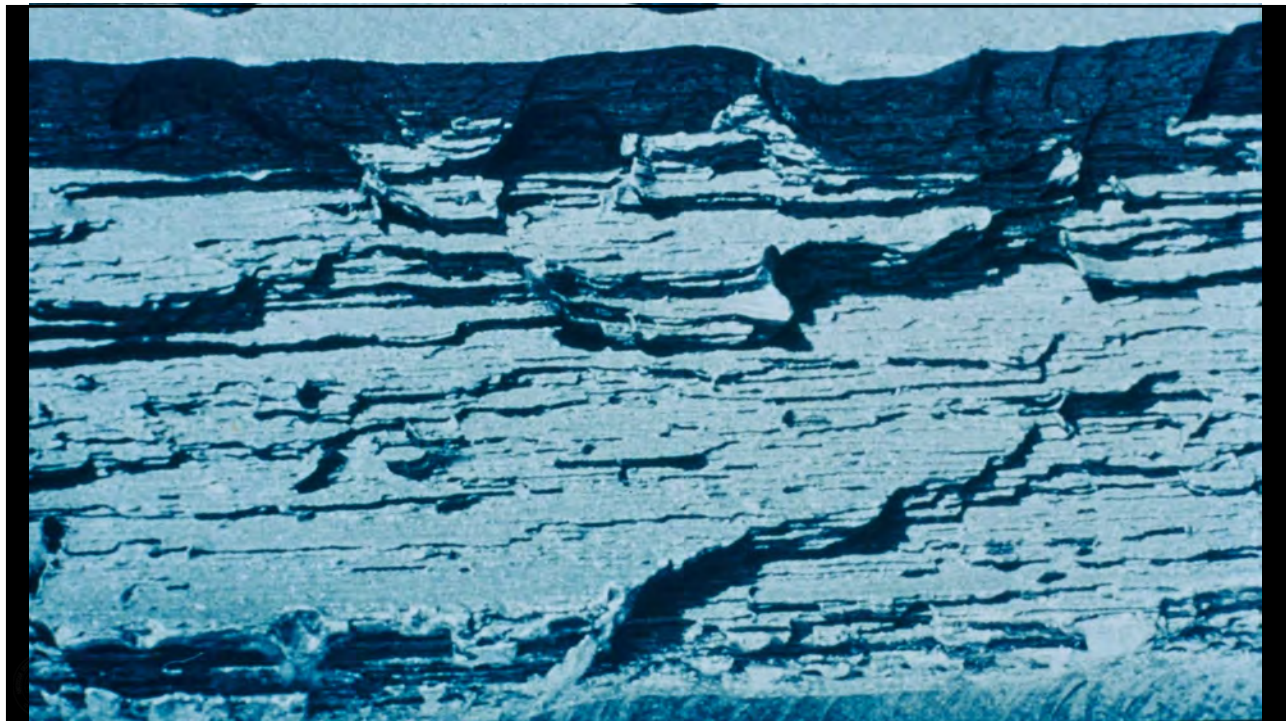
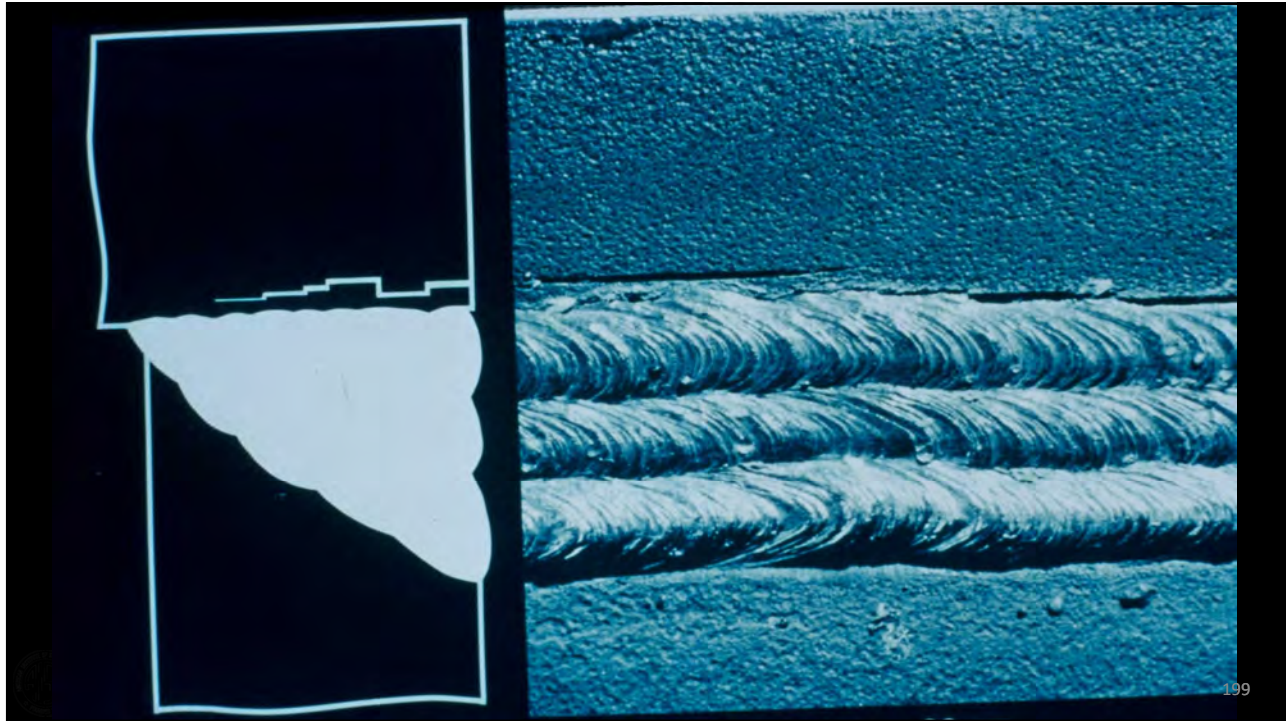


197

### LAMELLAR TEARING



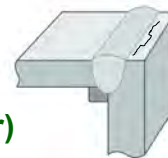
198





## LAMELLAR TEARING


**Cause:** Through thickness weld shrinkage strains cause planar inclusions to join together (tear)





### LAMELLAR TEARING

**Characteristics:**

- Typically occurs immediately outside the heat affected zone
- Typically is not delayed
- Is aggravated by hydrogen (but not caused by hydrogen)
- Occurs less frequently today (2012) than it did in the past (due to improved steel making practices)
- Typically associated with steel thicknesses  $>3/4$ "
- Not to be confused with de-lamination, which typically occurs at the mid-thickness



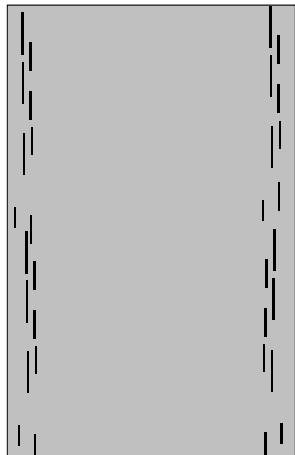



203


### LAMELLAR TEARING

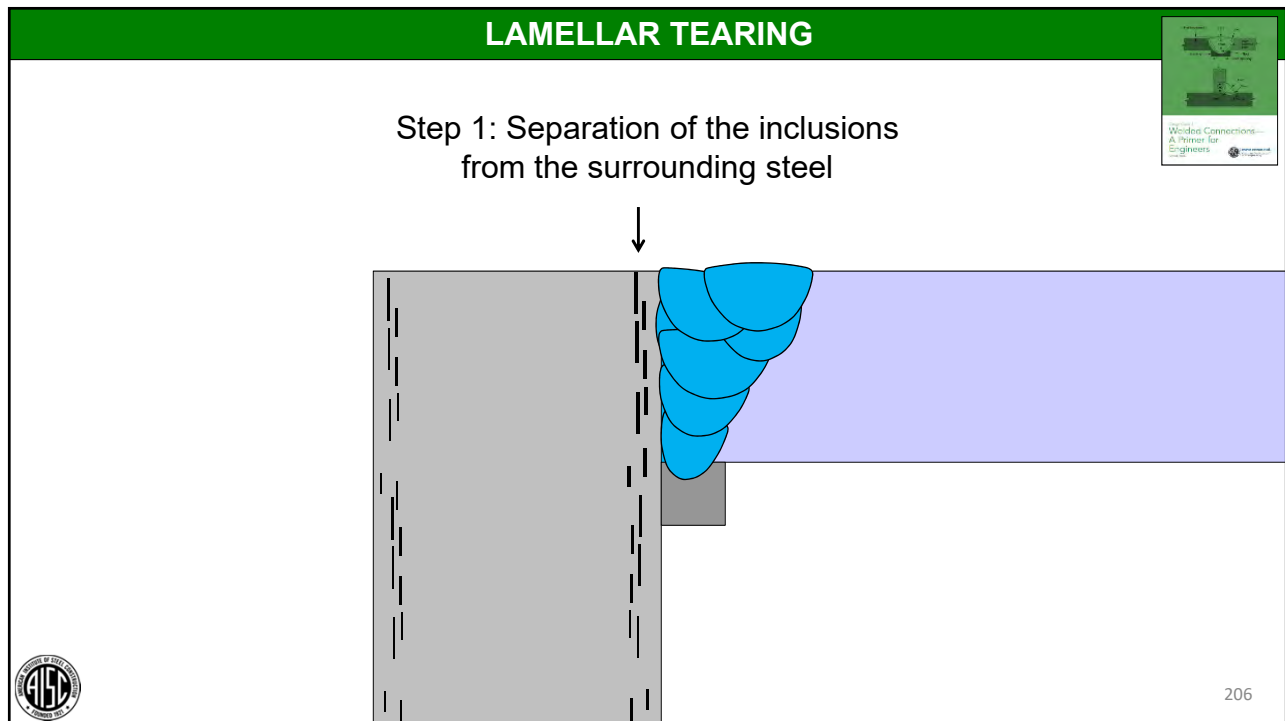
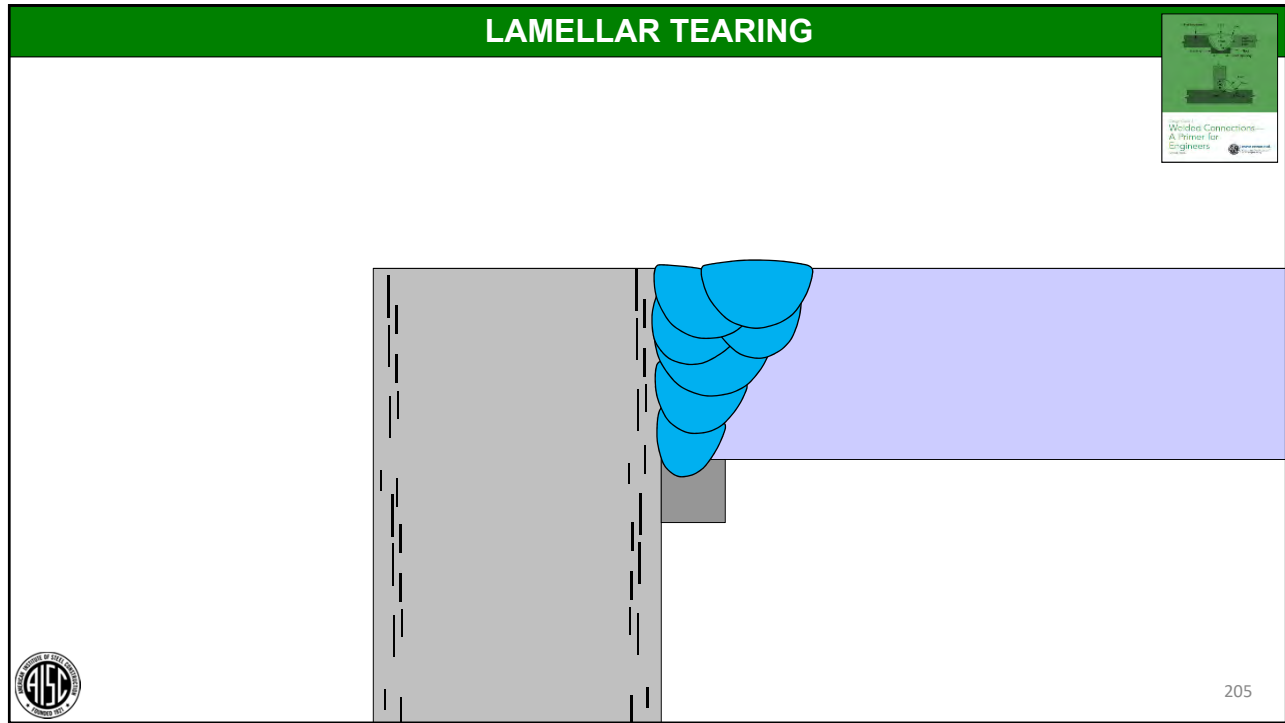
Inclusions, typically manganese sulfides

↓



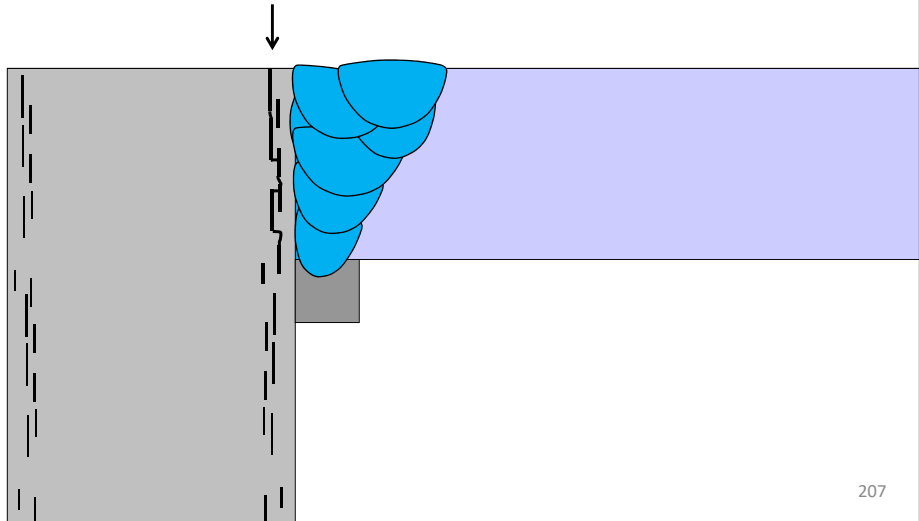


204




### LAMELLAR TEARING

Step 2: Ductile tearing of the ligaments between the inclusions




Welded Connections—  
A Primer for  
Engineers



207

### LAMELLAR TEARING


**Cause:** Through thickness weld shrinkage strains cause planar inclusions to join together (tear)



**Solution:**

- Use appropriate joint configurations

Welded Connections—  
A Primer for  
Engineers





208

### LAMELLAR TEARING

Non-preferred Details

**Fillets instead of CJP**                      **CJP with bevel on the problematic side**





209

### LAMELLAR TEARING

Preferred Details

**Fillets instead of CJP**                      **CJP with bevel on the problematic side**





210

### LAMELLAR TEARING

**Preferred Details**

PJP instead of CJP                      A corner-like tee joint





211

### LAMELLAR TEARING

**Preferred Details**

Weld applied to ends of plate





212

### LAMELLAR TEARING

**Buttering Solution**

Sensitive Detail                      Buttered Detail



213

### LAMELLAR TEARING

**Cause:** Through thickness weld shrinkage strains cause planar inclusions to join together (tear)



**Solution: Better Material**



- Reduce inclusions in the steel
- Control the inclusion shape in the steel



214


## LAMELLAR TEARING

**Cause:** Through thickness weld shrinkage strains cause planar inclusions to join together (tear)



**Solution: Better Detailing**

- Bevel the sensitive member
- Minimize weld volumes: PJP's vs. CJP's
- Minimize weld volumes: Optimized details
- Butter the joint



215

## LAMELLAR TEARING

**Cause:** Through thickness weld shrinkage strains cause planar inclusions to join together (tear)



**Solution: Better Fabrication**

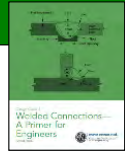
- Minimize shrinkage strains (peening can be helpful when properly done)
- Increased preheat, lower hydrogen
- Weld only once (plan the work)



216

## LAMELLAR TEARING

**Cause:** Through thickness weld shrinkage strains cause planar inclusions to join together (tear)



**Solution:**

- Better Material
- Better Detailing
- Better Fabrication



217

## PREHEAT



218

## AWS STANDARD WELDING TERMS & DEFINITIONS (A3.0:2010)



### **preheat temperature.**

The temperature of the base metal in the volume surrounding the point of welding immediately before welding is started. In a multiple pass weld, it is also the temperature immediately before the second and subsequent passes are started.



219

## AWS STANDARD WELDING TERMS & DEFINITIONS (A3.0:2010)



### **interpass temperature.**

In a multipass weld, the temperature of the weld area between weld passes.



220



AWS D1.1: 2015 Structural Welding Code – Steel								
Table 3.3 Prequalified Minimum Preheat and Interpass Temperature (see 3.5)								
C a t e g o r y	Steel Specification	Welding Process	Thickness of Thickest Part at Point of Welding		Minimum Preheat and Interpass Temperature			
			in	mm	°F	°C		
B	ASTM A36							
	ASTM A53	Grade B						
	ASTM A106	Grade B						
	ASTM A131	Grades A, B, CS, D, DS, E						
	ASTM A139	Grade B						
	ASTM A381	Grade Y35						
	ASTM A500	Grade A						
		Grade B						
		Grade C						
	ASTM A501	Grade A						
	ASTM A516			1/8 to 3/4 incl.	3 to 20 incl.	32 <sup>a</sup>	0 <sup>a</sup>	
	ASTM A524	Grades I & II						
	ASTM A573	Grade 65						
	ASTM A709	Grade 36	SMAW	Over 3/4 thru 1-1/2	Over 20 thru 38	150	65	221
ASTM A1008 SS	Grade 30	with other						

AWS D1.1: 2015 Structural Welding Code – Steel								
B (Cont'd)	ASTM A808							
	ASTM A913 <sup>b</sup>	Grade 50						
	ASTM A992							
	ASTM A1008 HSLAS	Grade 45 Class 1						
		Grade 45 Class 2						
		Grade 50 Class 1						
		Grade 50 Class 2						
		Grade 55 Class 1						
		Grade 55 Class 2						
	ASTM A1008 HSLAS-F	Grade 50						
	ASTM A1011 HSLAS	Grade 45 Class 1	SMAW with low- hydrogen electrodes, SAW, GMAW, FCAW	Over 3/4 thru 1-1/2 incl.	Over 20 thru 38 incl.	50	10	
		Grade 45 Class 2						
		Grade 50 Class 1						
		Grade 50 Class 2						
	Grade 55 Class 1							
	Grade 55 Class 2							
ASTM A1011 HSLAS-F	Grade 50		Over 1-1/2 thru 2-1/2 incl.	Over 38 thru 65 incl.	150	65		
ASTM A1018 HSLAS	Grade 45 Class 1		Over 2-1/2	Over 65	225	110		
	Grade 45 Class 2							
	Grade 50 Class 1							
	Grade 50 Class 2							
	Grade 55 Class 1							
	Grade 55 Class 2							

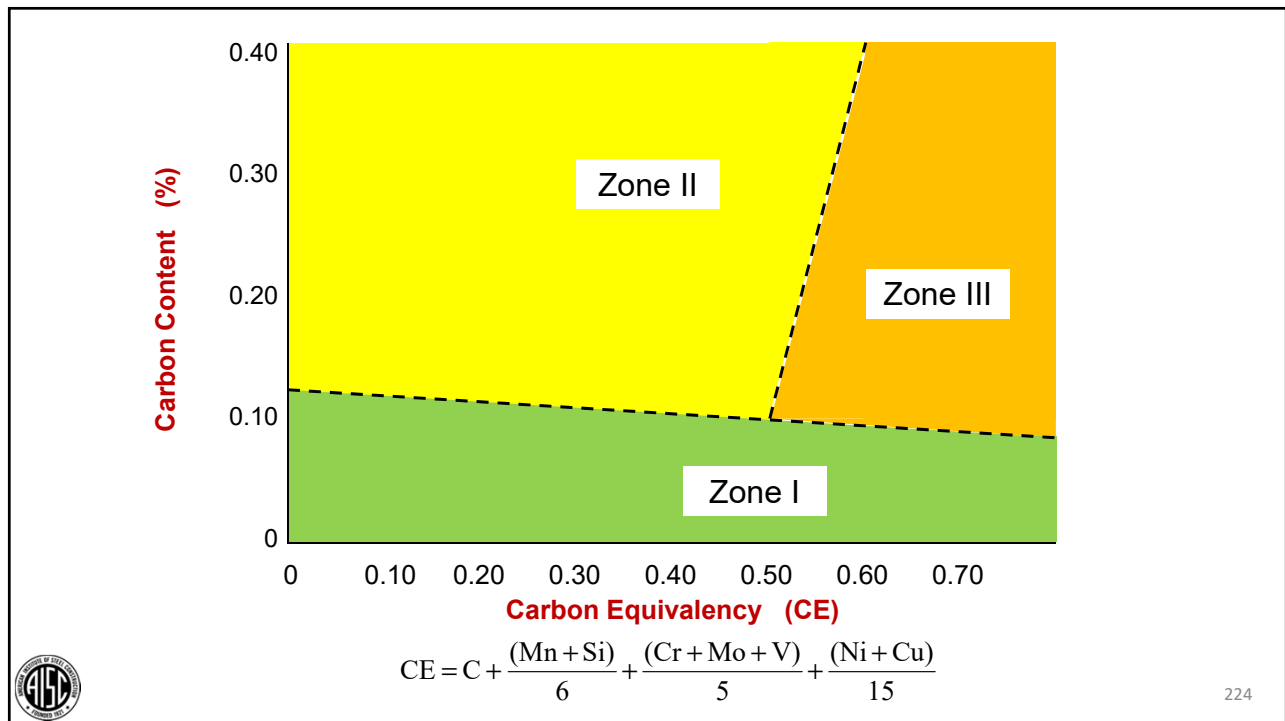
**AWS D1.1: 2015 Structural Welding Code – Steel**

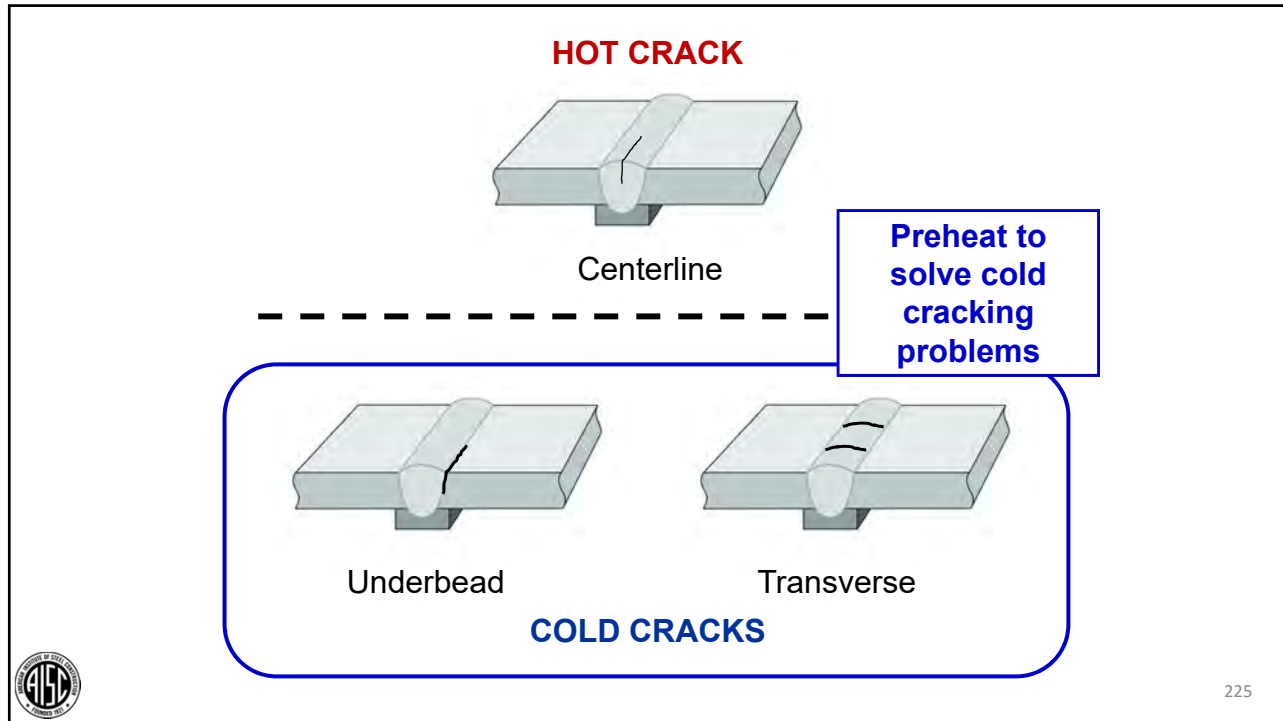
**Annex H**

Guideline on Alternative Methods for Determining Preheat



223






### POSTHEAT



**Postheat:**

- Heating weldments to 400-450°F immediately after welding
- Holding at elevated temperatures for an hour per inch of thickness of weld deposit
- Significantly reduces diffusible hydrogen levels
- Effective for “cold cracking” problems




226


## POSTHEAT



**Apply post heat before cold cracking can occur**  
(i.e., before the steel cools to below 400°F).


227

## POSTHEAT



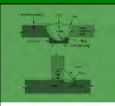
**Wrapping weldments in insulating blankets—essentially the same concept as post heat**

- Caveat 1: Wrapping slows cooling rate, but weldment cools from interpass temperature which is often less than 400 °F at time weldment is wrapped.
- Caveat 2: wrapping works best when the whole weldment is at elevated temperatures


228

### WRAPPING

The diagram shows two stages of the wrapping process. In the top stage, a rectangular steel component is shown with red arrows indicating uniform stress applied from all four sides. A blue horizontal line represents a weld or crack. In the bottom stage, the component is wrapped with a material, shown as a grey layer. Red arrows indicate the stress is still applied, but the wrapping material is shown to be under tension, with horizontal arrows pointing outwards from the component, suggesting it is restraining the component's expansion.




Welded Connections—  
A Primer for  
Engineers




229

### WRAPPING

The diagram shows two stages of the wrapping process. In the top stage, a rectangular steel component with rounded ends is shown with red arrows indicating uniform stress applied from all four sides. A blue horizontal line represents a weld or crack. In the bottom stage, the component is wrapped with a material, shown as a grey layer. Red arrows indicate the stress is still applied, but the wrapping material is shown to be under tension, with horizontal arrows pointing outwards from the component, suggesting it is restraining the component's expansion.



Welded Connections—  
A Primer for  
Engineers



230

**AASHTO/AWS D1.5: 2015 Bridge Welding Code**



**12.15.1.1 Minimum Temperature Prior to Hydrogen Diffusion Postheat.**

When hydrogen diffusion postheat is required, the weld shall not be allowed to cool below the minimum preheat and interpass temperature before being raised to the postheat temperature.



231

**AASHTO/AWS D1.5: 2015 Bridge Welding Code**



**12.15.1.2 Hydrogen Diffusion Postheat Temperature Limitations.**

When hydrogen diffusion postheat is required, welds and adjacent base metal shall be heated to a temperature of 230°C [450°F] minimum to 315°C [600°F] maximum for not less than one hour for each 25 mm [1 in.] of weld thickness, or two hours, whichever is less. The minimum heating time for repair welds shall be one hour for each 25 mm [1 in.] of repair weld depth from the surface, but not less than one hour. Longer heating periods may be used.



232

## METALLURGY AND CRACKING

### Outline

- Welding and Metallurgy
- Steel Categories
- Cracking
- ➔ • Special Steels



233

## 5.4 WELDING REQUIREMENTS FOR SPECIFIC STEELS

- 5.4.1 Weathering Steels
- 5.4.2 Quenched and Tempered Steels
- 5.4.3 Quenched and Self-Tempered Steels
- 5.4.4 Multigrade Steels
- 5.4.5 Historical (Obsolete) Steels
- 5.4.6 Cast Iron
- 5.4.7 Wrought Iron
- 5.4.8 Steel Castings
- 5.4.9 Steel Forgings
- 5.4.10 Stainless Steels
- 5.4.11 Bolts
- 5.4.12 Nuts
- 5.4.13 Washers
- 5.4.14 Anchor Rods



234

## 5.4 WELDING REQUIREMENTS FOR SPECIFIC STEELS

### Weathering Steels



235

## 5.4 WELDING REQUIREMENTS FOR SPECIFIC STEELS

### Weathering Steels

- A588 (A709 Grade 50W)
- HPS 50W, HPS 70W, and HPS 100W
- A606 (sheet steel)
- A847 (cold-formed tubing)
- A514
- A852
- A242



236

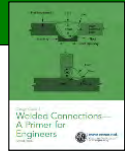
## 5.4 WELDING REQUIREMENTS FOR SPECIFIC STEELS

### Weathering Steels

- Unique welding concern: similar atmospheric corrosion resistance
- “Color match”
- If painted, no unusual welding concerns



237



## 5.4 WELDING REQUIREMENTS FOR SPECIFIC STEELS

### Weathering Steels

Three approaches:

- Use alloy filler metal
- Rely on admixture
- “Cap” the final surface with alloy filler metal



238



**AWS D1.1: 2015 Structural Welding Code – Steel**



**3.7.3 Weathering Steel Requirements.** For exposed, bare, unpainted applications of weathering steel requiring weld metal with atmospheric corrosion resistance and coloring characteristics similar to that of the base metal, the electrode or electrode-flux combination shall conform to Table 3.4. The exceptions to this requirement are as follows:

**3.7.3.1 Single-Pass Groove Welds.** Groove welds made with a single pass or a single pass each side may be made using any of the filler metals for Group II base metals in Table 3.2.

**3.7.3.2 Single-Pass Fillet Welds.** Single-pass fillet welds up to the following sizes may be made using any of the filler metals for Group II base metals listed in Table 3.2:



**AWS D1.1: 2015 Structural Welding Code – Steel**



**Table 3.4 (see 3.7.3)  
Filler Metal Requirements for Exposed Bare  
Applications of Weathering Steels**

Process	AWS Filler Metal Specification	Approved Electrodes <sup>a</sup>
SMAW	A5.5	All electrodes that deposit weld metal meeting a B2L, C1, C1L, C2, C2L, C3, or WX analysis per A5.5.
SAW	A5.23	All electrode-flux combinations that deposit weld metal with a Ni1, Ni2, Ni3, Ni4, or WX analysis per A5.23.
FCAW	A5.29 and A5.36	All electrodes that deposit weld metal with a B2L, K2, Ni1, Ni2, Ni3, Ni4, or WX analysis per A5.29 or A5.36.
GMAW	A5.28 and A5.36	All electrodes that meet filler metal composition requirements of B2L, G <sup>a</sup> , Ni1, Ni2, Ni3, analysis per A5.28 or A5.36.

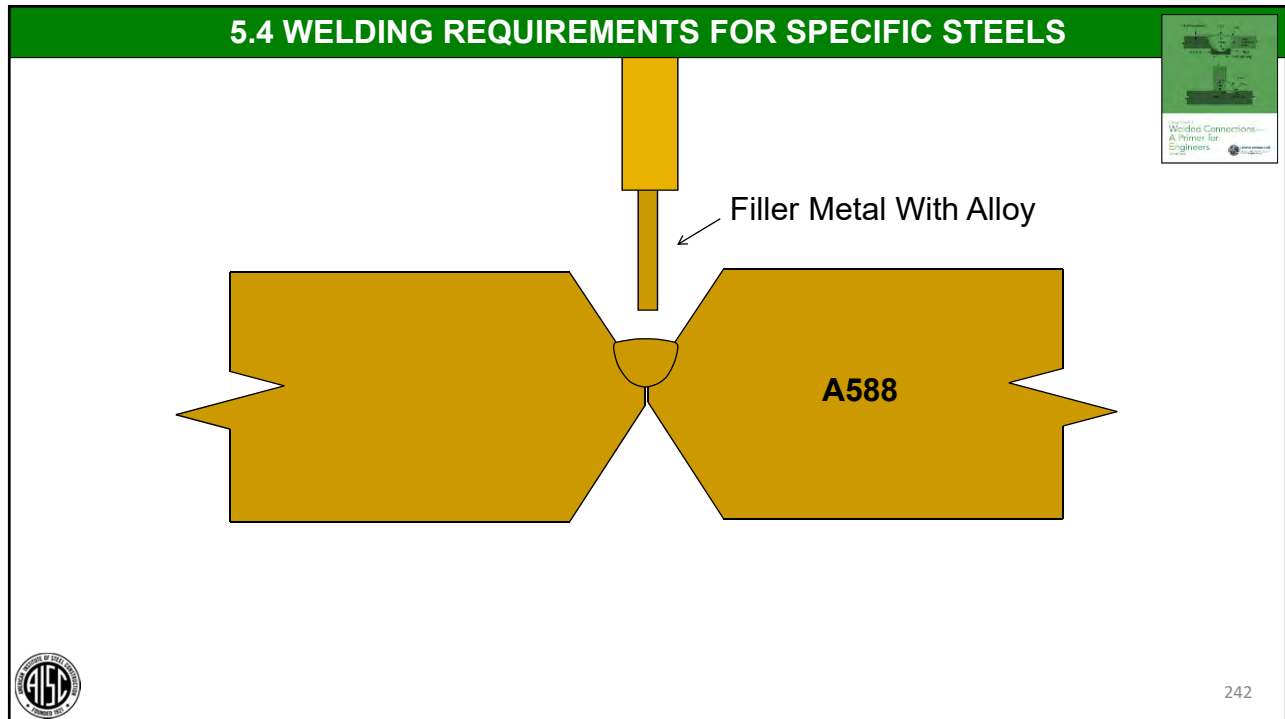


**AWS D1.1: 2015 Structural Welding Code – Steel**

**Table 3.4 (see 3.7.3)**  
**Filler Metal Requirements for Exposed Bare Applications of Weathering Steels**

Process	AWS Filler Metal Specification	Approved Electrodes <sup>a</sup>
SMAW	A5.5	All electrodes that deposit weld metal meeting a B2L, C1, C1L, C2, C2L, C3, or WX analysis per A5.5.
SAW	A5.23	All electrode-flux combinations that deposit weld metal with a Ni1, Ni2, Ni3, Ni4, or WX analysis per A5.23.

241



**AWS D1.1: 2015 Structural Welding Code – Steel**



**3.7.3 Weathering Steel Requirements (cont'd)**.....The exceptions to this requirement are as follows:

**3.7.3.1 Single-Pass Groove Welds.** Groove welds made with a single pass or a single pass each side may be made using any of the filler metals for Group II base metals in Table 3.2.

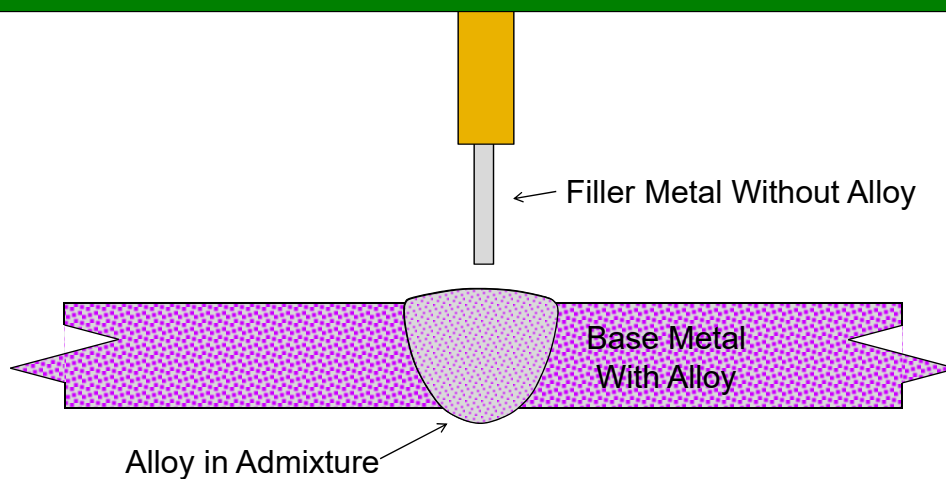
**3.7.3.2 Single-Pass Fillet Welds.** Single-pass fillet welds up to the following sizes may be made using any of the filler metals for Group II base metals listed in Table 3.2:

SMAW	1/4 in [6 mm]
SAW	5/16 in [8 mm]
GMAW/FCAW	5/16 in [8 mm]



243

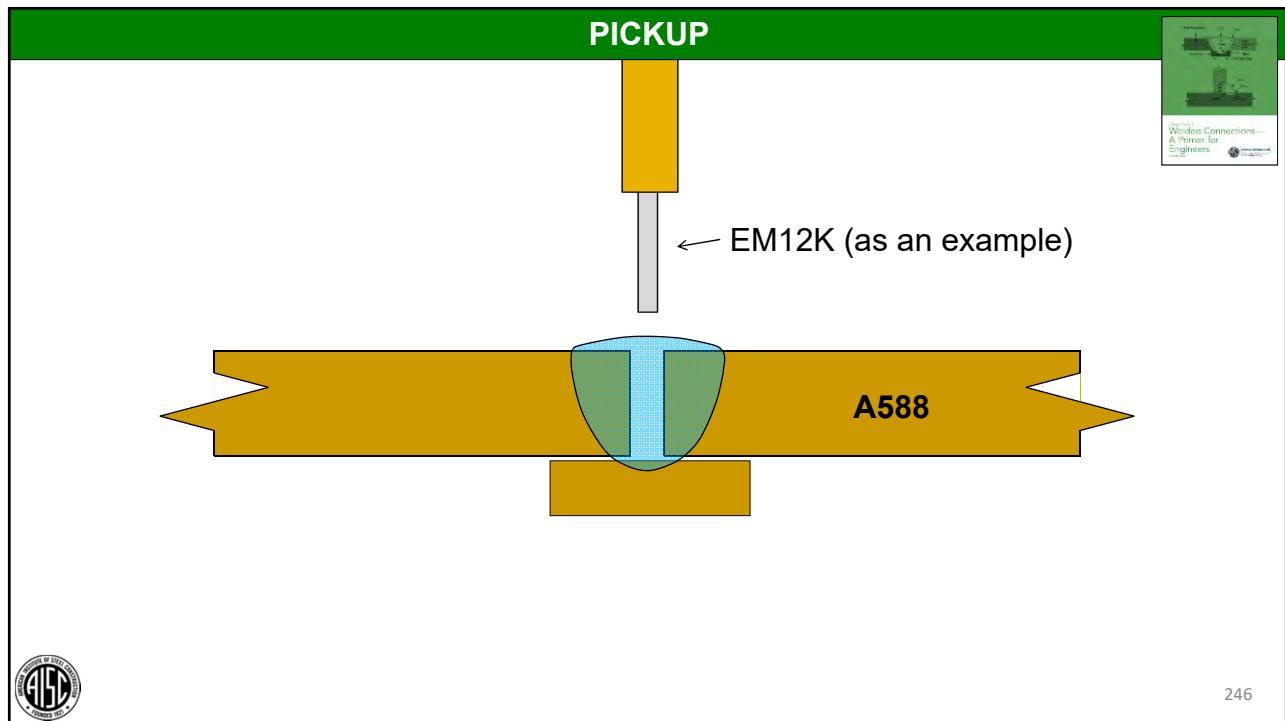
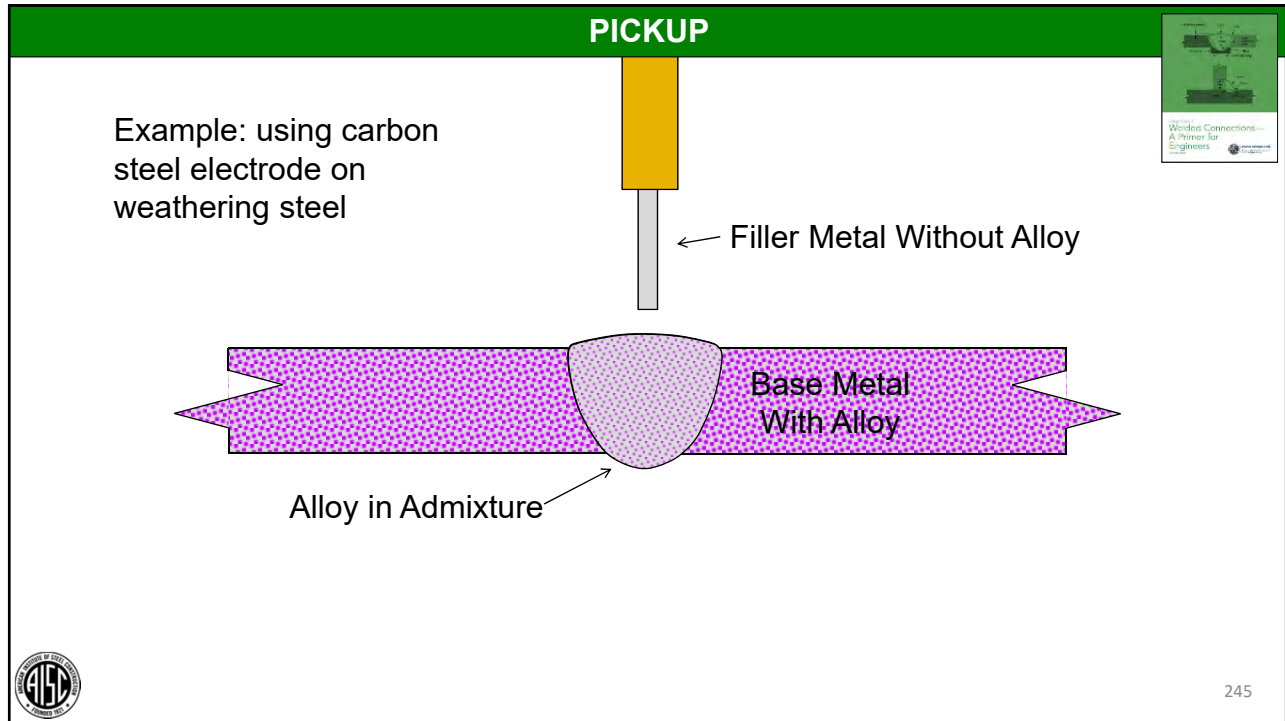
**PICKUP**



**Alloy in Filler Metal < Alloy in Base Metal → Pickup**

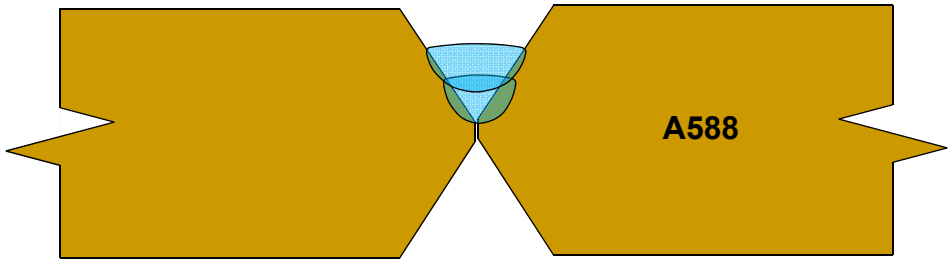


244





### 5.4 WELDING REQUIREMENTS FOR SPECIFIC STEELS

## Weathering Steels



**A588**

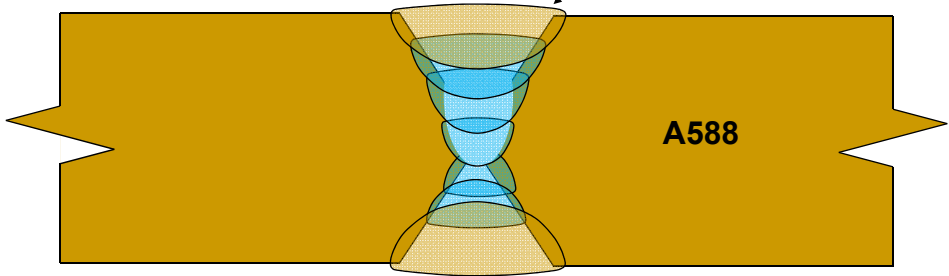


247

This diagram illustrates a weathering steel weld joint. Two steel plates, labeled 'A588', are joined by a weld. The weld pool is depicted as a small, shallow, blue-shaded area at the center of the joint, indicating a minimal weld deposit.



### 5.4 WELDING REQUIREMENTS FOR SPECIFIC STEELS

## Weathering Steels



**A588**

\*Faces, ends of weld




248


This diagram illustrates a weathering steel weld joint with a large, deep weld pool. The weld pool is shown as a blue-shaded area with a textured surface. An arrow points to the top surface of the weld pool, labeled "Cap with alloy deposit\*". The steel plates are labeled 'A588'. Below the diagram, the text "\*Faces, ends of weld" is displayed.

5.4 WELDING REQUIREMENTS FOR SPECIFIC STEELS

Quenched and Steels (Q&T)




249



5.4 WELDING REQUIREMENTS FOR SPECIFIC STEELS


Quenched and Steels (Q&T)



**Table 5-1. Quenched and Tempered Steels**

Steel Specification		Specified Minimum Yield Strength, ksi (MPa)	Specified Minimum Tensile Strength, ksi (MPa)	Processing Method	D1.1 Coverage
<b>API 2Y</b>	<b>Gr. 42</b>	42–67 (290–462)	62 (427)	Q&T	Prequalified (AWS Table 3.1)
	<b>Gr. 50</b>	50–75 (345–517)	65 (448)		
	<b>Gr. 60</b>	60–90 (414–621)	75 (517)		
<b>ASTM A709</b>	<b>HPS 70W</b>	70 (485) min.	85–110 (585–760)	Q&T	
<b>ASTM A514</b>	<b>&gt; 2½ in. (65 mm)</b>	90 (620) min.	100–130 (690–895)	Q&T	Code approved (AWS Table 4.9)
	<b>≤ 2½ in. (65 mm)</b>	100 (690) min.	110–130 (760–895)		

250



**AWS D1.1: 2015 Structural Welding Code – Steel**



**5.7 Heat Input Control for Quenched and Tempered Steels**

When quenched and tempered steels are welded, the heat input shall be restricted in conjunction with the maximum preheat and interpass temperatures required. Such considerations shall include the additional heat input produced in simultaneous welding on the two sides of a common member. The preceding limitations shall be in conformance with the producer’s recommendations.



**AASHTO/AWS D1.5: 2015 Bridge Welding Code**



**Table 12.5**  
**M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W]**  
**Minimum and Maximum Preheat/Interpass Temperature, °C [°F] (see 12.14)**

Thickness t, mm [in]	Heat Input (as calculated by 5.12) kJ/mm [kJ/in]				
	1.2 [30] ≤ HI < 1.6 [40]	1.6 [40] ≤ HI < 2.0 [50]	2.0 [50] ≤ HI < 2.8 [70]	2.8 [70] ≤ HI < 3.6 [90]	3.6 [90] ≤ HI
6 [1/4] ≤ t ≤ 10 [3/8]	40–60 [100–150]	—	—	—	—
10 [3/8] < t ≤ 13 [1/2]	60–160 [150–300]	40–100 [100–200]	—	—	—
13 [1/2] < t ≤ 20 [3/4]	120–200 [250–400]	100–180 [200–350]	40–120 [100–250]	—	—
20 [3/4] < t ≤ 25 [1]	—	120–200 [250–400]	120–200 [250–400]	60–160 [150–300]	—
25 [1] < t ≤ 50 [2]	—	—	120–200 [250–400]	120–200 [250–400]	100–180 [200–350]
t > 50 [2]	—	—	150–240 [300–450]	140–240 [300–450]	140–240 [300–450]



AASHTO/AWS D1.5: 2015 Bridge Welding Code		
Thickness t, mm [in]	1.2 [30] ≤ HI < 1.6 [40]	1.6 [40] ≤ HI < 2.0 [50]
6 [1/4] ≤ t ≤ 10 [3/8]	40–60 [100–150]	—
10 [3/8] < t ≤ 13 [1/2]	60–160 [150–300]	40–100 [100–200]
13 [1/2] < t ≤ 20 [3/4]	120–200 [250–400]	100–180 [200–350]
20 [3/4] < t ≤ 25 [1]	—	120–200 [250–400]
25 [1] < t ≤ 50 [2]	—	—
t > 50 [2]	—	—



253

5.4 WELDING REQUIREMENTS FOR SPECIFIC STEELS	
Quenched and Steels (Q&T)	
<ul style="list-style-type: none"> <li>• Heat input limits, preheat and maximum interpass temperature limits</li> <li>• Heat shrinking temperature limits</li> <li>• Welding process limits (ESW, EGW)</li> <li>• Plug and slot weld prohibitions</li> <li>• Tack weld restrictions</li> <li>• Special welder qualification requirements</li> </ul>	



254

## 5.4 WELDING REQUIREMENTS FOR SPECIFIC STEELS

### Historical (Obsolete) Steels

- ASTM A7
- ASTM A9
- ASTM A373
- ASTM A242

Discussed in terms of weldability



255



## 5.4 WELDING REQUIREMENTS FOR SPECIFIC STEELS

### Historical (Obsolete) Steels

The weldability of A7 must be evaluated on a case-by-case basis. The ASTM A7 specification was in effect for 67 years and mill practices varied over the years. However, in 1957, the 11th edition of *The Procedure Handbook of Arc Welding* (Lincoln Foundation, 1957) stated “Although specifications are not intended to control carbon content, experiences with the material, as it has been delivered, indicate that the carbon content is within the readily weldable range.” Thus, by the late 1950s the general experience with the material being delivered was that the weldability was good.



256



### 5.4 WELDING REQUIREMENTS FOR SPECIFIC STEELS



#### Historical (Obsolete) Steels

Steel of unknown weldability

Attempt to break this way first

Break fillet weld this way

(a) (b) (c)



257

### 5.4 WELDING REQUIREMENTS FOR SPECIFIC STEELS

#### Historical (Obsolete) Steels

Poor weldability (a)

Good weldability (b)



258

## METALLURGY AND CRACKING

### Outline

- Welding and Metallurgy
- Steel Categories
- Cracking
- Special Steels



259

# Thank you!

**AISC** | Questions?



**Smarter.  
Stronger.  
Steel.**

## Individual Session Registrants

---

### PDH Certificates

- You will receive an email on how to report attendance from:  
[registration@aisc.org](mailto:registration@aisc.org).
- Be on the lookout: Check your spam filter! Check your junk folder!
- Completely fill out online form. Don't forget to check the boxes next to each attendee's name!



## Individual Session Registrants

---

### PDH Certificates

- Reporting site (URL will be provided in the forthcoming email).
- Username: Same as AISC website username.
- Password: Same as AISC website password.



## 8-Session Registrants

---

### PDH Certificates

One certificate will be issued at the conclusion of all 8 sessions.



## 8-Session Registrants

---

### Access to the quiz

Information for accessing the quiz will be emailed to you by Thursday. It will contain a link to access the quiz. EMAIL COMES FROM [NIGHTSCHOOL@AISC.ORG](mailto:NIGHTSCHOOL@AISC.ORG).

### Quiz and attendance records

Posted Thursday mornings. [www.aisc.org/nightschool](http://www.aisc.org/nightschool) -- Click on Current Course Details.

### Reasons for quiz

- EEU – You must take all quizzes and the final exam to receive EEU.
- PDHs – If you watch a recorded session, you must pass quiz for PDHs.
- REINFORCEMENT – Reinforce what you learn tonight. Get more out of the course.

*Note: If you attend the live presentation, you do not have to take the quizzes to receive PDHs*



## 8-Session Registrants

---

### Access to the recording

Information for accessing the recording will be emailed to you by Thursday. The recording will be available for four weeks. (For 8-session registrants only.) EMAIL COMES FROM [NIGHTSCHOOL@AISC.ORG](mailto:NIGHTSCHOOL@AISC.ORG).

### PDHs via recording

If you watch a recorded session, you must take *and pass* the quiz for PDHs.



## 8-Session Registrants

---

### Night School Resources

Find all your handouts, quizzes and quiz scores, recording access, and attendance information all in one place!



## 8-Session Registrants

### Night School Resources

Go to [www.aisc.org](http://www.aisc.org) and sign in.



#### Login

If you're an existing customer, please enter your username and password.

<p><b>USERNAME</b></p> <input type="text" value="Enter your username"/>	<p><b>DON'T HAVE AN ACCOUNT?</b></p> <p>My AISC allows you to access Engineering Journal articles and Design Guides you have downloaded from the bookstore.</p> <p><b>REGISTER NOW</b></p>
<p><b>PASSWORD</b></p> <input type="text" value="Enter your password"/>	
<input type="checkbox"/> Remember Me	



## 8-Session Registrants

### Night School Resources

Go to [www.aisc.org](http://www.aisc.org) and sign in.

<p><b>IN THIS SECTION</b></p> <ul style="list-style-type: none"><li>Edit Profile</li><li>My Downloads</li><li>My Pending Quizzes</li><li>My Events</li><li>Order History</li><li>Course History</li><li><b>Course Resources</b></li></ul>	<p><b>MyAISC</b></p> <hr/> <p><b>MY PROFILE</b></p> <p>Update your contact and address information.</p> <p><b>EDIT PROFILE</b></p> <hr/> <p><b>MY PURCHASED DOWNLOADS</b></p> <p>Access articles and documents that you have purchased.</p> <p><b>VIEW DOWNLOADS</b></p> <hr/> <p><b>MY COURSE RESOURCES</b></p> <p>View online resources for Night School and Live Webinar package registrations.</p> <p><b>VIEW RESOURCES</b></p>
---	---



# 8-Session Registrants

## Night School Resources

Course Resources

Event	Start Date
NS 13 8-Session Package-Night School 13 - Design of Industrial Buildings	1/30/2017 7:00:00 PM
NS 14 8-Session Package-Night School 14 - Fundamentals of Stability	6/5/2017 7:00:00 PM

# 8-Session Registrants

## Night School Resources

Night School 13: Design of Industrial Buildings

**8-SESSION PACKAGE RESOURCES**

Event	Date	Handouts	Video	Quiz	Attendance
NS13 - Design Criteria	1/30/2017 7:00:00 PM	<a href="#">Handouts</a>	<a href="#">View</a> Passcode: NS13DSN	Pass Score: 80	Pending
NS13 - Economic Considerations	2/6/2017 7:00:00 PM	<a href="#">Handouts</a>	Available 02/08/2017 5pm EST	Available 02/08/2017 5pm EST	Pending
NS13 - Lateral Load Systems and Details	2/13/2017 7:00:00 PM	<a href="#">Handouts</a>	Available 02/15/2017 5pm EST	Available 02/15/2017 5pm EST	Pending
NS13 - Preliminary Design Procedures	2/27/2017 7:00:00 PM	<a href="#">Handouts</a>	Available 03/01/2017 5pm EST	Available 03/01/2017 5pm EST	Pending
NS13 - Crane Girder Design and Frame Analysis	3/6/2017 7:00:00 PM	<a href="#">Handouts</a>	Available 03/08/2017 5pm EST	Available 03/08/2017 5pm EST	Pending
NS13 - Frame Member and Connection Design	3/13/2017 7:00:00 PM	<a href="#">Handouts</a>	Available 03/15/2017 5pm EST	Available 03/15/2017 5pm EST	Pending
NS13 - Transfer Crane Girder & Longitudinal Bldg Bracing Dn	3/27/2017 7:00:00 PM	<a href="#">Handouts</a>	Available 03/29/2017 5pm EST	Available 03/29/2017 5pm EST	Pending
NS13 - Building Envelope and Bracing Design	4/10/2017 7:00:00 PM	<a href="#">Handouts</a>	Available 04/08/2017 5pm EST	Available 04/08/2017 5pm EST	Pending

270

## 8-Session Registrants

---

### Night School Resources

- Weekly “quiz and recording” email.
- Weekly updates of the master quiz and attendance record, found at [www.aisc.org/nightschool21](http://www.aisc.org/nightschool21). Scroll down to Quiz and Attendance records.
  - Updated on Thursday mornings.



## 8-Session Registrants

---

### Night School Resources

- Webinar connection information
  - Reminder email sent out Tuesday mornings
- Links to handouts also found here





**AISC** | Thank you



**Smarter.  
Stronger.  
Steel.**

273