2020 Mid-Atlantic Quality Assurance Workshop

Causes and Prevention of Weld Cracking

by

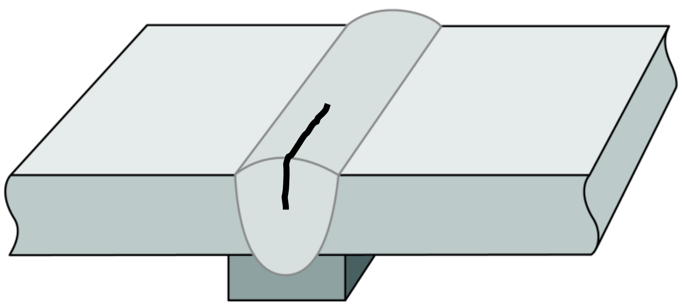
Duane K. Miller, P.E., Sc.D

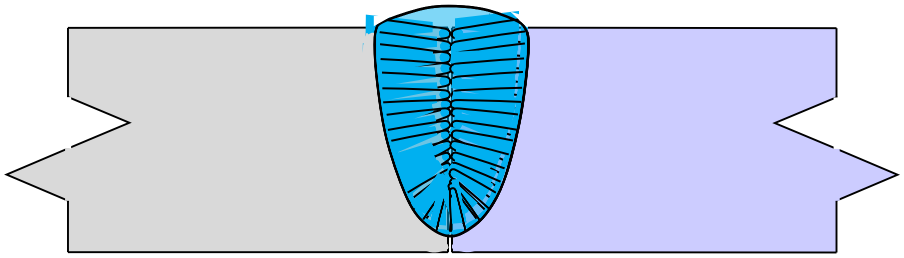
LINCOLN ELECTRIC

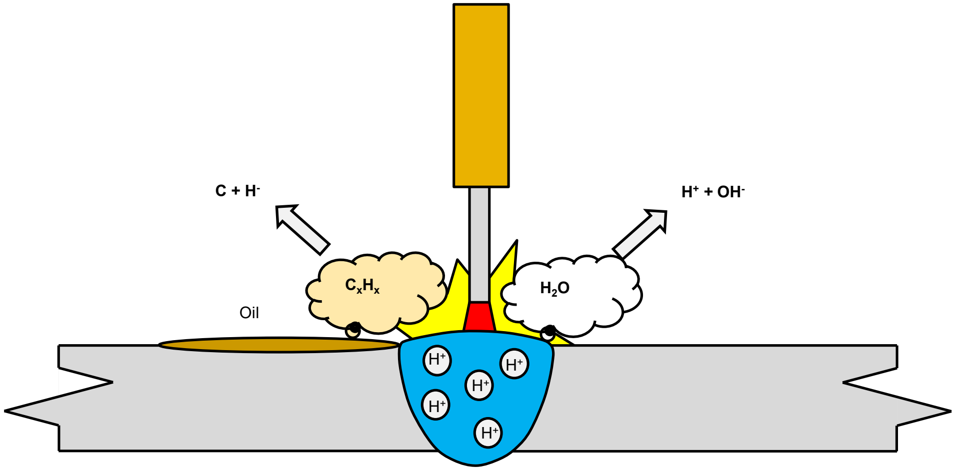
Causes and Prevention of Weld Cracking

and Tearing

in bridge welding applications







Causes and Prevention of Weld Cracking

If you have a weld cracking problem...

….the first question to ask is this: "**When** did the cracking occur?"

Possible answers

- During fabrication
- In service
- I don't know

If you have a weld cracking problem...

….the second question to ask is this: "**Where** is the crack located?"

Possible answers

- In the weld
- Next to the weld
- I don't know

Causes and Prevention of Weld Cracking

and Tearing

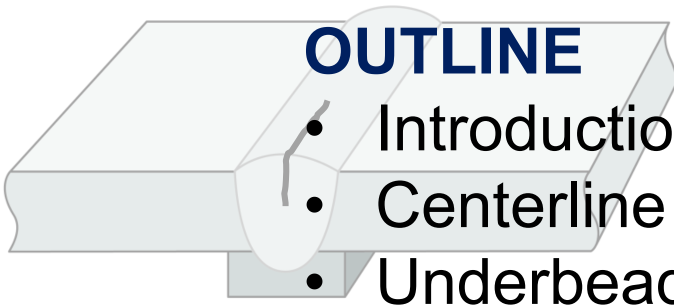
in bridge welding applications

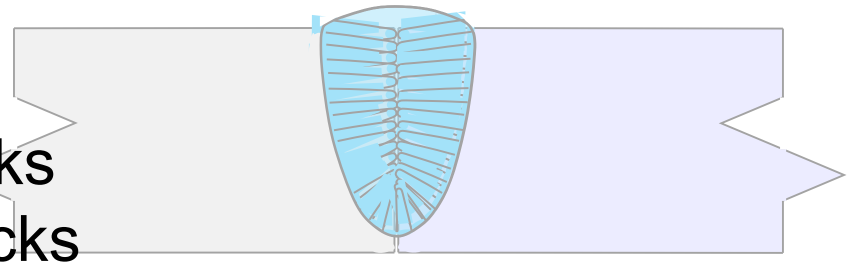
- New construction: A709 steels
- New construction: Unlisted steels
- Existing inventory: Historic, obsolete steels

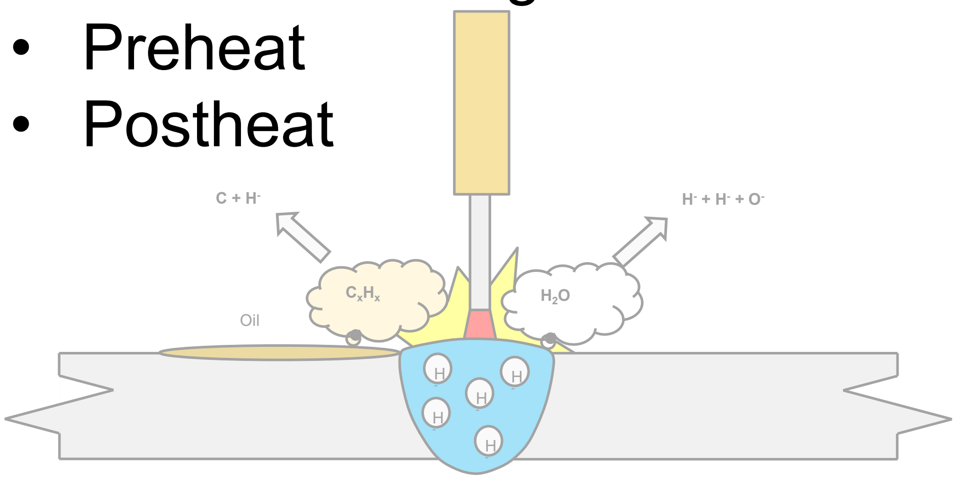
Causes and Prevention of Weld Cracking

OUTLINE

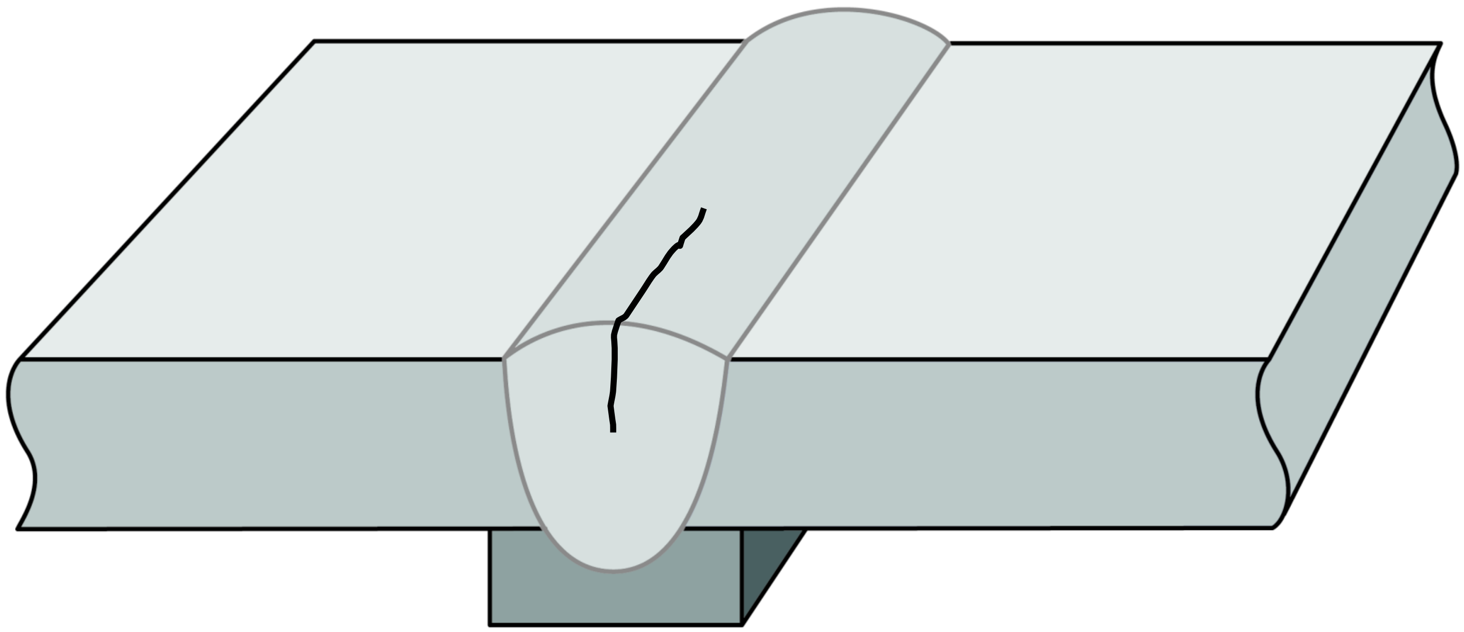
- Introduction
- Centerline cracks
- Underbead cracks
- Transverse cracks
- Lamellar tearing
- Preheat
- Postheat



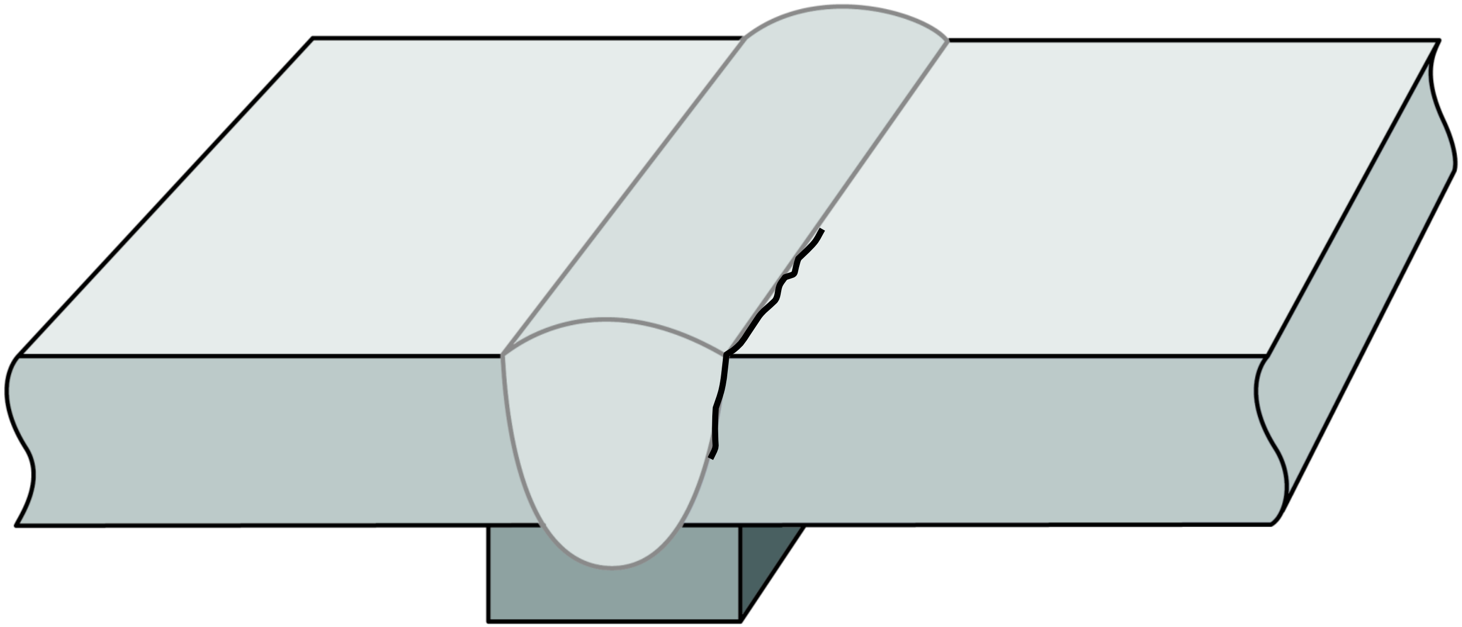




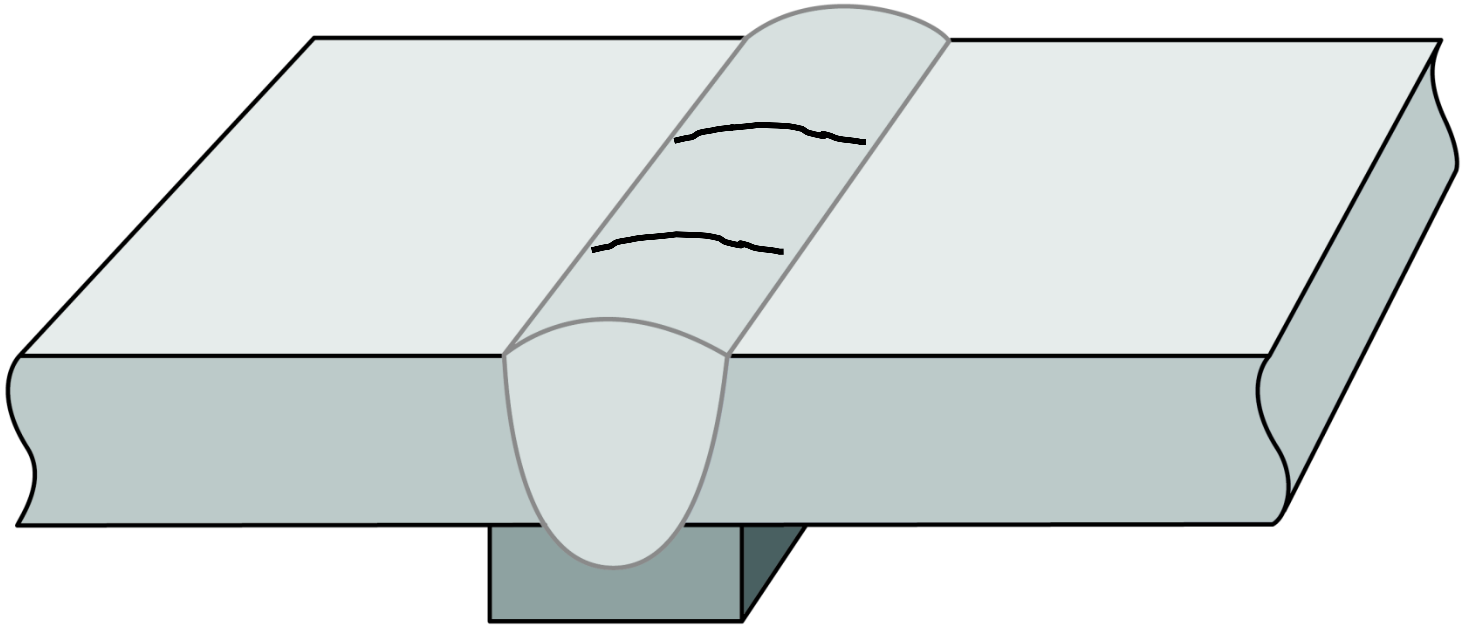
Centerline Cracking



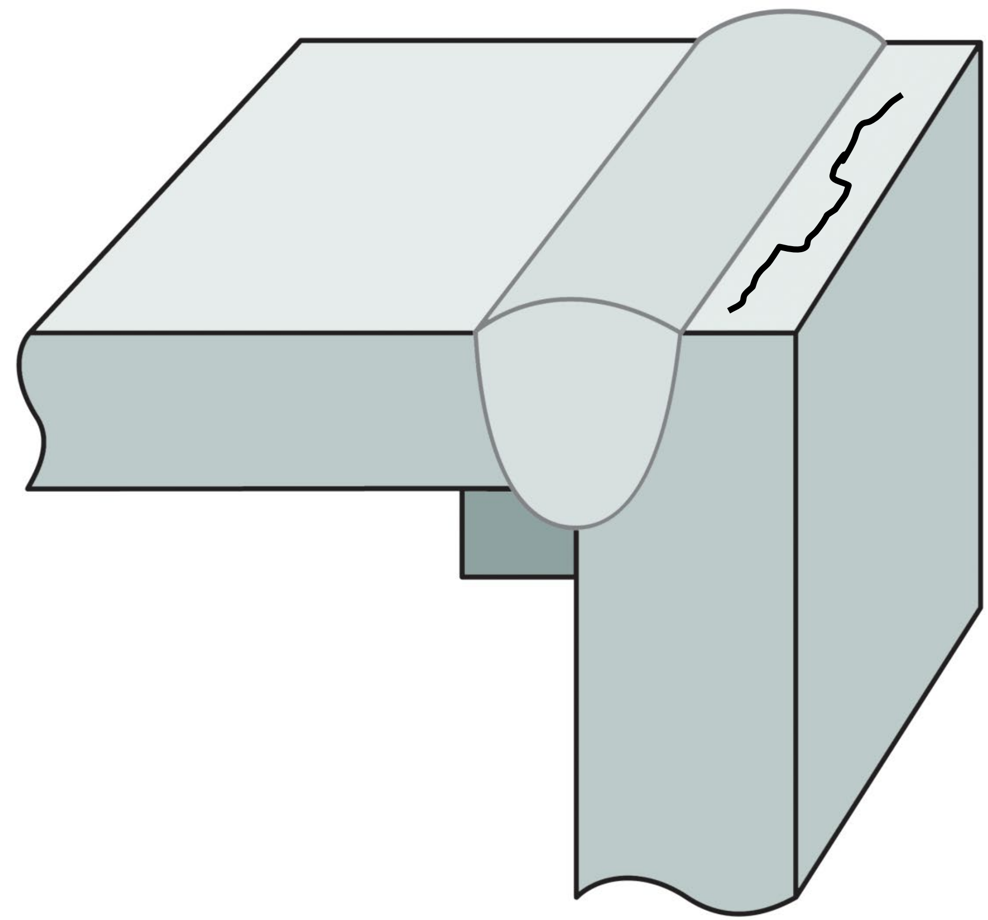
Underbead Cracking



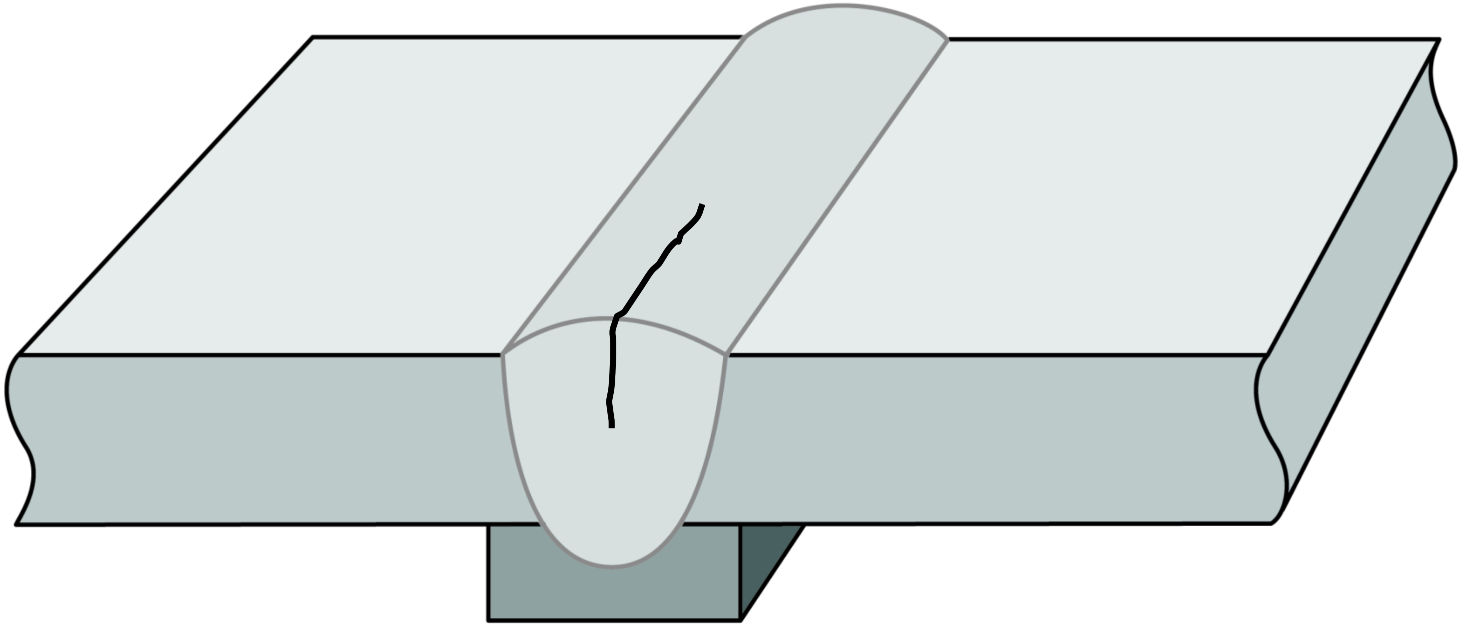
Transverse Cracking



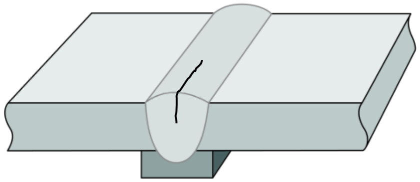
Lamellar Tearing



Centerline Cracking

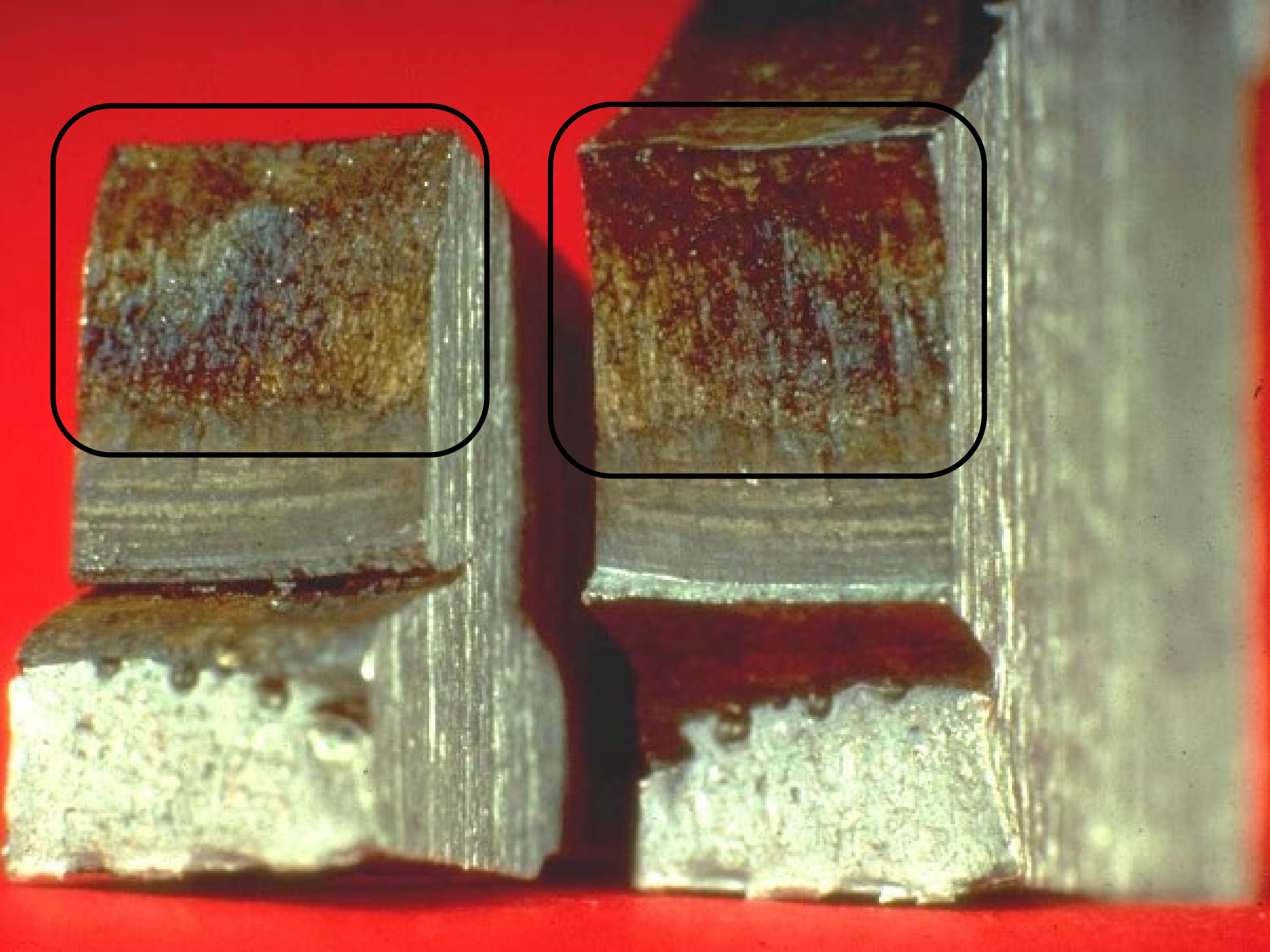


Centerline Cracking

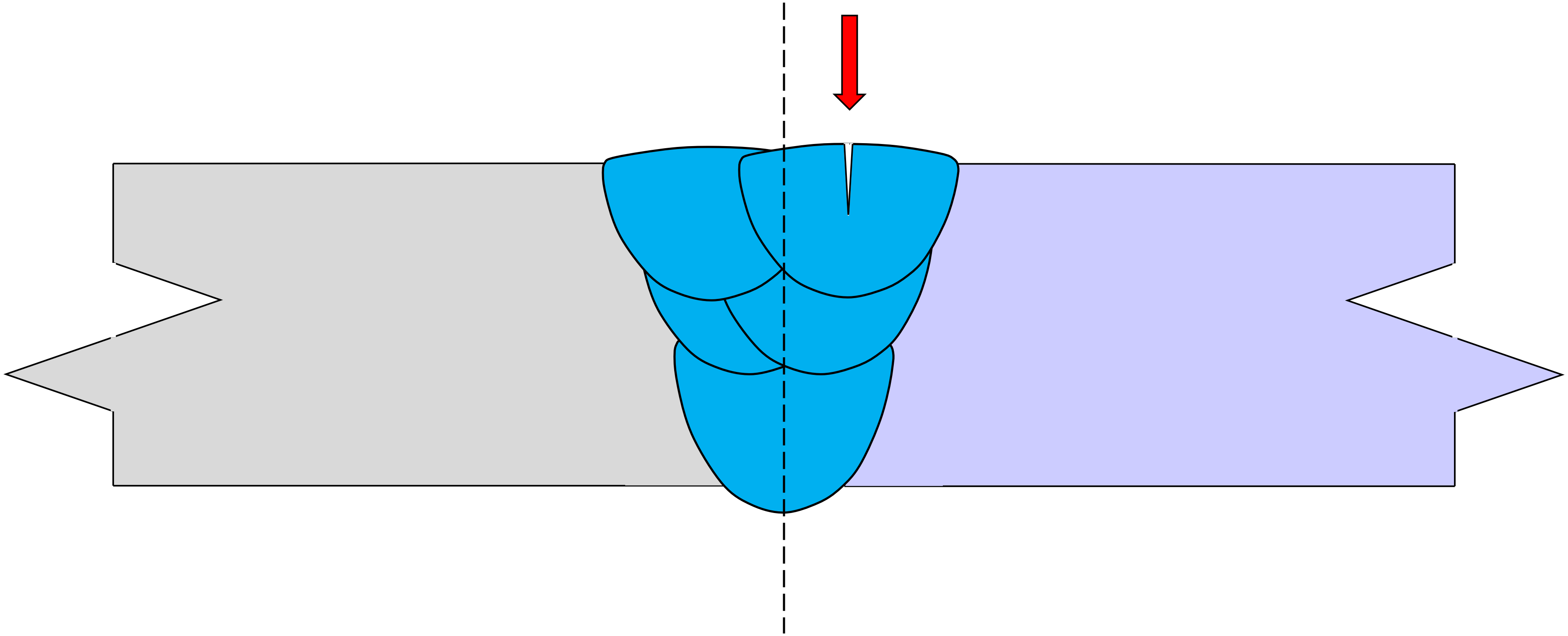


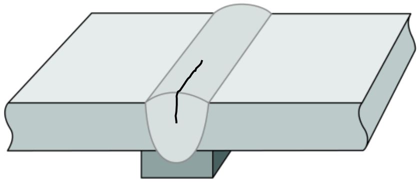
Characteristics

- Near the center of a weld 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



Centerline Cracking

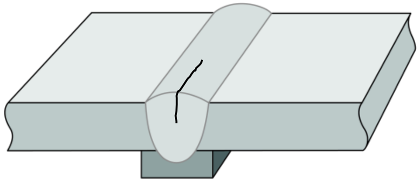




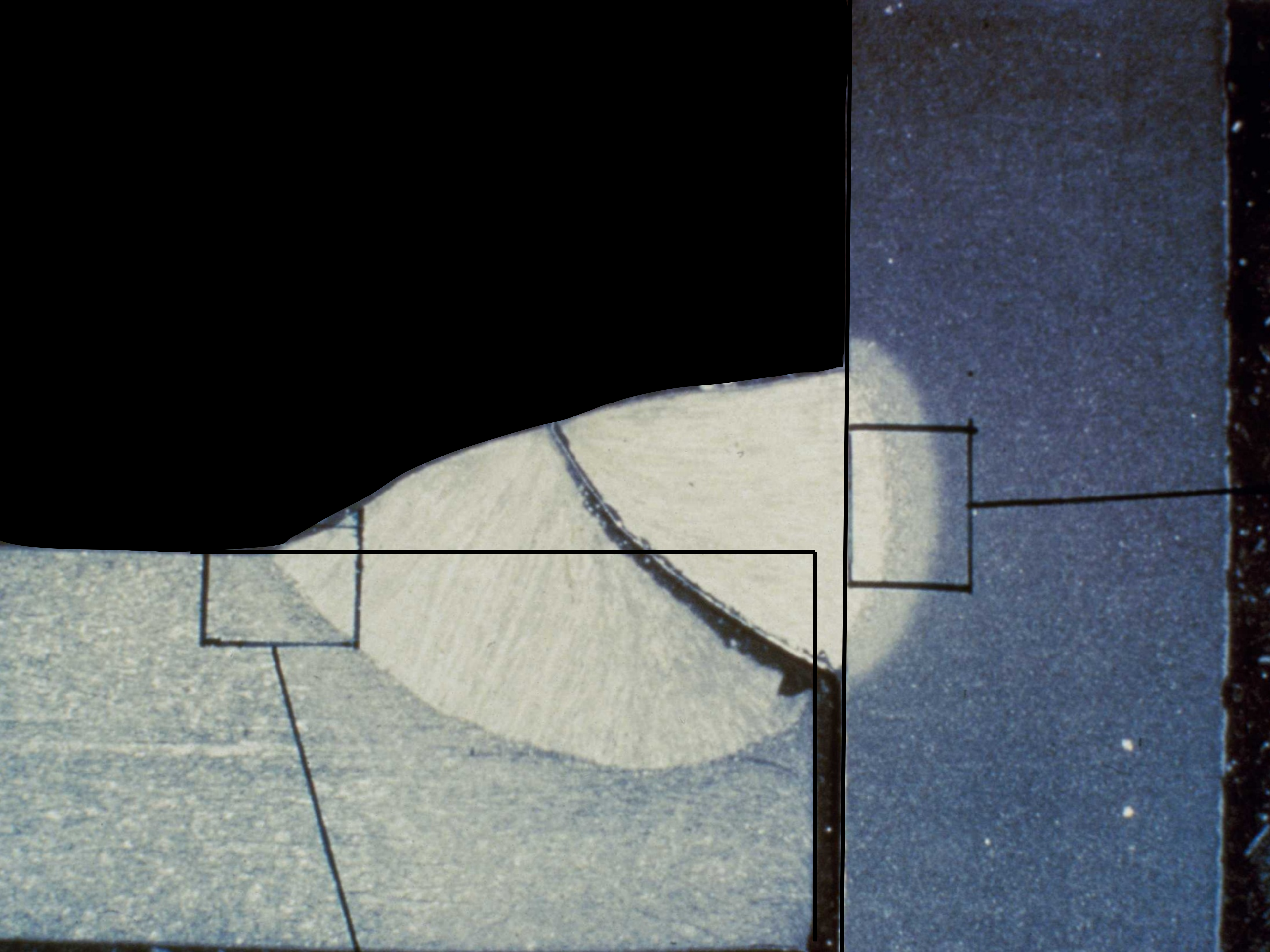
Centerline cracks are near the weld bead centerline; may not be in the center of the joint.

Centerline Cracking

Cause 1: Segregation Cracking



Low melting point ingredients segregate to the center during solidification



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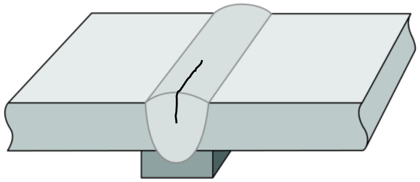
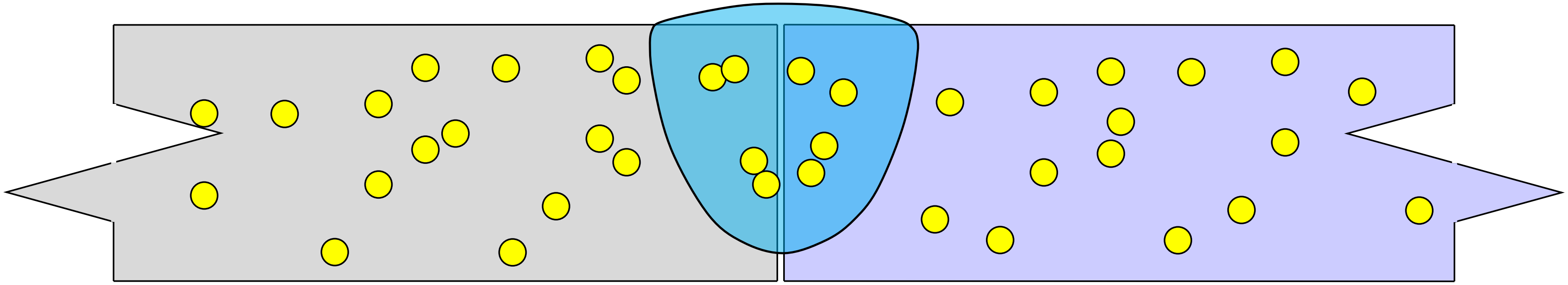
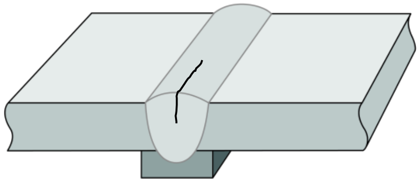
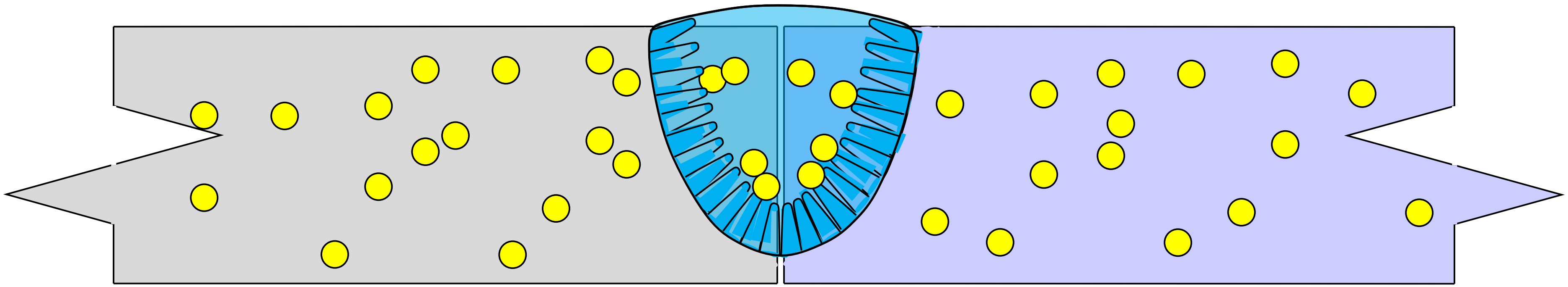




Centerline Cracking





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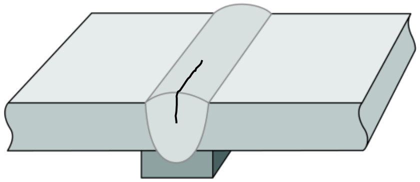

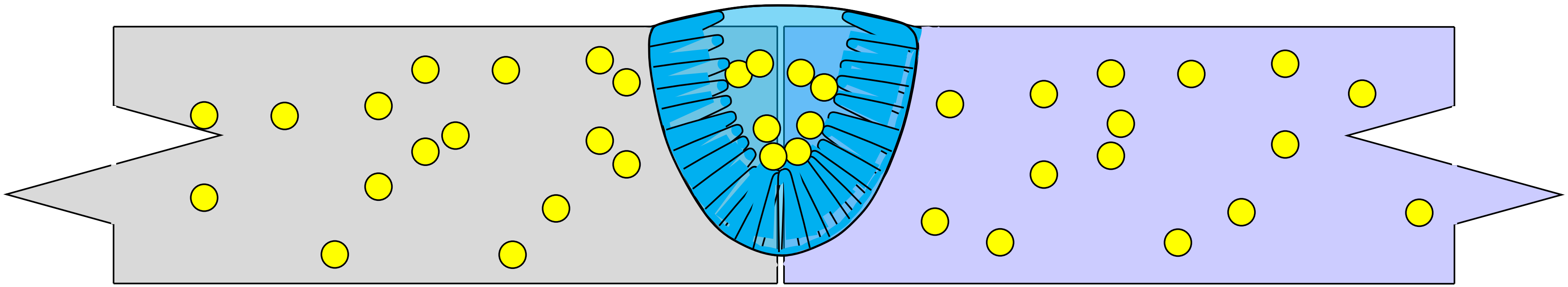

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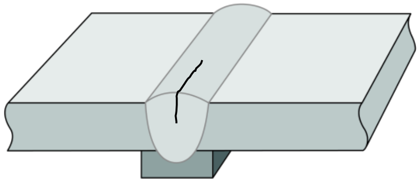

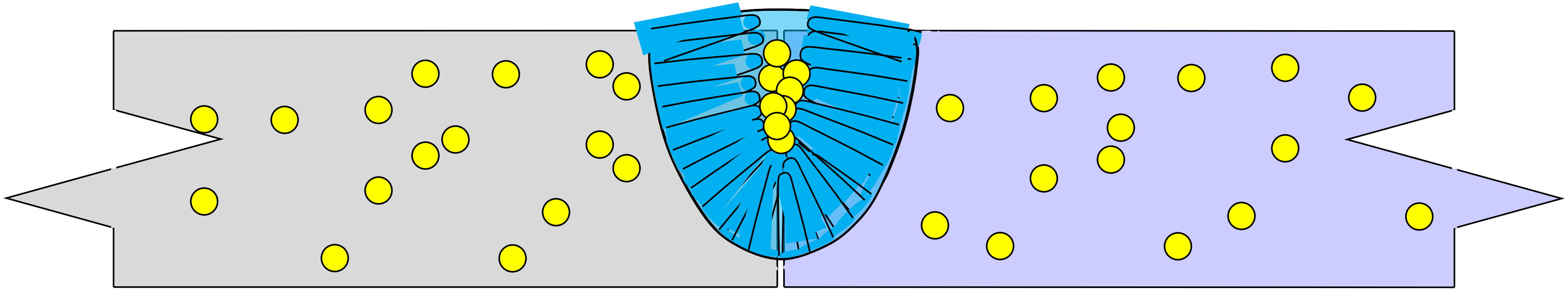

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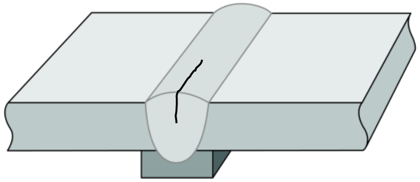

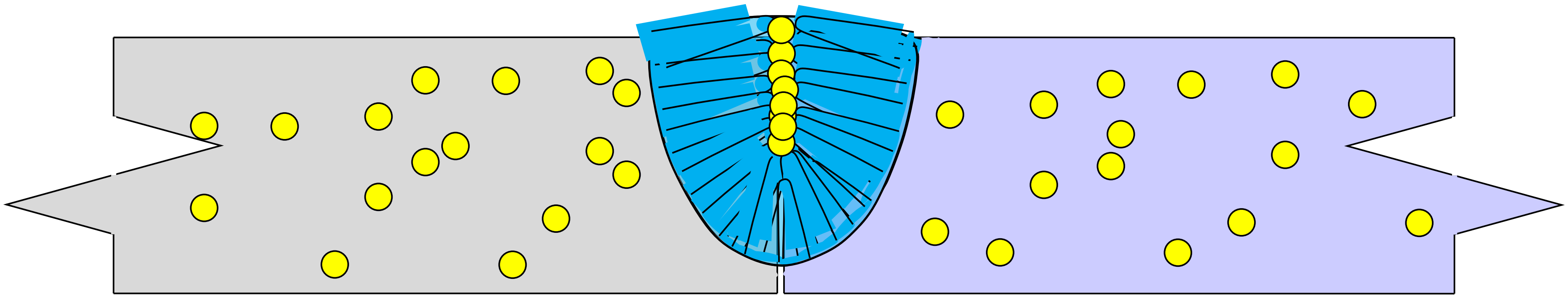

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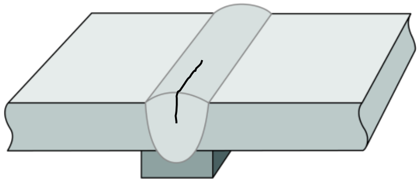


Cause 1: Segregation Cracking

Low melting point ingredients segregate to the center during solidification

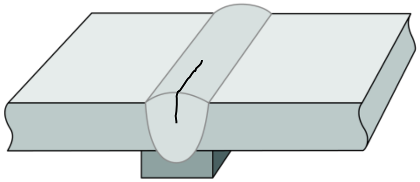
Solution: Minimize low melting point ingredients in the molten weld metal

- Use "good" steel

  Low levels of
  - Phosphorous (P)
  - Sulfur (S)
  - Zinc (Zn)
  - Tin (Sn)
  - Copper (Cu)
  - Carbon (C)

Centerline Cracking

Cause 1: Segregation Cracking



TWI Hot Cracking Susceptibility

(Unit of Crack Susceptibility)

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

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

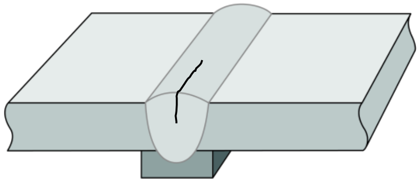
UCS > 30 “Strong Susceptibility to Cracking”

Based on WELD METAL Composition

From Welding Metallurgy by Linnert, 4th Edition, Volume 1

Centerline Cracking

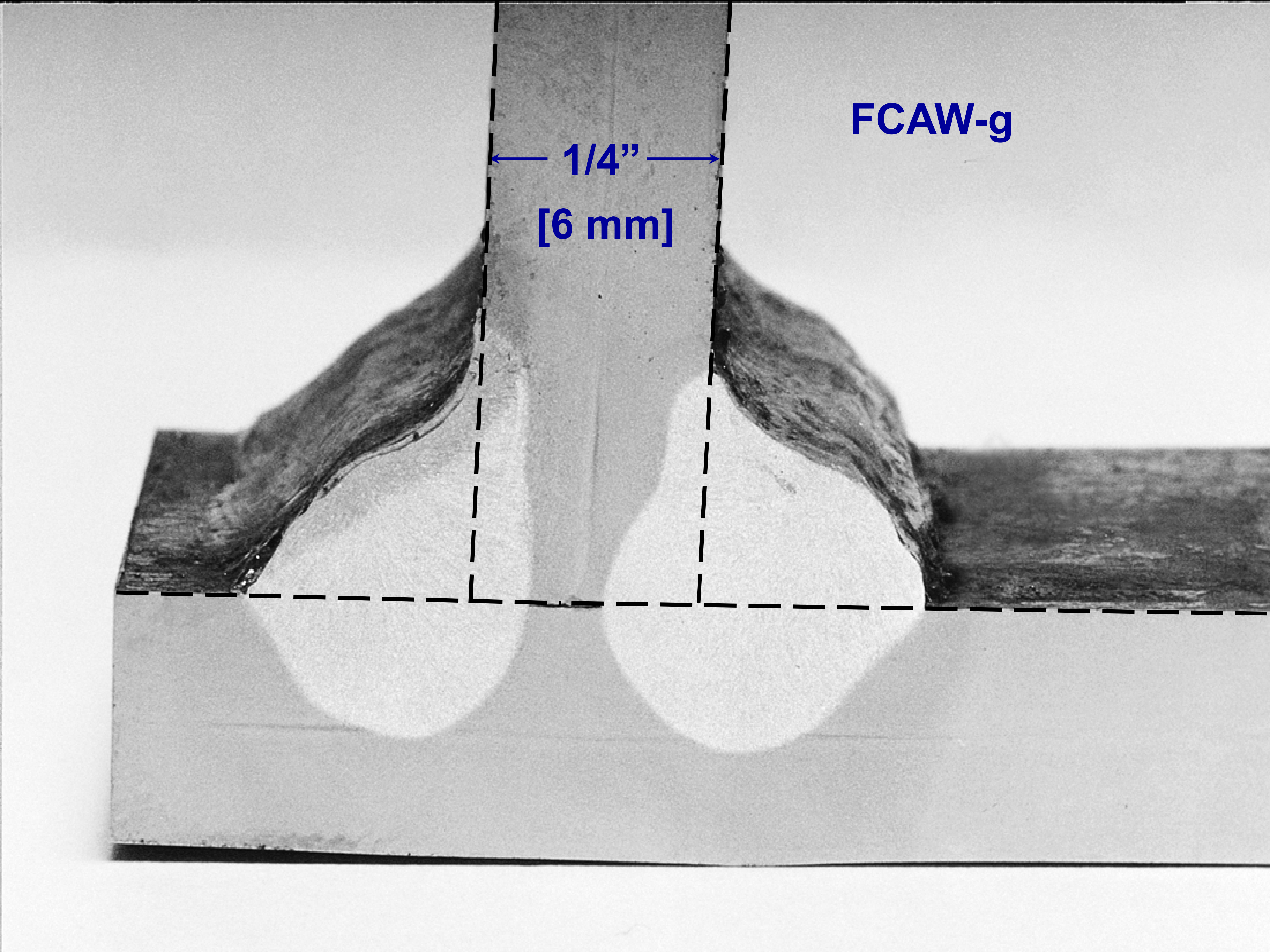
Cause 1: Segregation Cracking

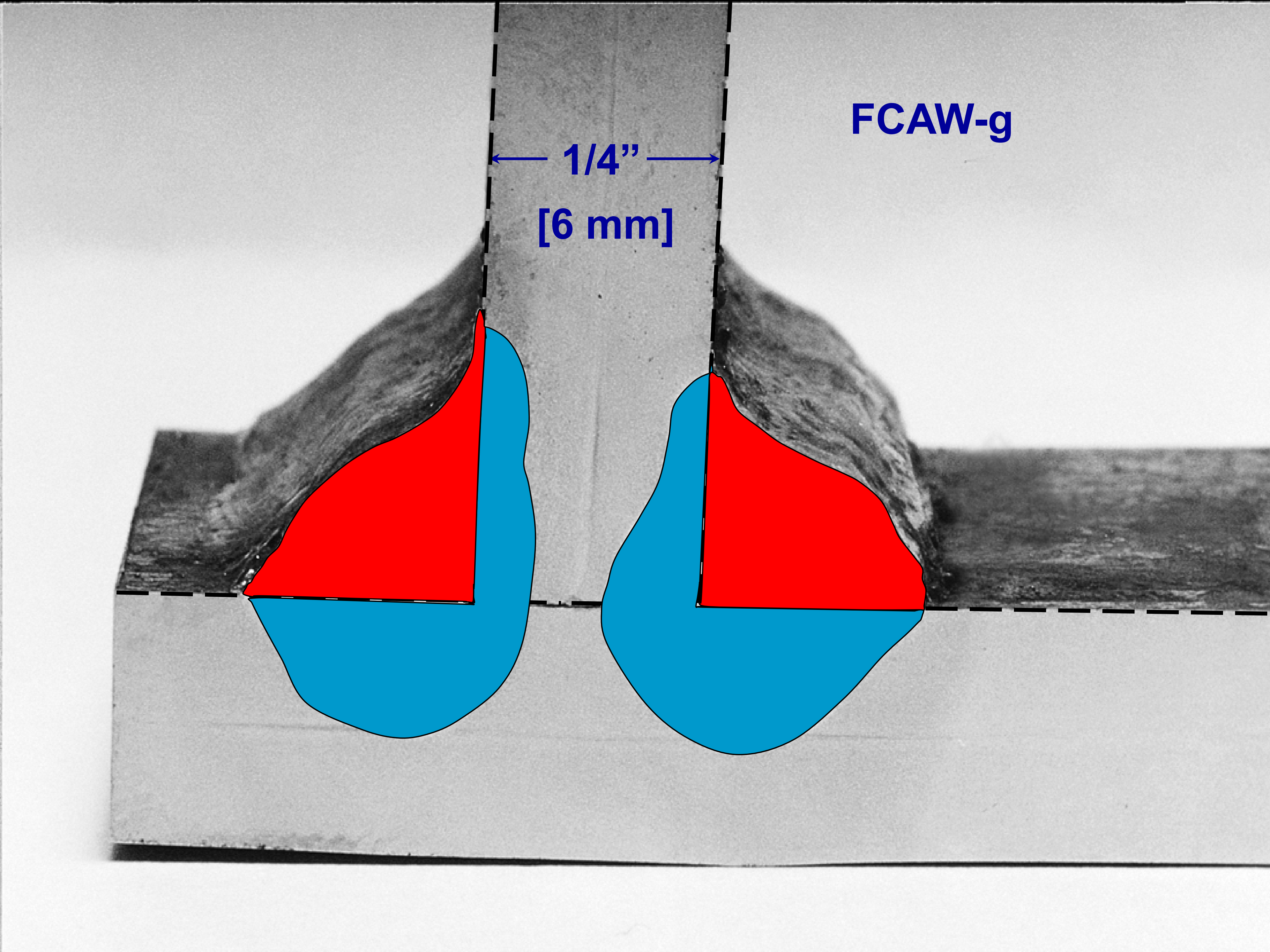


Low melting point ingredients segregate to the center during solidification

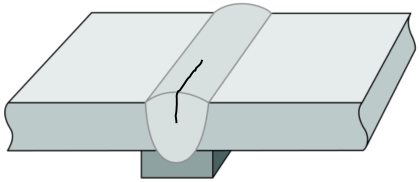
Solution: Minimize low melting point ingredients in the molten weld metal

- Use "good" steel
- Minimize admixture


FCAW-g
1/4”
[6 mm]


FCAW-g
1/4"
[6 mm]

Centerline Cracking



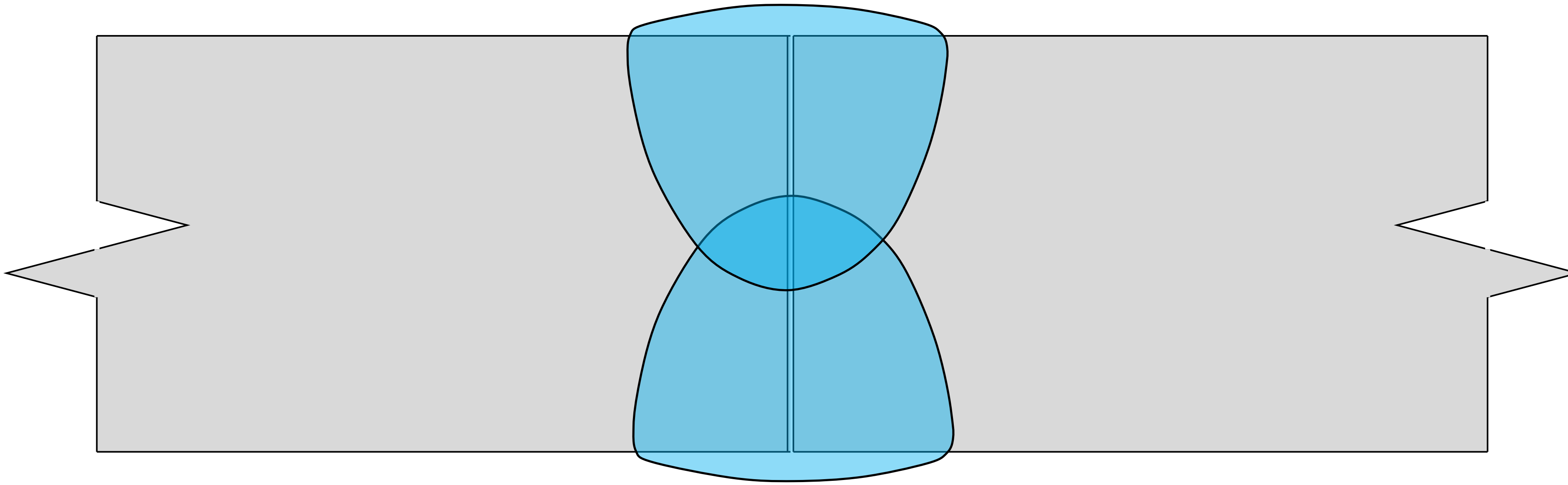
Cause 1: Segregation Cracking

Low melting point ingredients segregate to the center during solidification

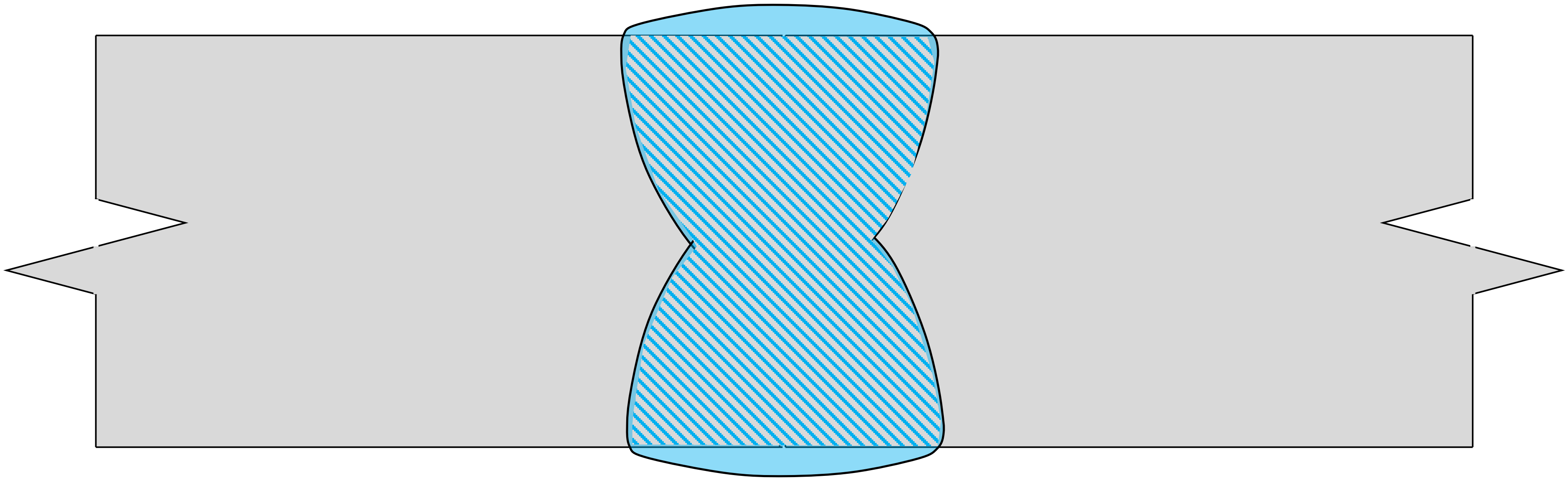
Solution: Minimize low melting point ingredients in the molten weld metal

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

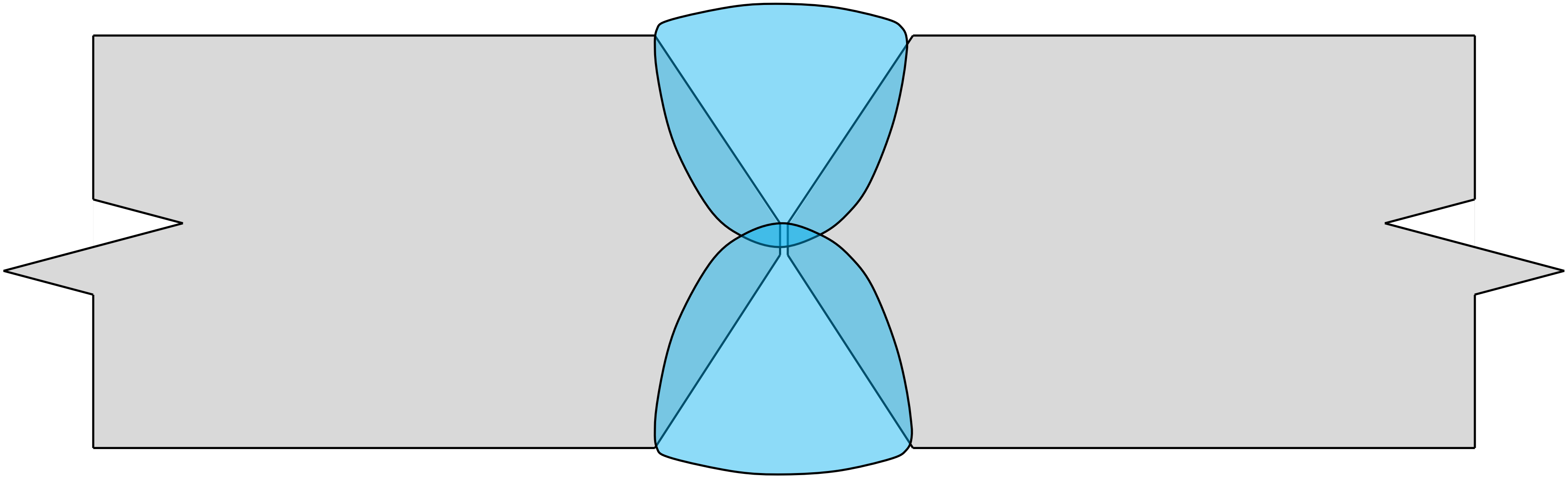
ADMIXTURE: High



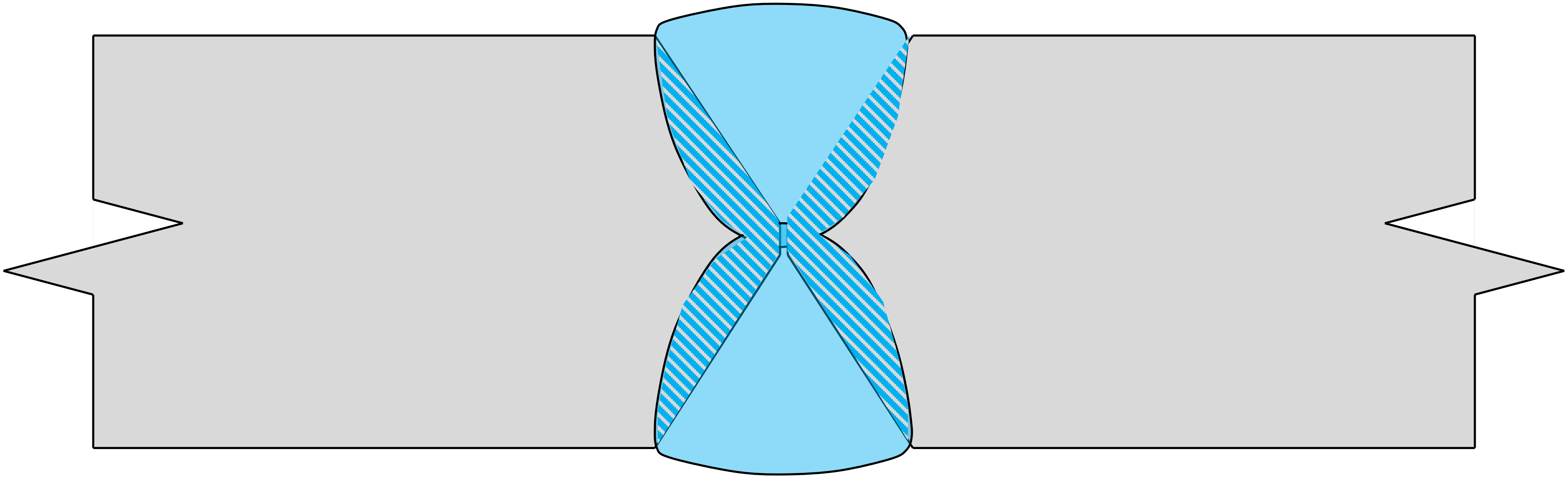
ADMIXTURE: High



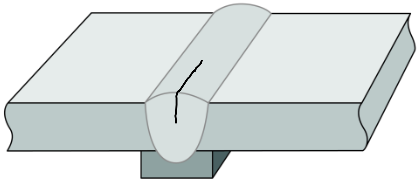
ADMIXTURE: Medium



ADMIXTURE: Medium



Centerline Cracking



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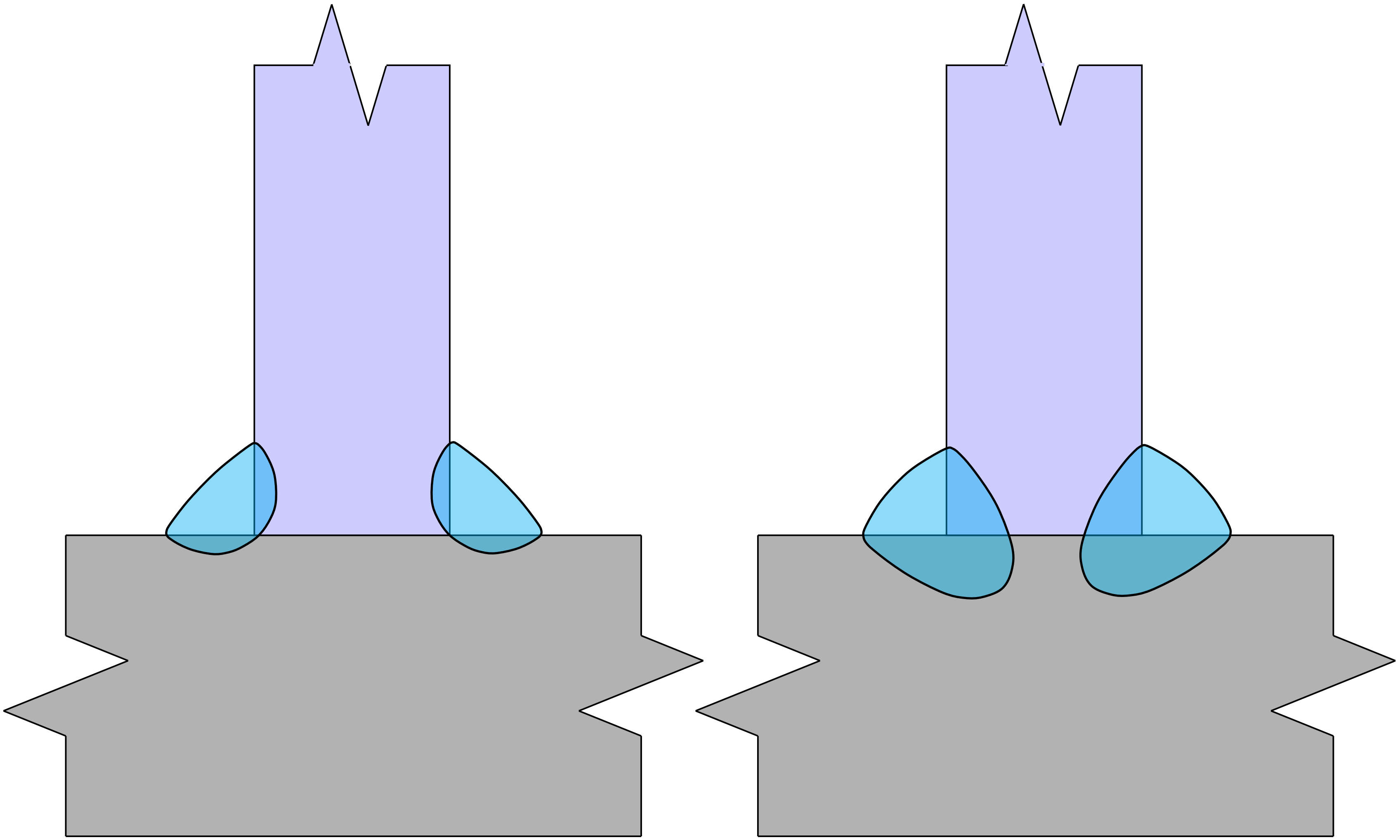
Low melting point ingredients segregate to the center during solidification

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)

ADMIXTURE

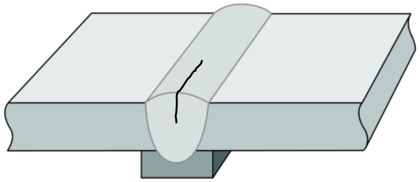
Acceptable fillet welds per AASHTO/AWS D1.5



Minimal Admixture **Significant Admixture**

Centerline Cracking

Cause 1: Segregation Cracking

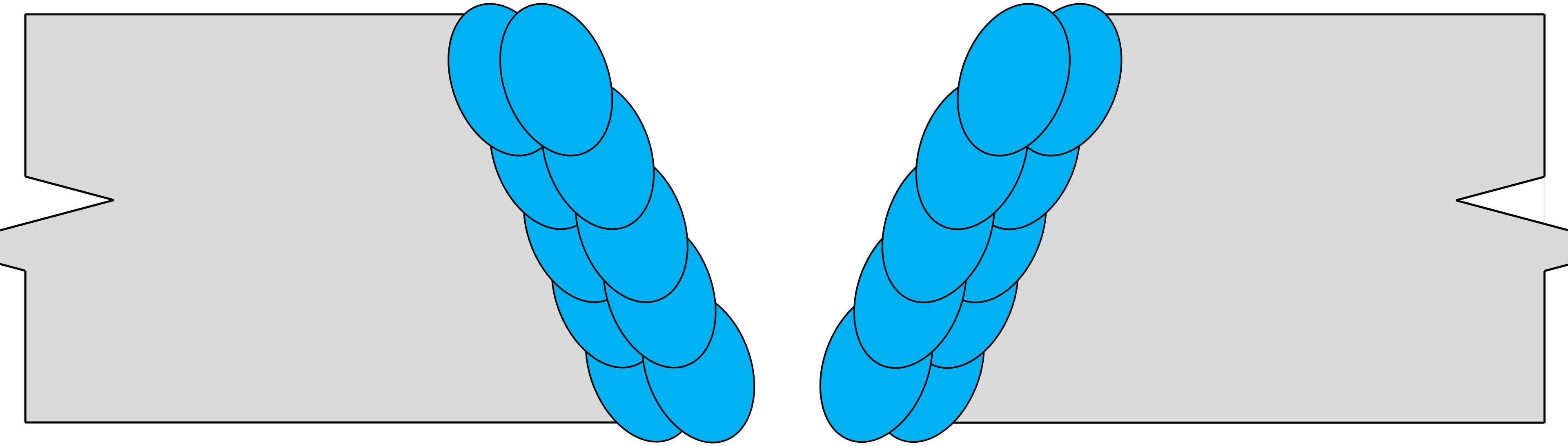


Low melting point ingredients segregate to the center during solidification

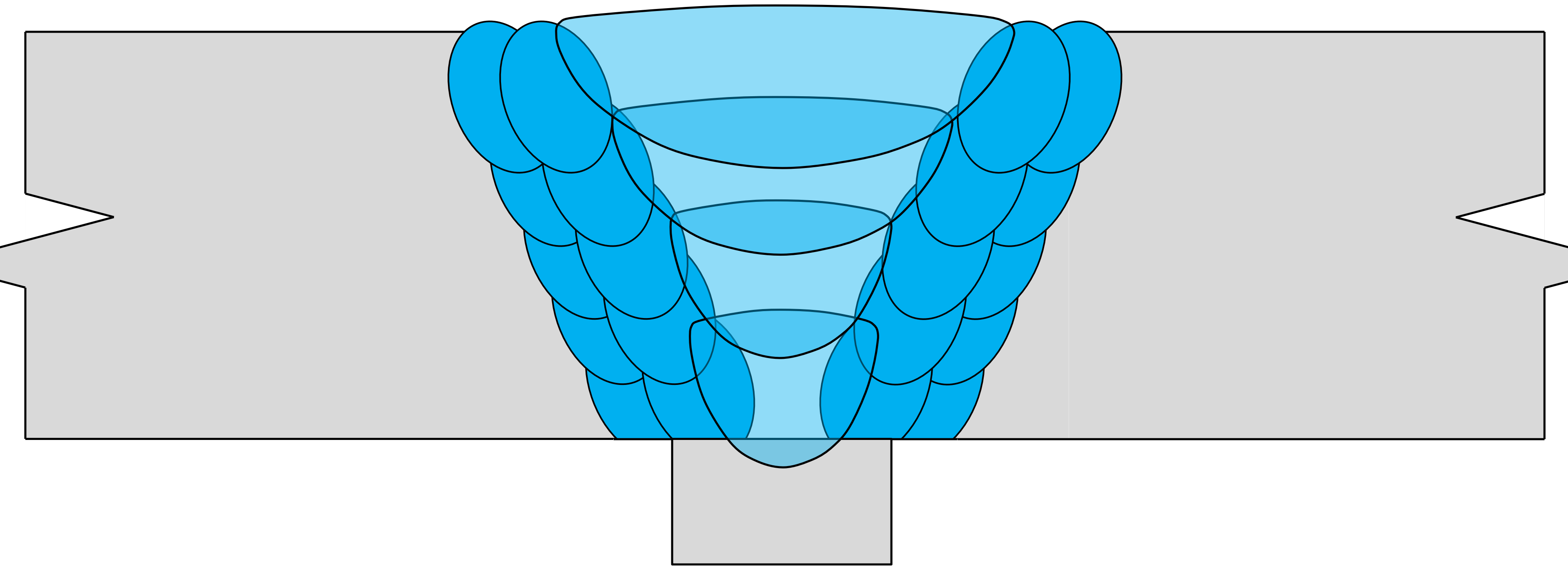
Solution: Minimize low melting point ingredients in the molten weld metal

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

BUTTERING



BUTTERING



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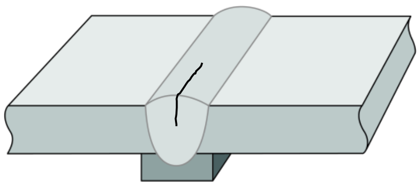


Cause 1: Segregation Cracking

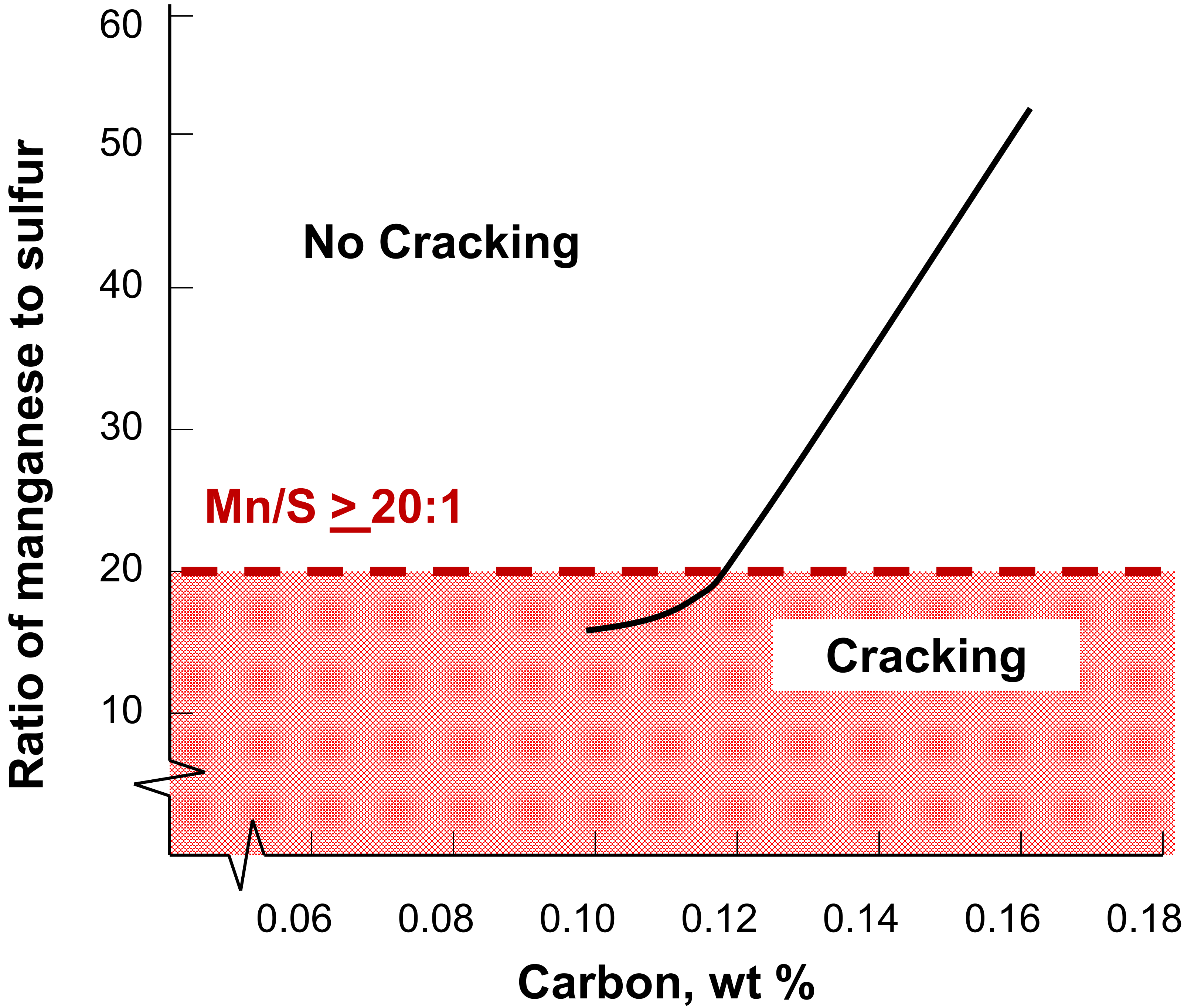
Low melting point ingredients segregate to the center during solidification

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

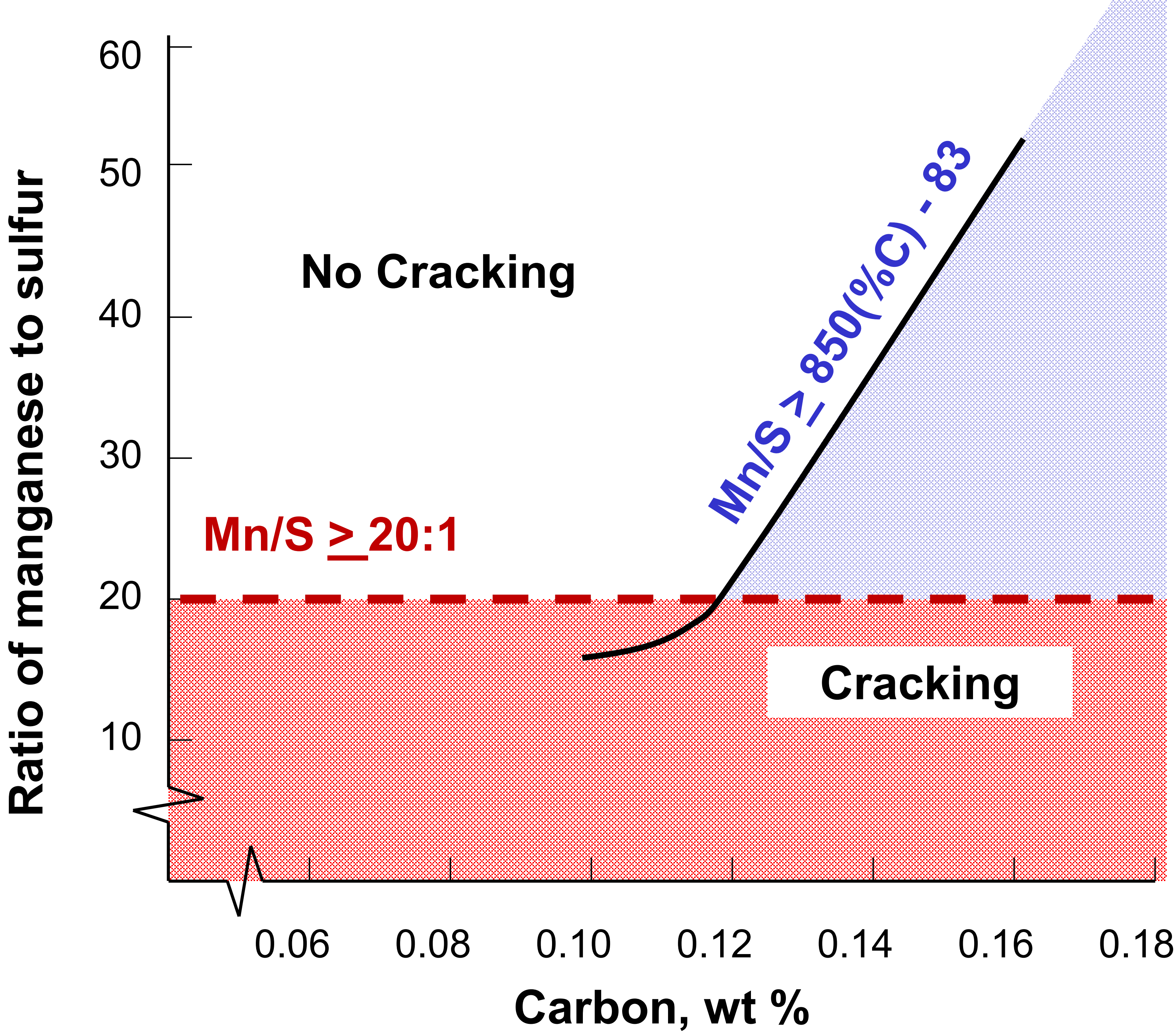
- Use “good” steel
- Minimize admixture

- For sulfur, use higher manganese (Mn) filler metal

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

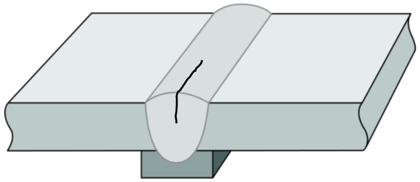


60
50
40
30
20
10
Ratio of manganese to sulfur
No Cracking
Mn/S ≥ 20:1
Cracking
0.06
0.08
0.10
0.12
0.14
0.16
0.18
Carbon, wt %



No Cracking
Cracking
Mn/S > 20:1
Mn/S > 850(%C) - 83
Ratio of manganese to sulfur
Carbon, wt %
60
50
40
30
20
10
0.06
0.08
0.10
0.12
0.14
0.16
0.18

Centerline Cracking



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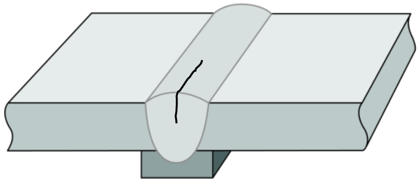
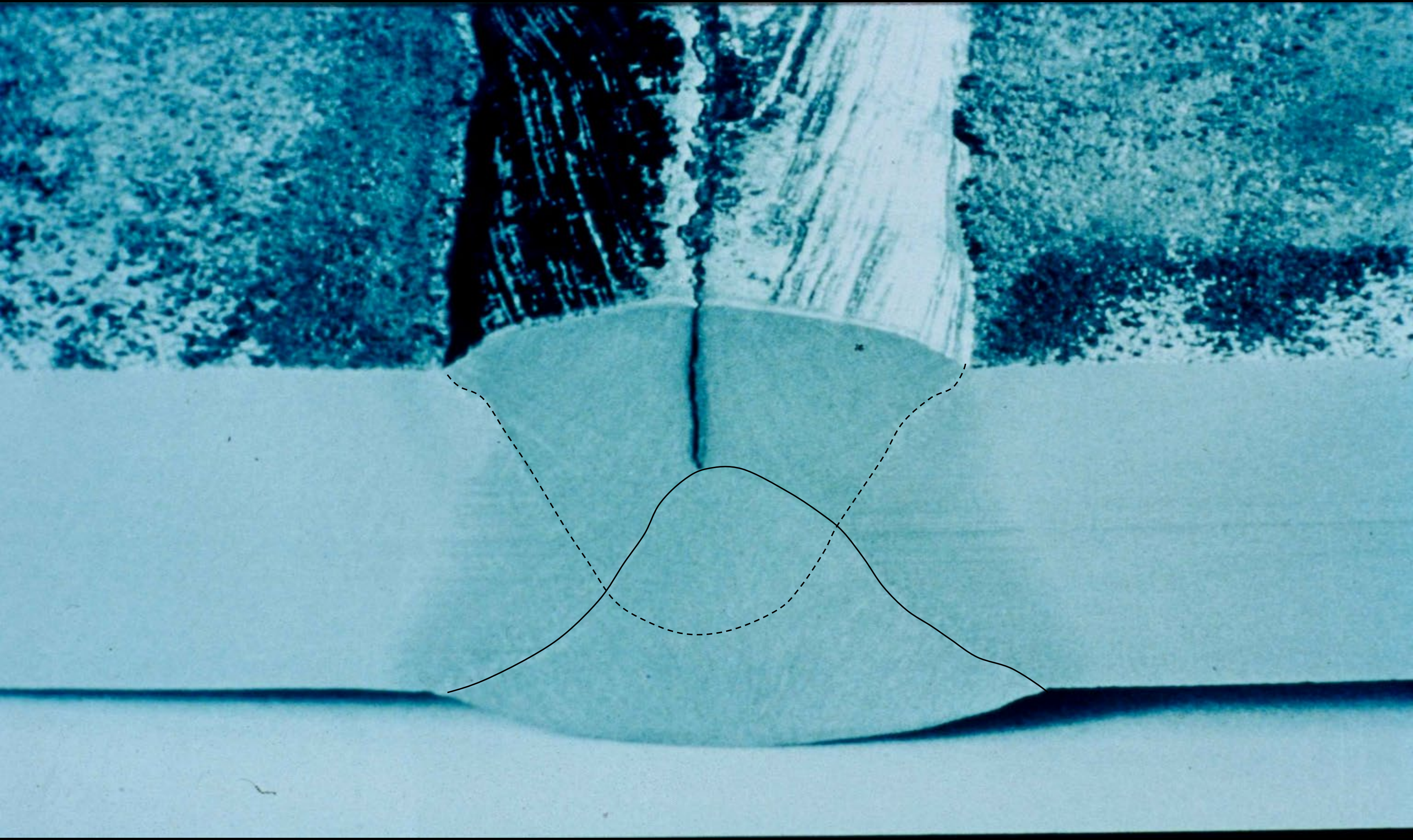
Centerline Cracking

Cause 2: Width-to-Depth Ratio Cracking



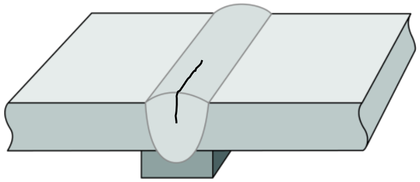
The cross-sectional width of the bead is less than the depth of the bead

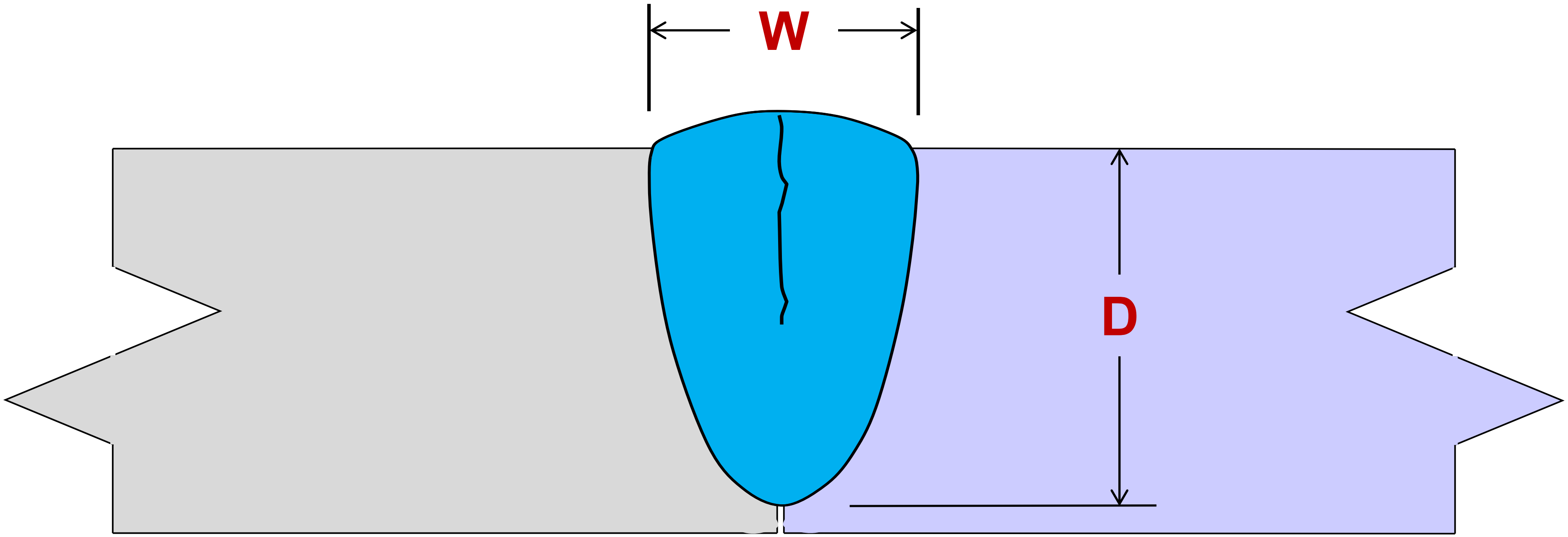
Solution: Make sure each bead is wider than it is deep



Centerline Cracking

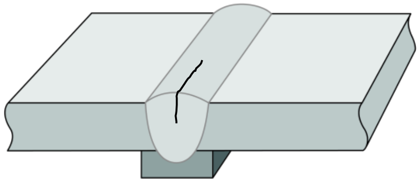
W is the width of the weld bead
D is the depth of the weld bead





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

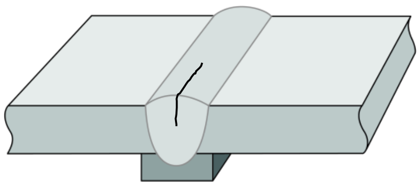
Centerline Cracking

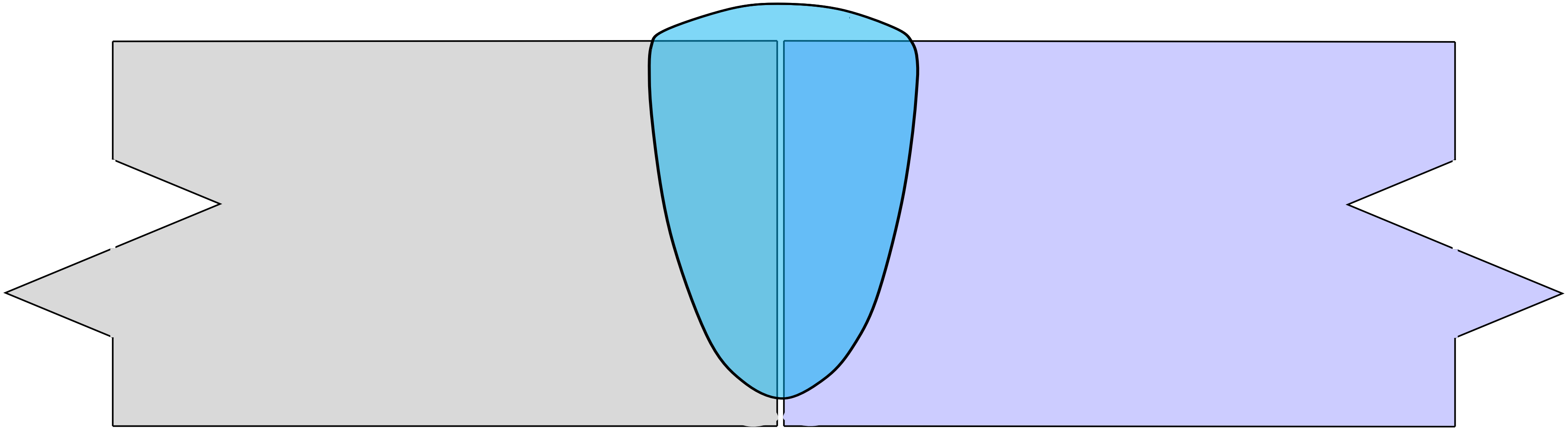


Cause 2: Width-to-Depth Ratio Cracking

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

Centerline Cracking





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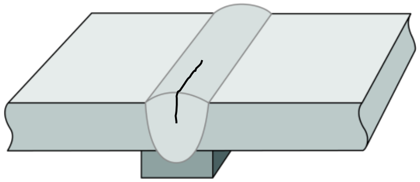

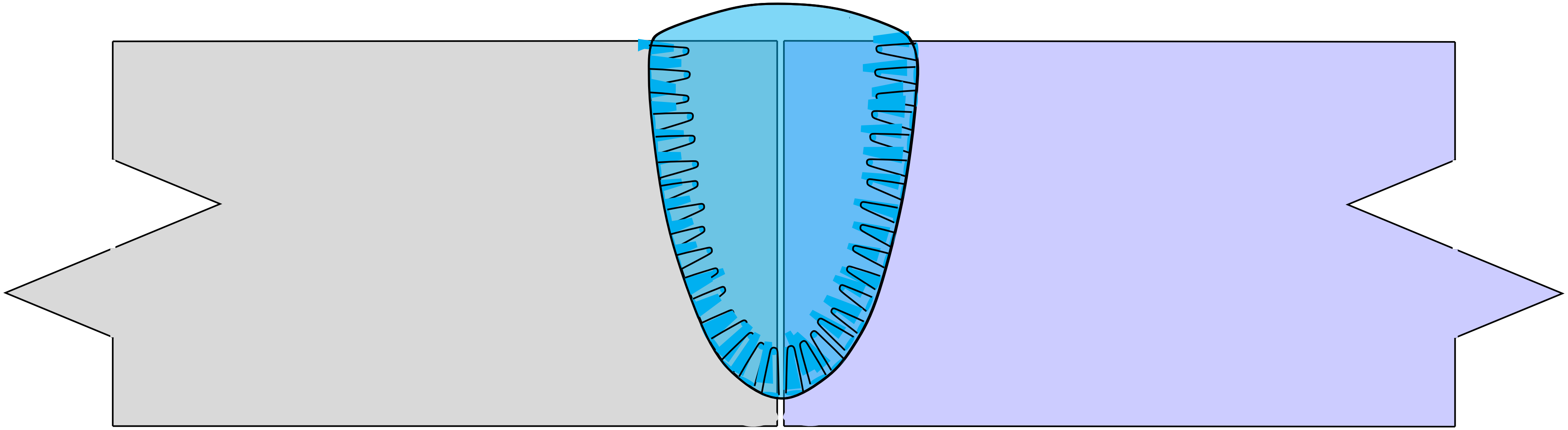

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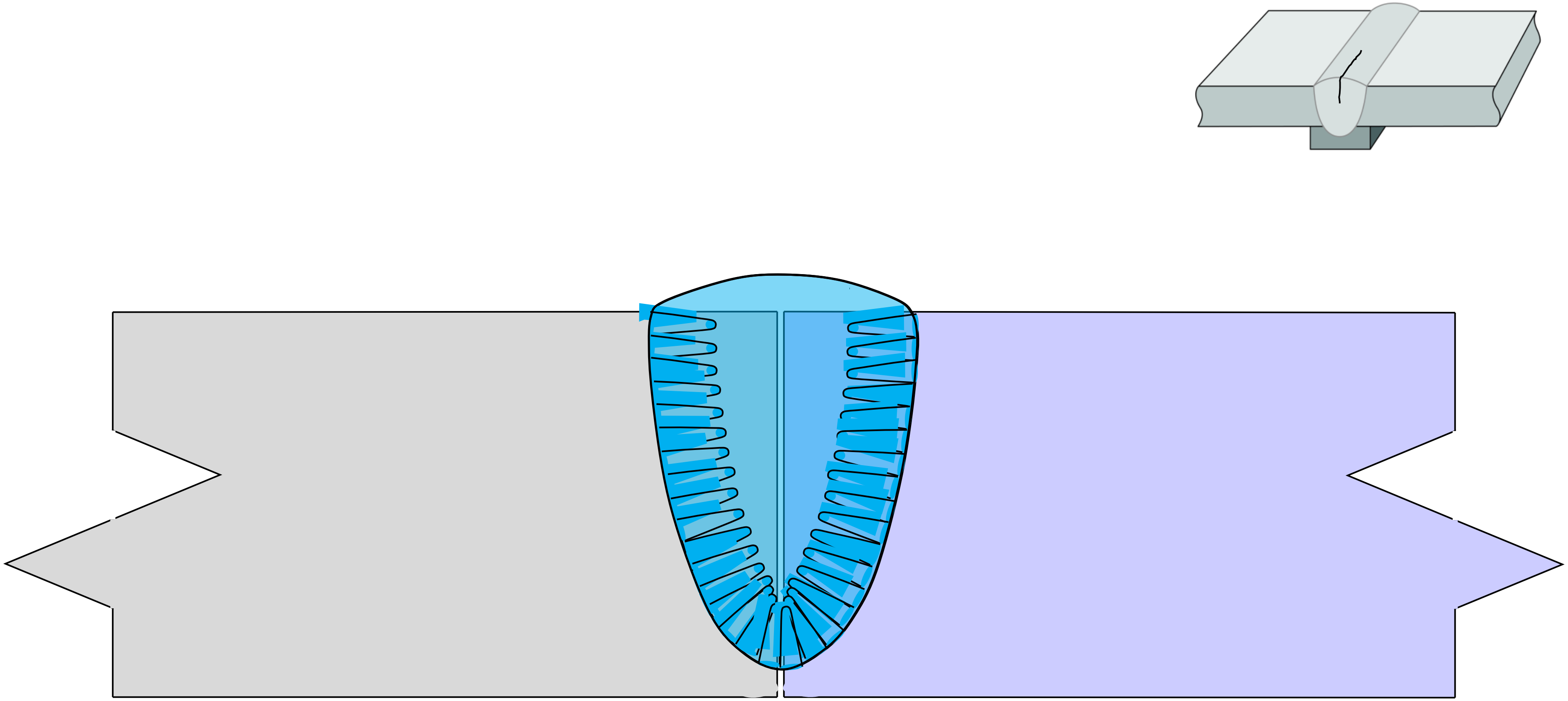

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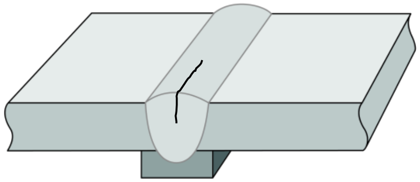

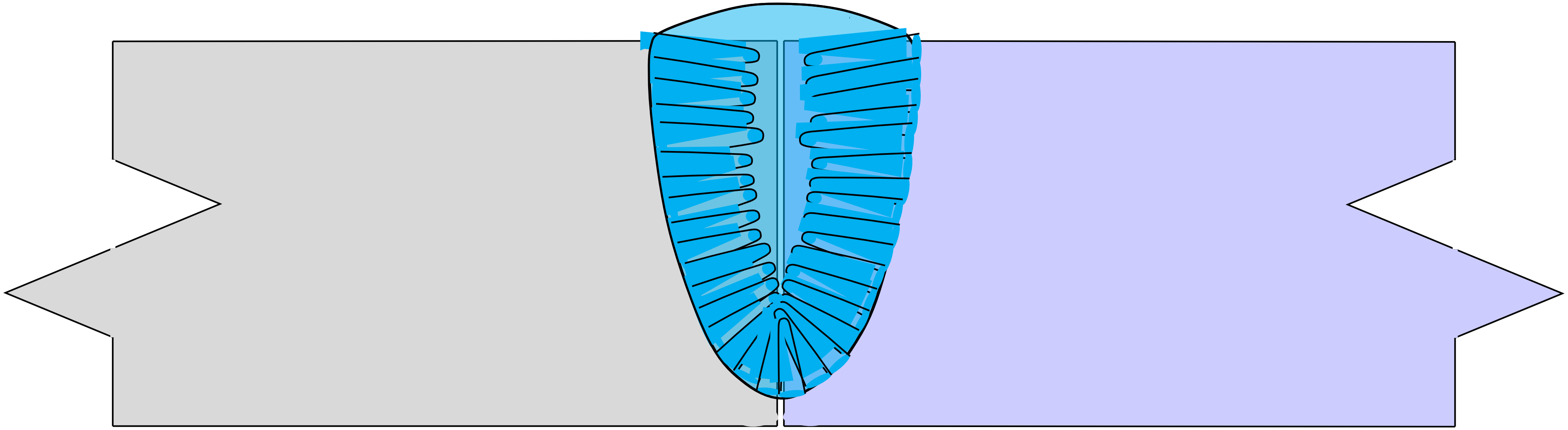

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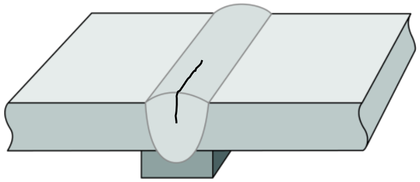
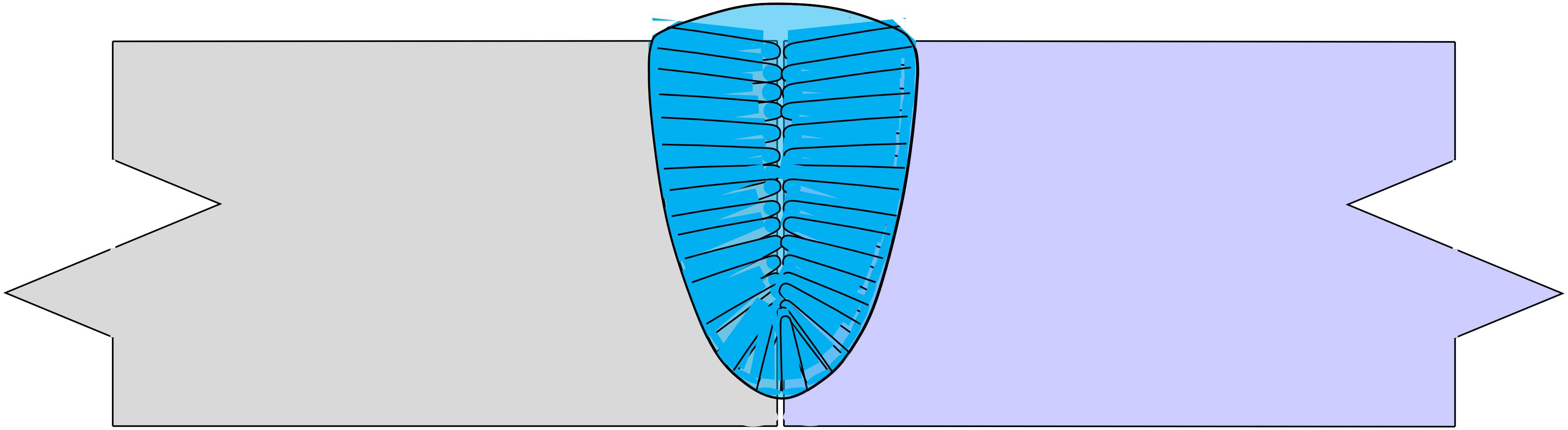
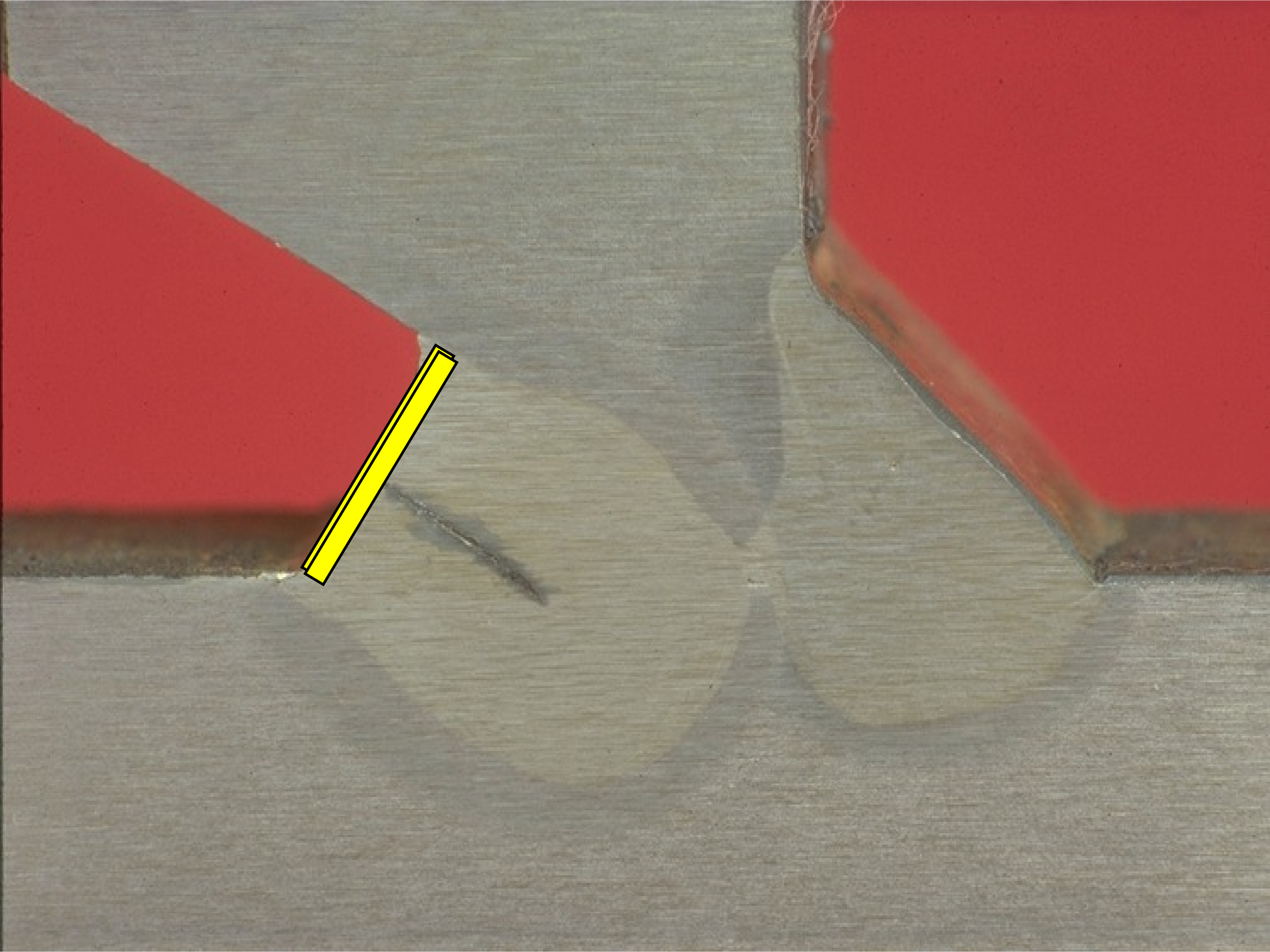
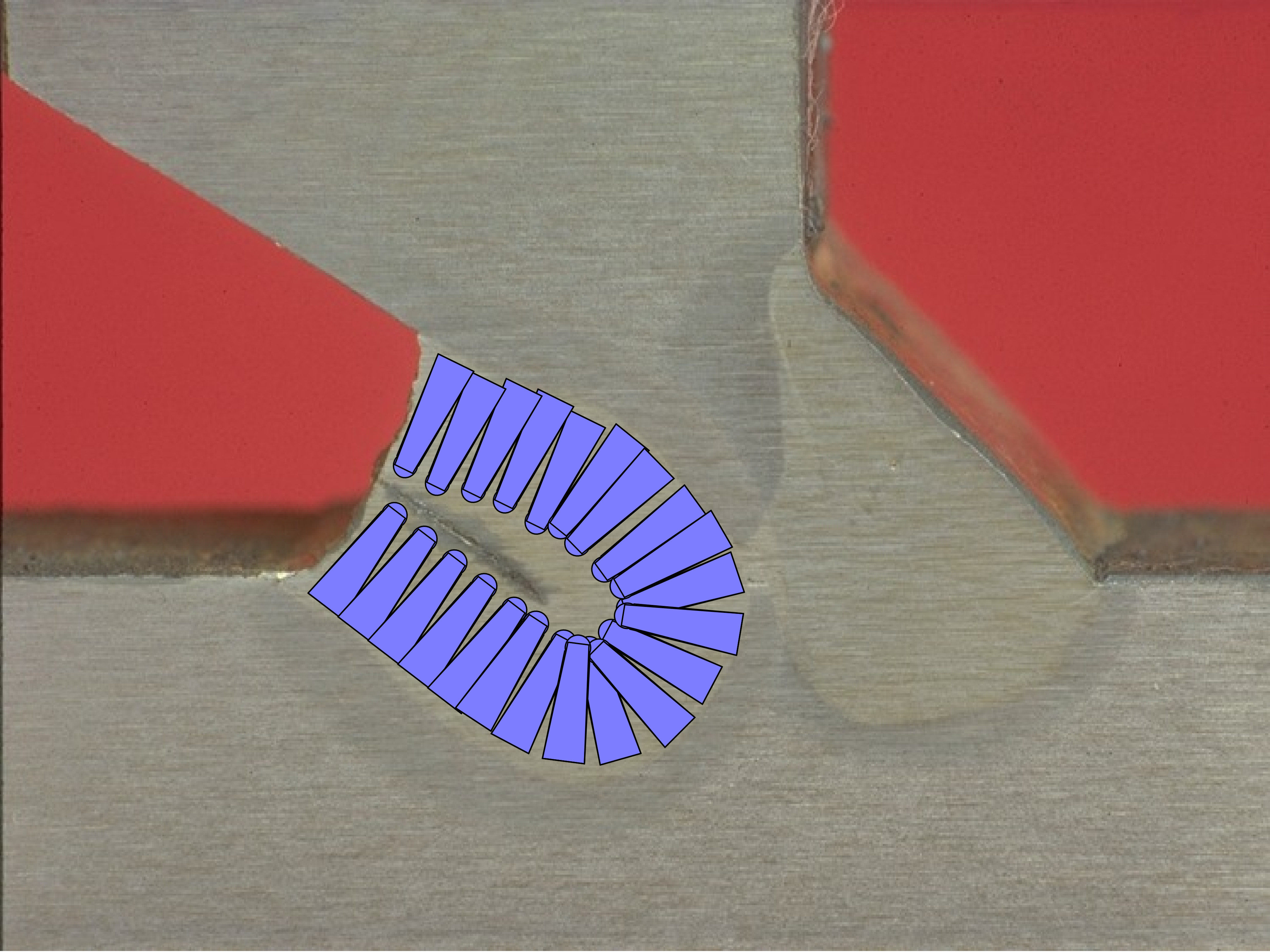
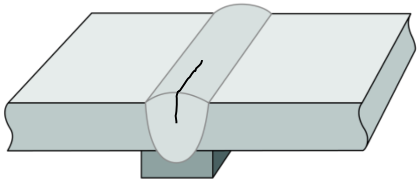








Centerline Cracking



Cause 2: Width-to-Depth Ratio Cracking

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

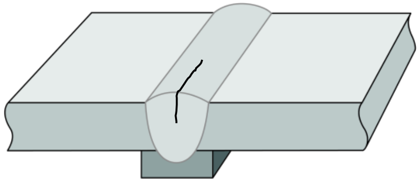
Solution: Make sure each bead is wider than it is deep

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

1:1 minimum
1.2: 1 preferred
1.4:1 is ideal

Centerline Cracking

Cause 2: Width-to-Depth Ratio Cracking

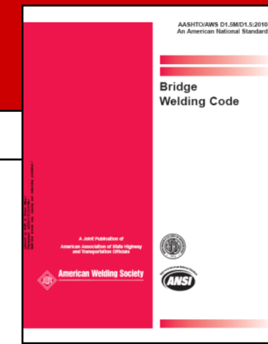


The cross-sectional width of the bead is less than the depth of the bead

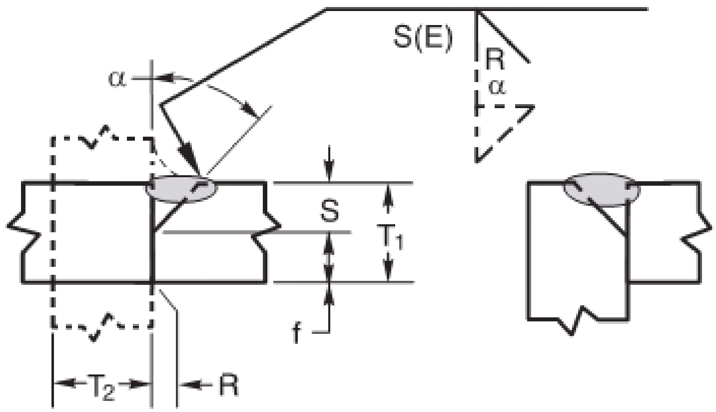
Solution: Make sure each bead is wider than it is deep

- Use a proper joint detail

AASHTO/AWS D1.5:2015 Bridge Welding Code

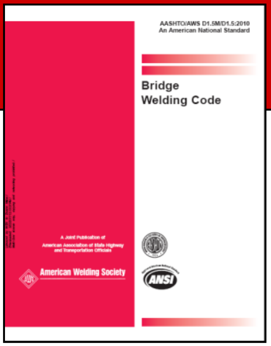


Single-bevel-groove weld (4)
Butt joint (B)
T-joint (T)
Corner joint (C)

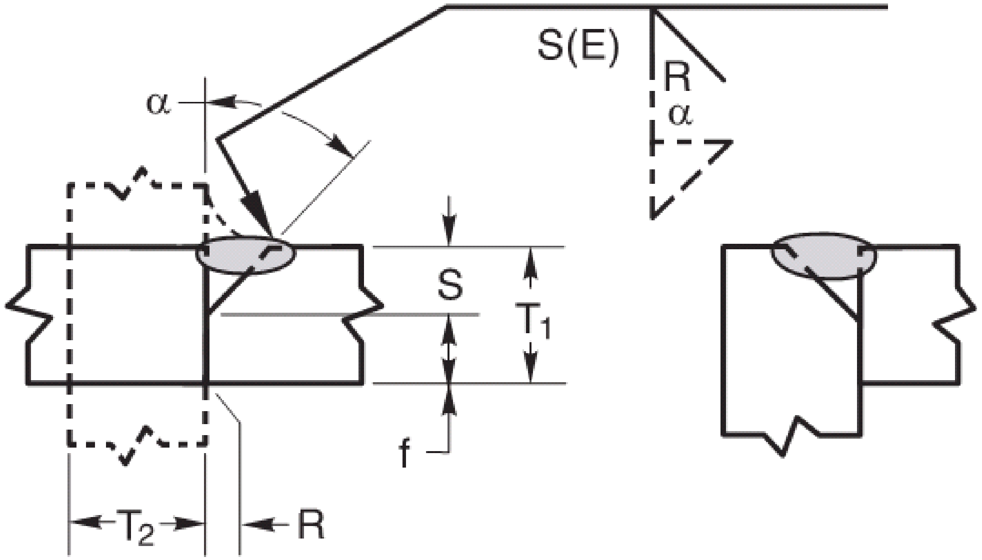


Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation			Allowed Welding Positions	Weld Size (E)	Notes
					Tolerances				
		T_1	T_2	Root Opening Root Face Groove Angle	As Detailed (see 3.12.3)	As Fit-Up (see 3.12.3)			
SMAW	BTC-P4	U	U	R = 0 f = 1/8 min. α = 45°	+1/16, –0 +U –0 +10°, –0°	+1/8, –1/16 ±1/16 +10°, –5°	All	S–1/8	b, e, f, g, j, 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	S	a, b, f, g, j, k
							V, OH	S–1/8	
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

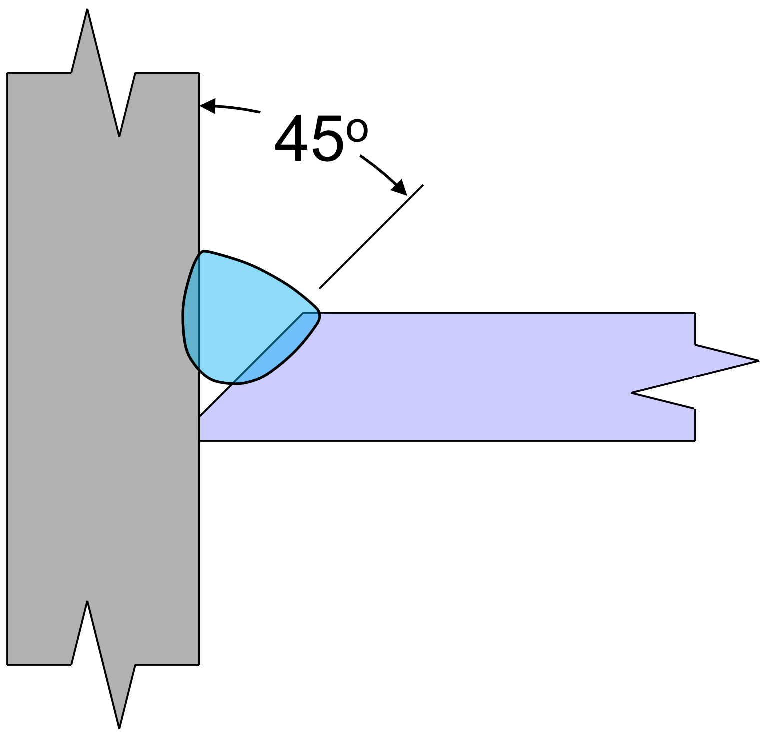
AASHTO/AWS D1.5:2015 Bridge Welding Code



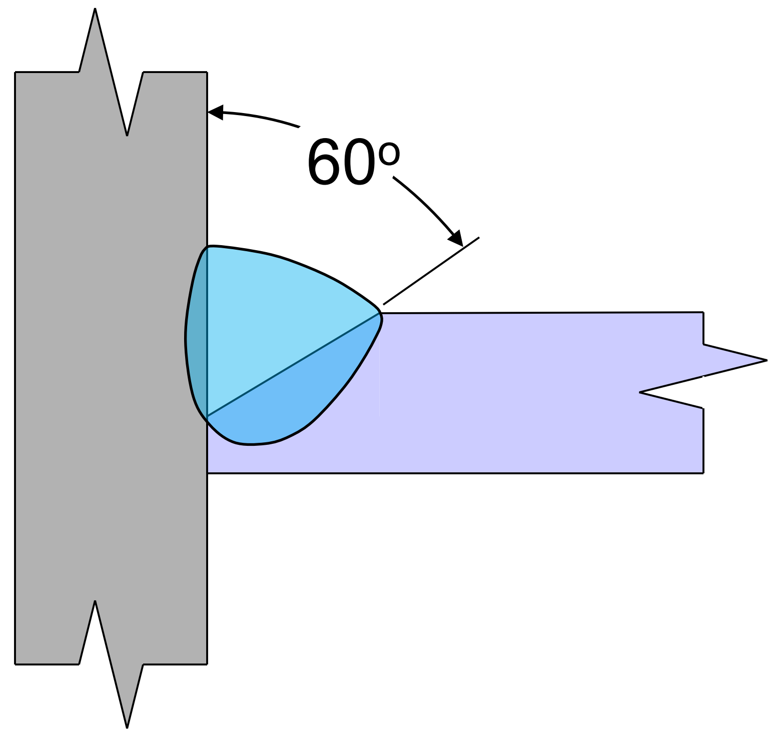
Welding Process	Root Opening Root Face Groove Angle
SMAW	R = 0 f = 1/8” min. α = 45°
GMAW FCAW	R = 0 f = 1/8” min. α = 45°
SAW	R = 0 f = 1/4” min. α = 60°



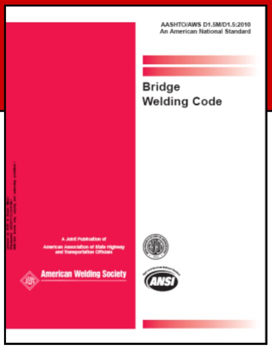
BTC-P4, BTC-P4-GF

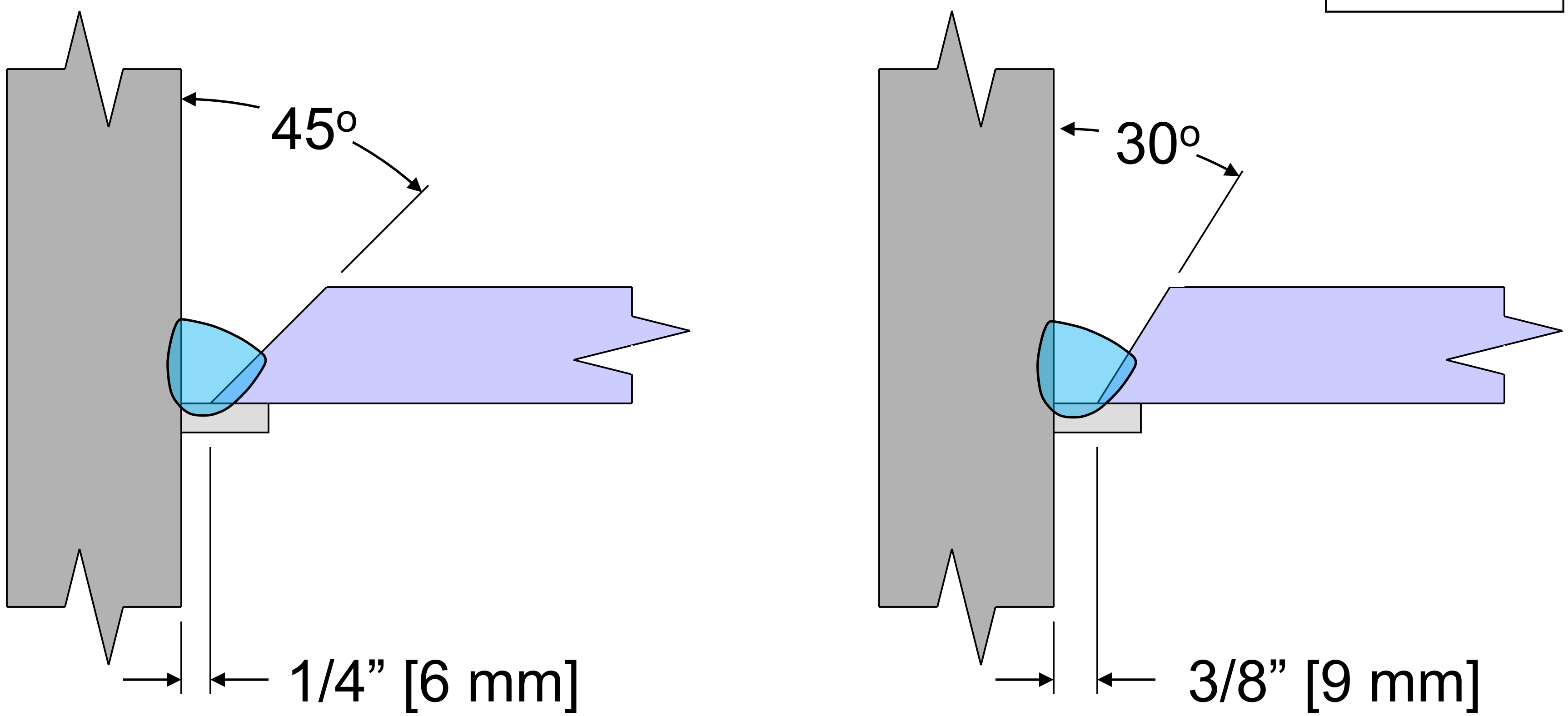


TC-P4-S

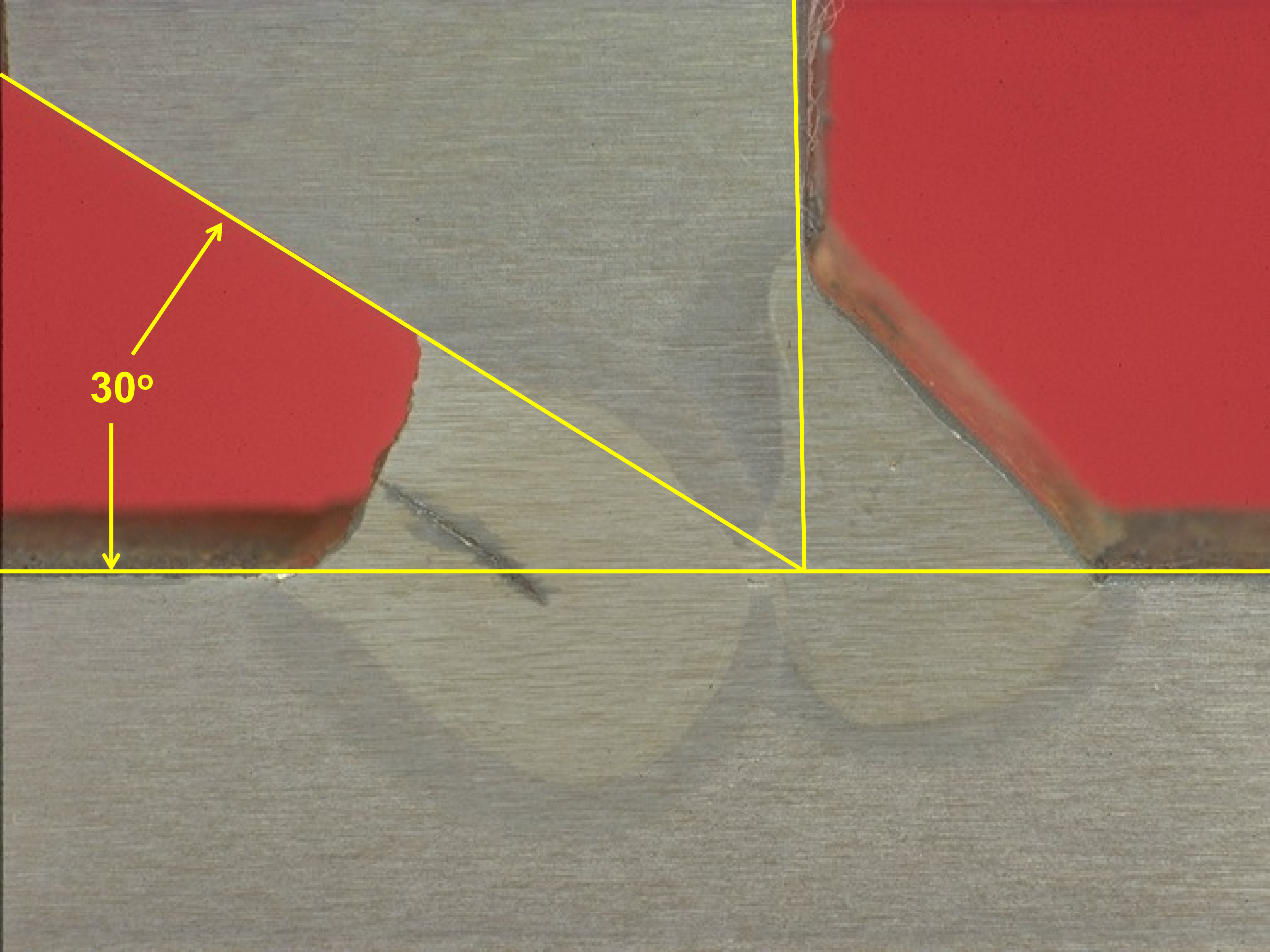


AASHTO/AWS D1.5:2015 Bridge Welding Code

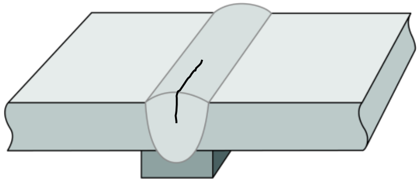




TC-U4


30°

Centerline Cracking



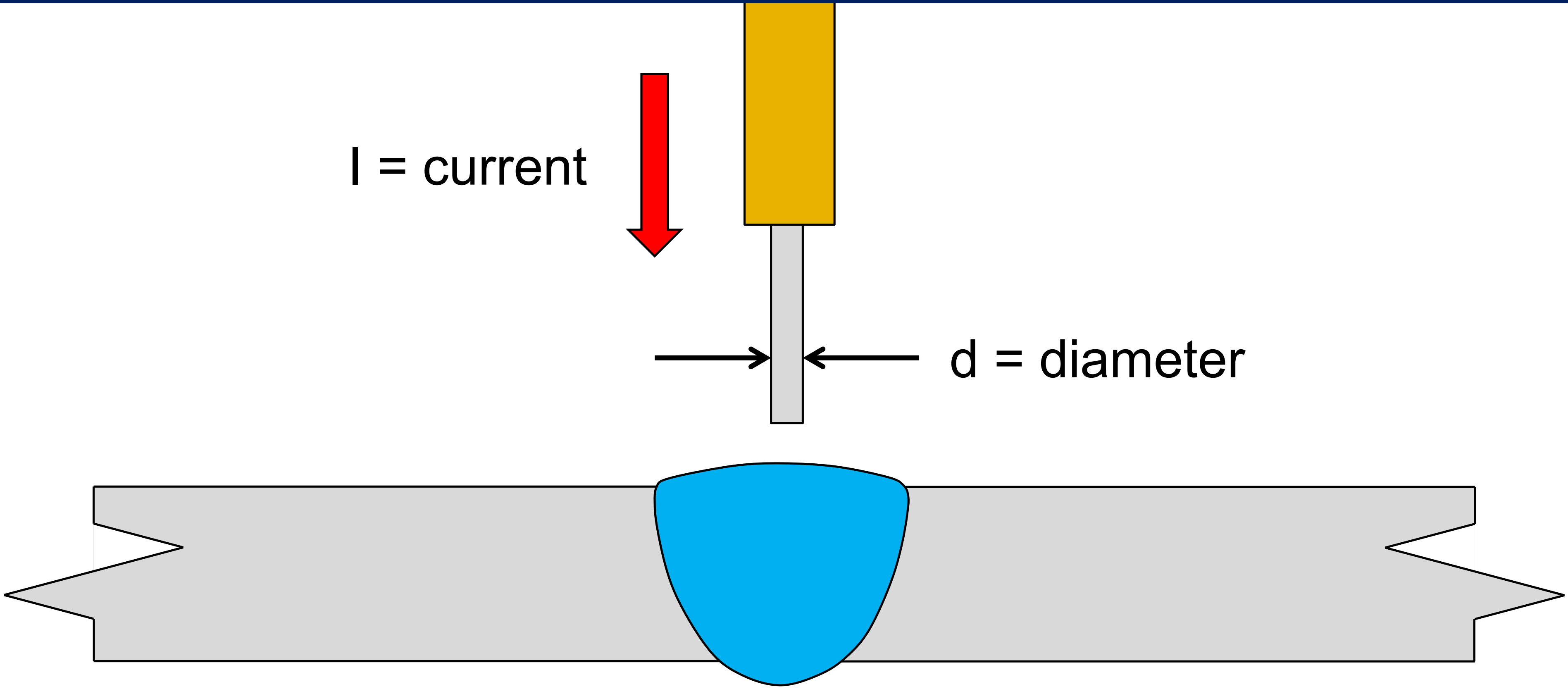
Cause 2: Width-to-Depth Ratio Cracking

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 (δ)

CURRENT DENSITY (δ)

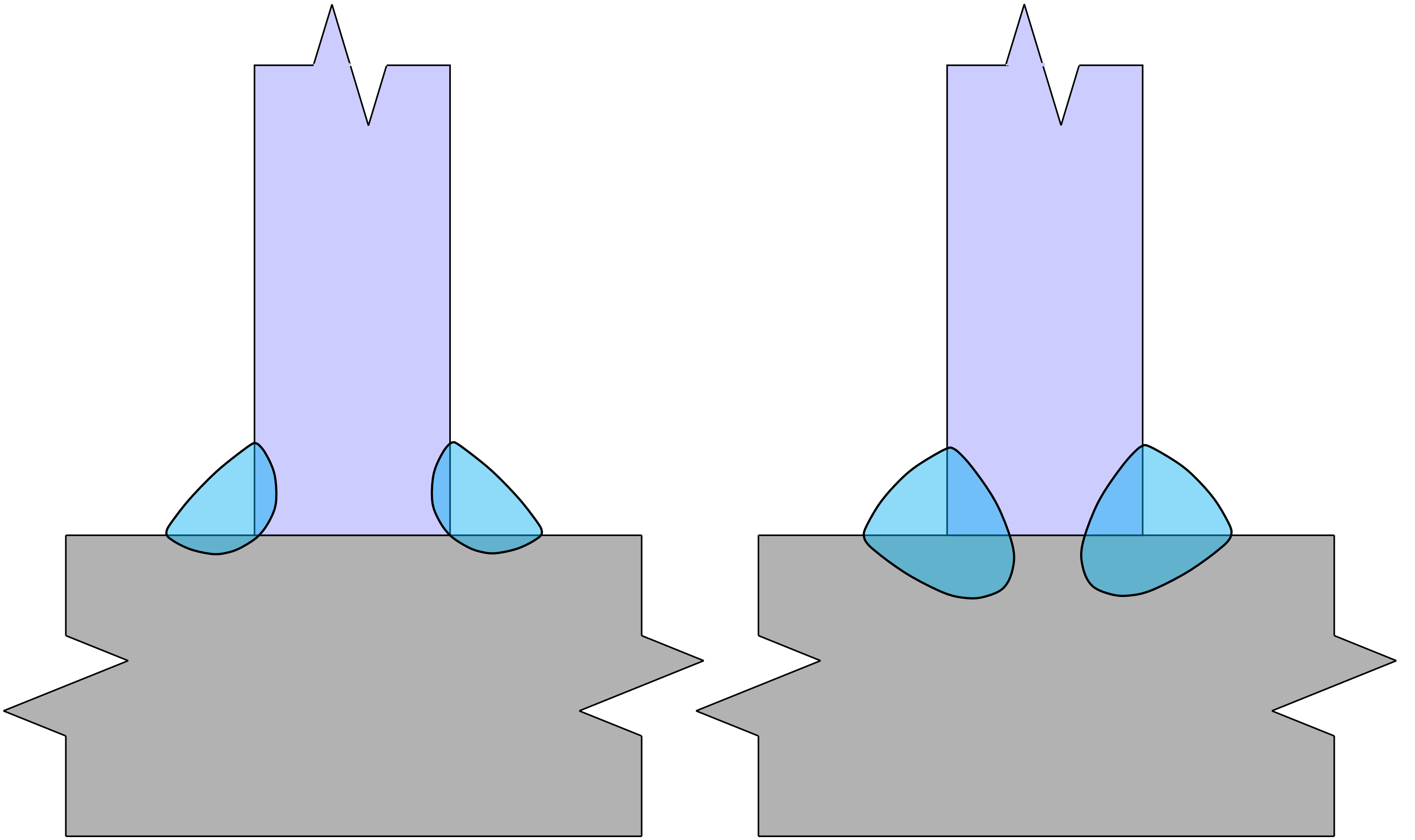


$$\delta = \left(\frac{I}{A}\right) \propto \left(\frac{I}{d^2}\right)$$

where
I = current (amps)
A = cross sectional area of filler metal
d = diameter of filler metal

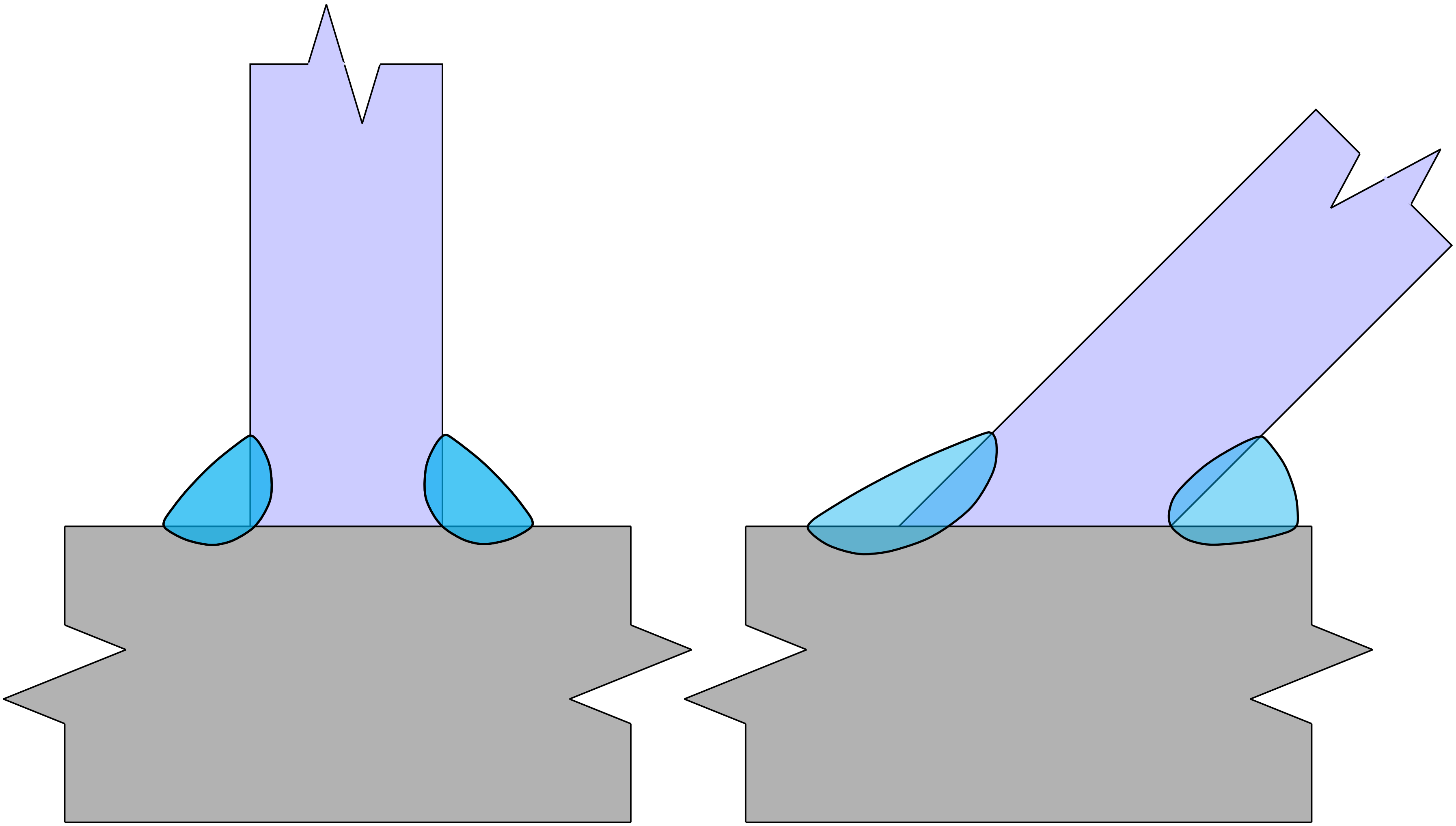
PENETRATION

Acceptable fillet welds per AISC, AWS D1.1



Normal Current Density **Excessive Current Density**

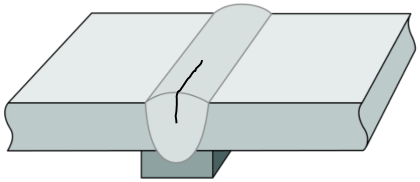
FILLET WELDS IN SKEWED TEE JOINTS



In 90° joint, W/D = 2:1

In 45° joint, acute side is problematic

Centerline Cracking



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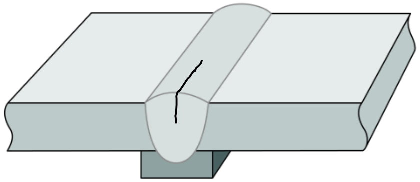
- Control current density (δ)

Centerline Cracking

Cause 2: Width-to-Depth Ratio Cracking

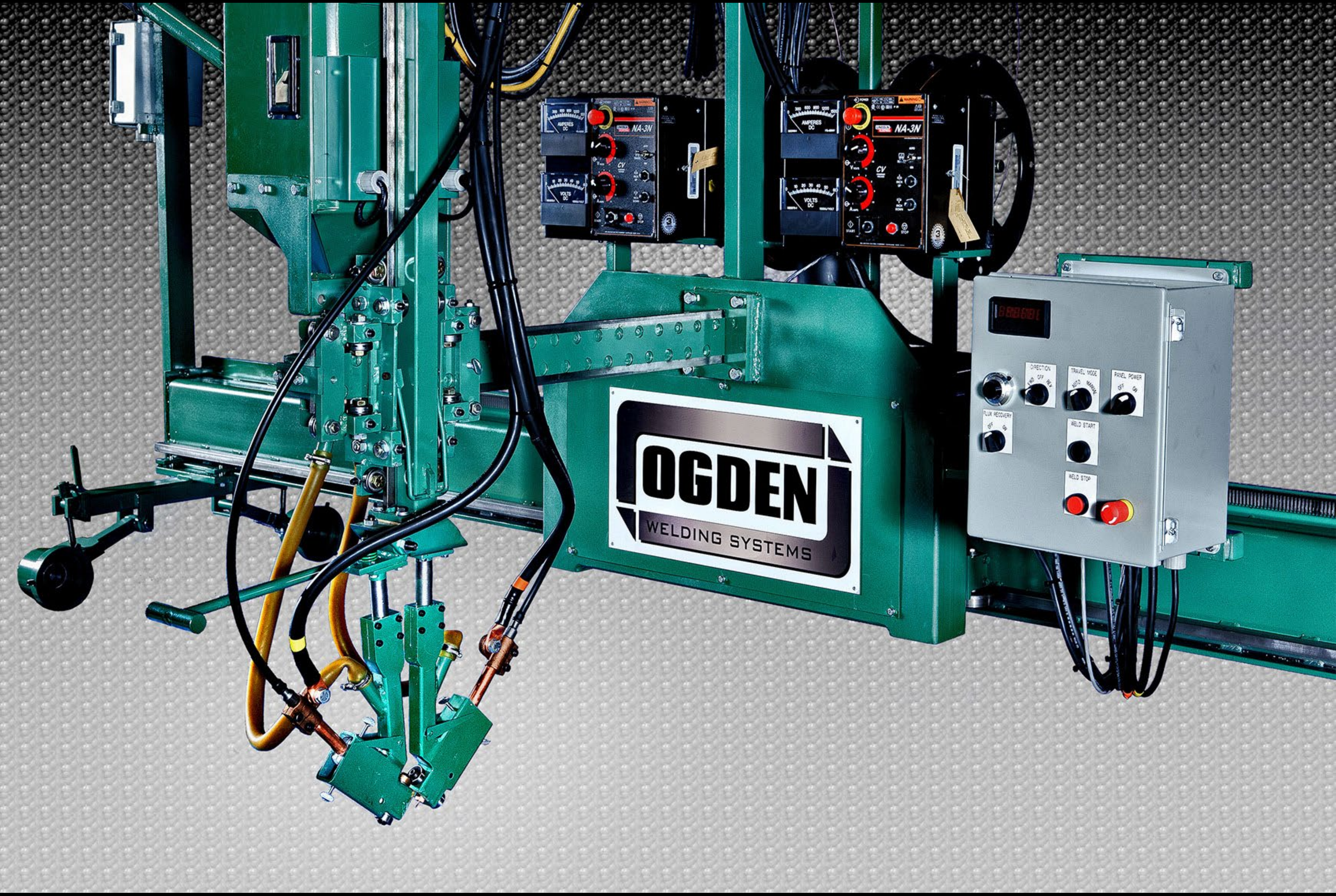


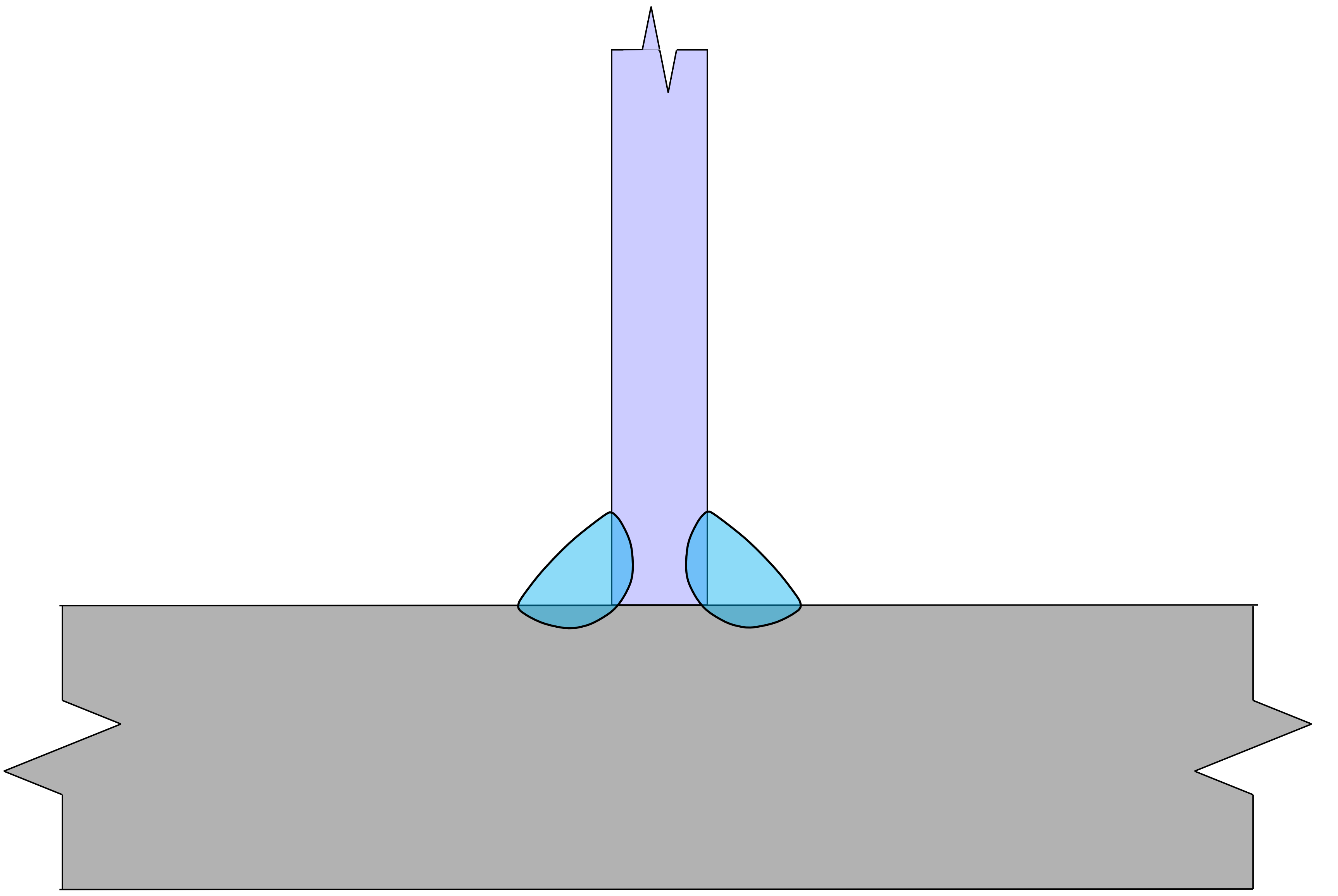
The cross-sectional width of the bead
is less than the depth of the bead

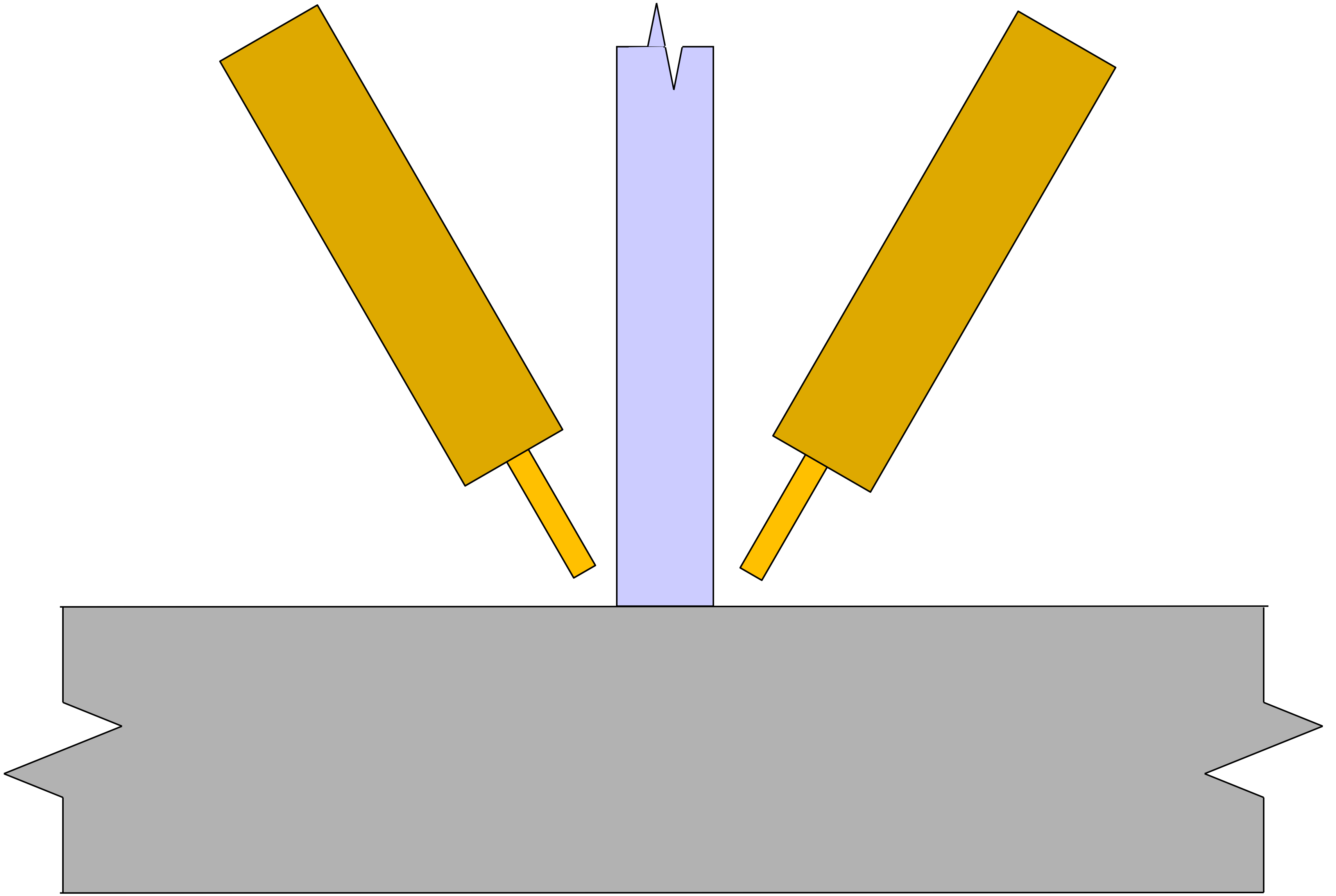
Solution: Make sure each bead is wider than it is deep

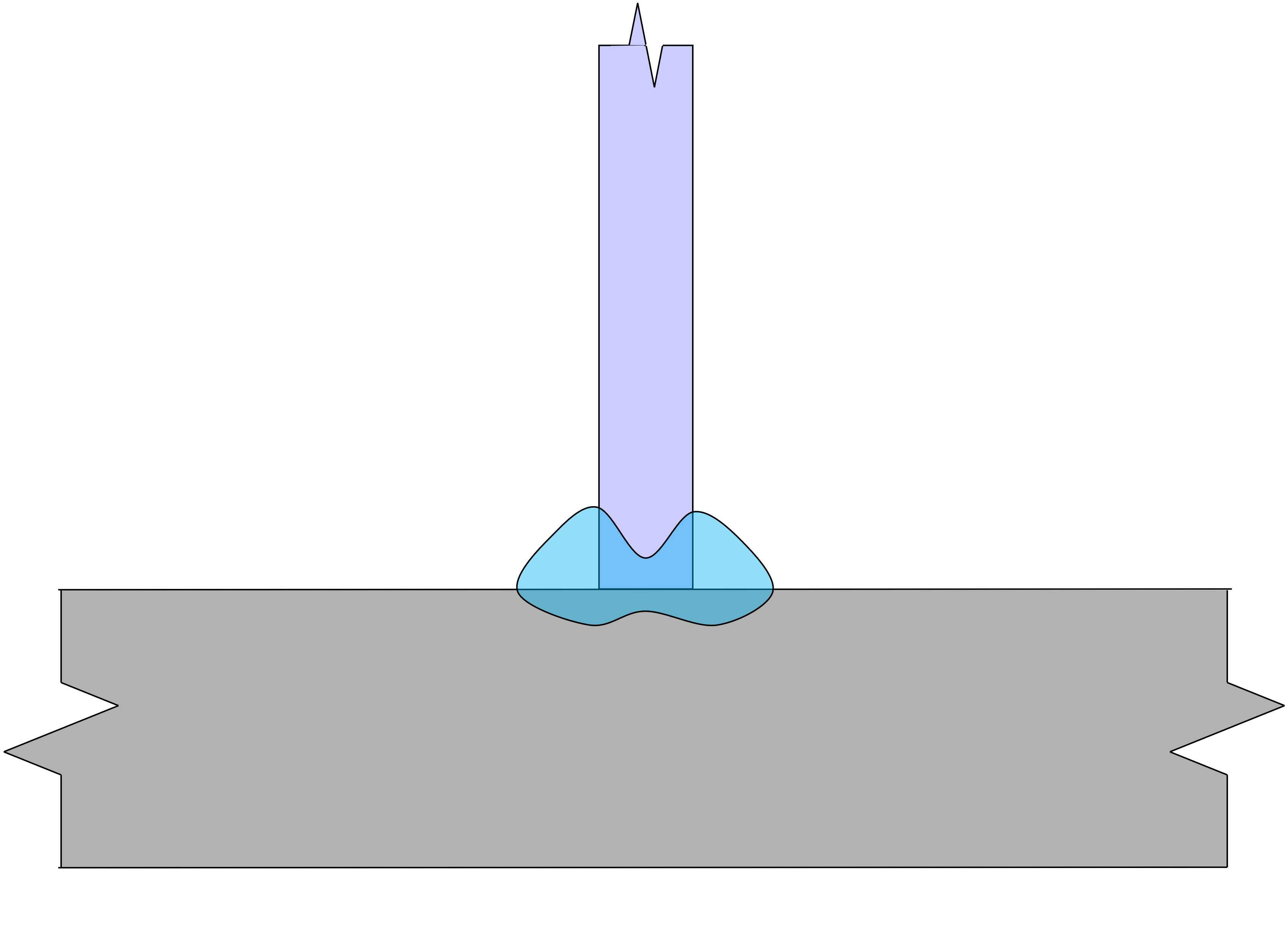
A special type of cracking in bridge applications:

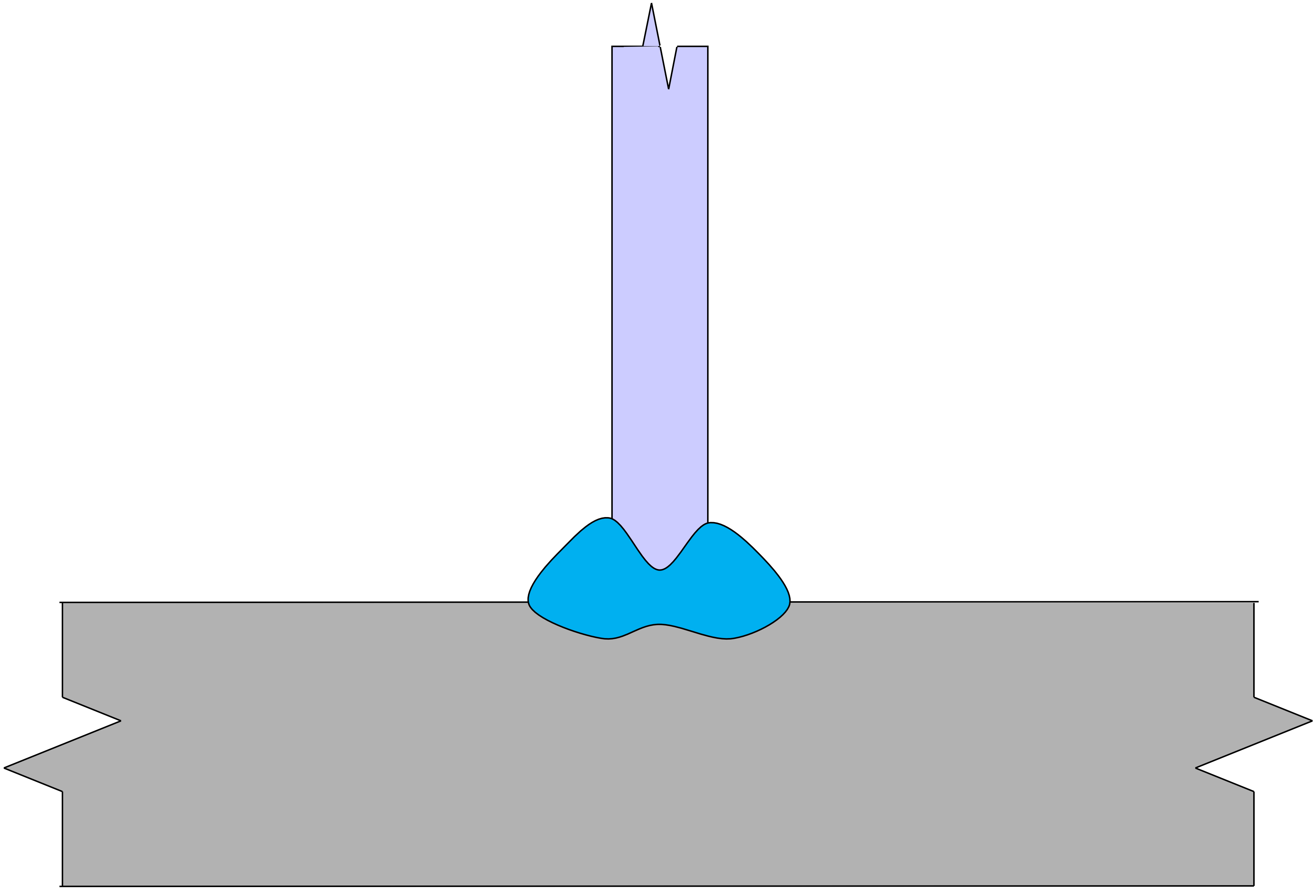
"opposed arc cracking"

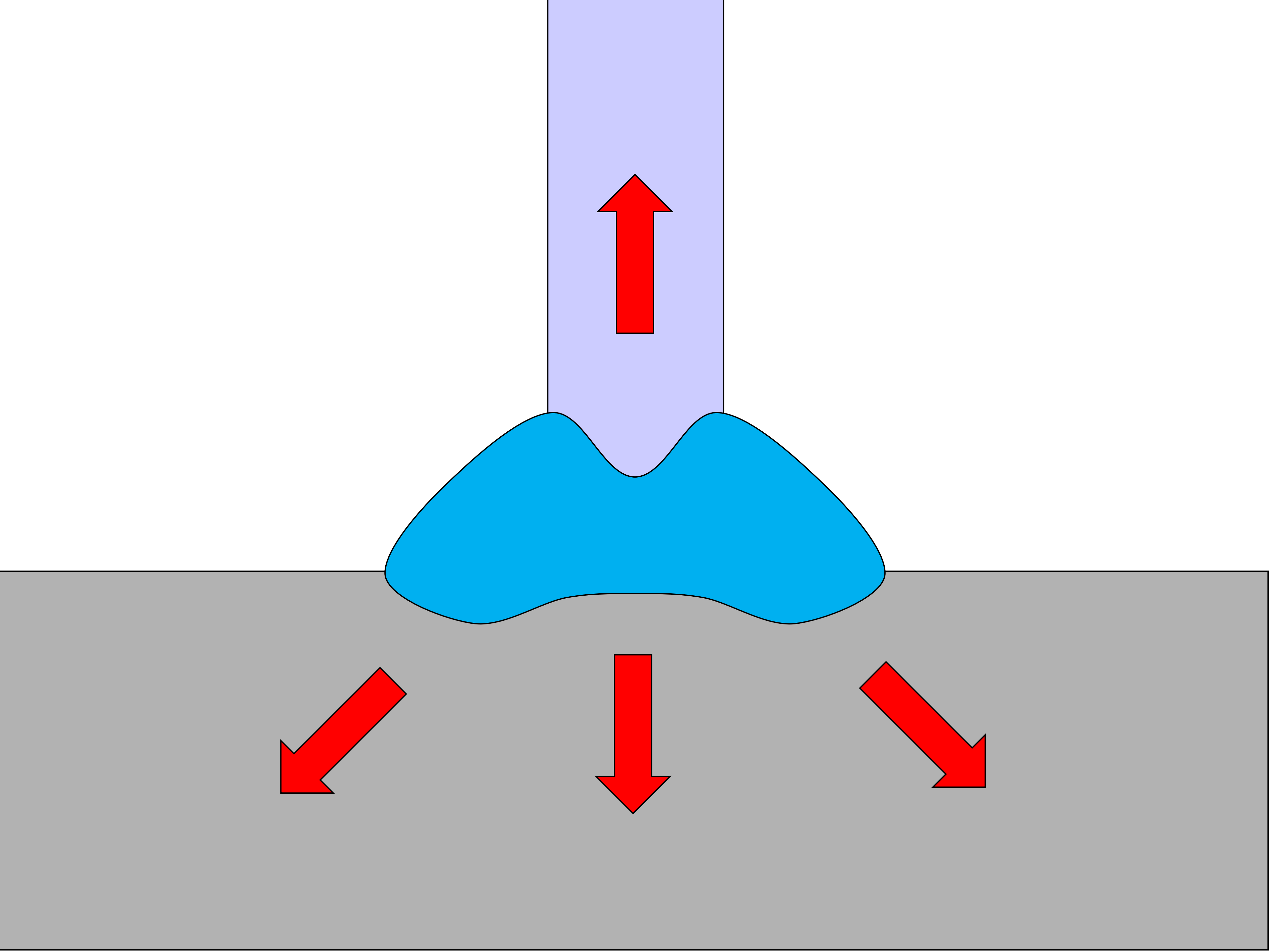

NA-3N
NA-3N
DIRECTION
TRAVEL MODE
PANEL POWER
FLUX RECOVERY
WELD START
WELD STOP
OGDEN
WELDING SYSTEMS

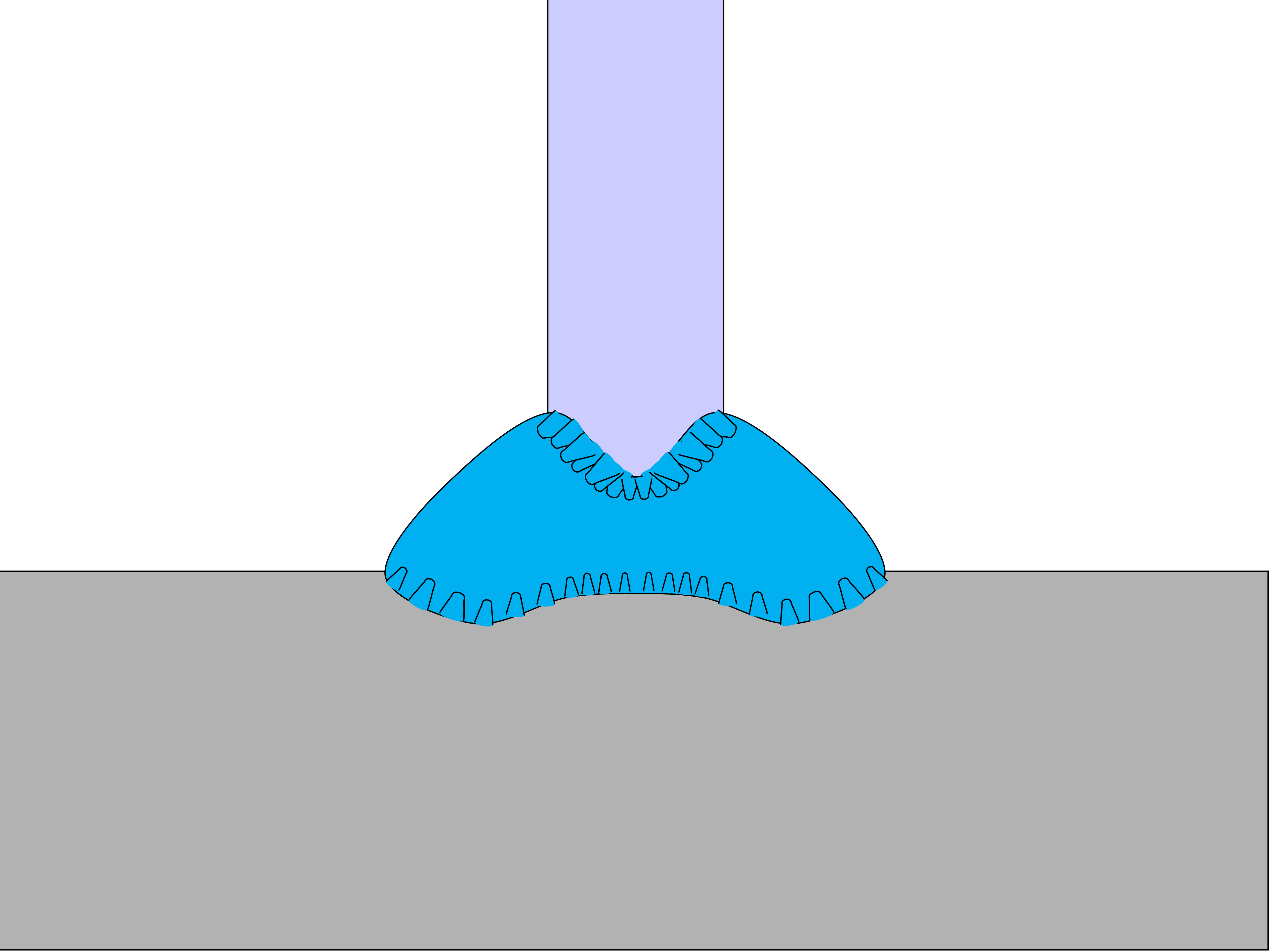


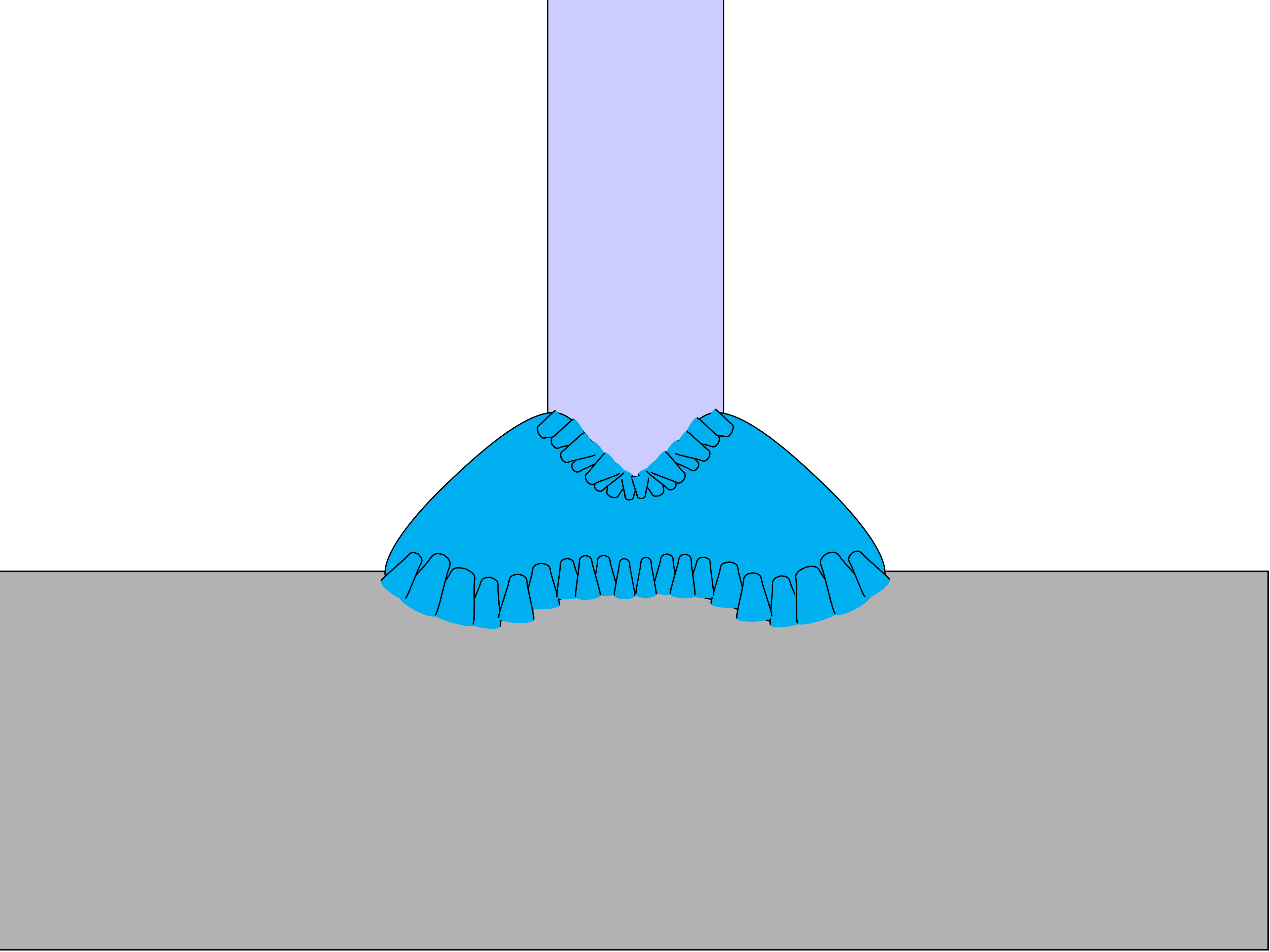


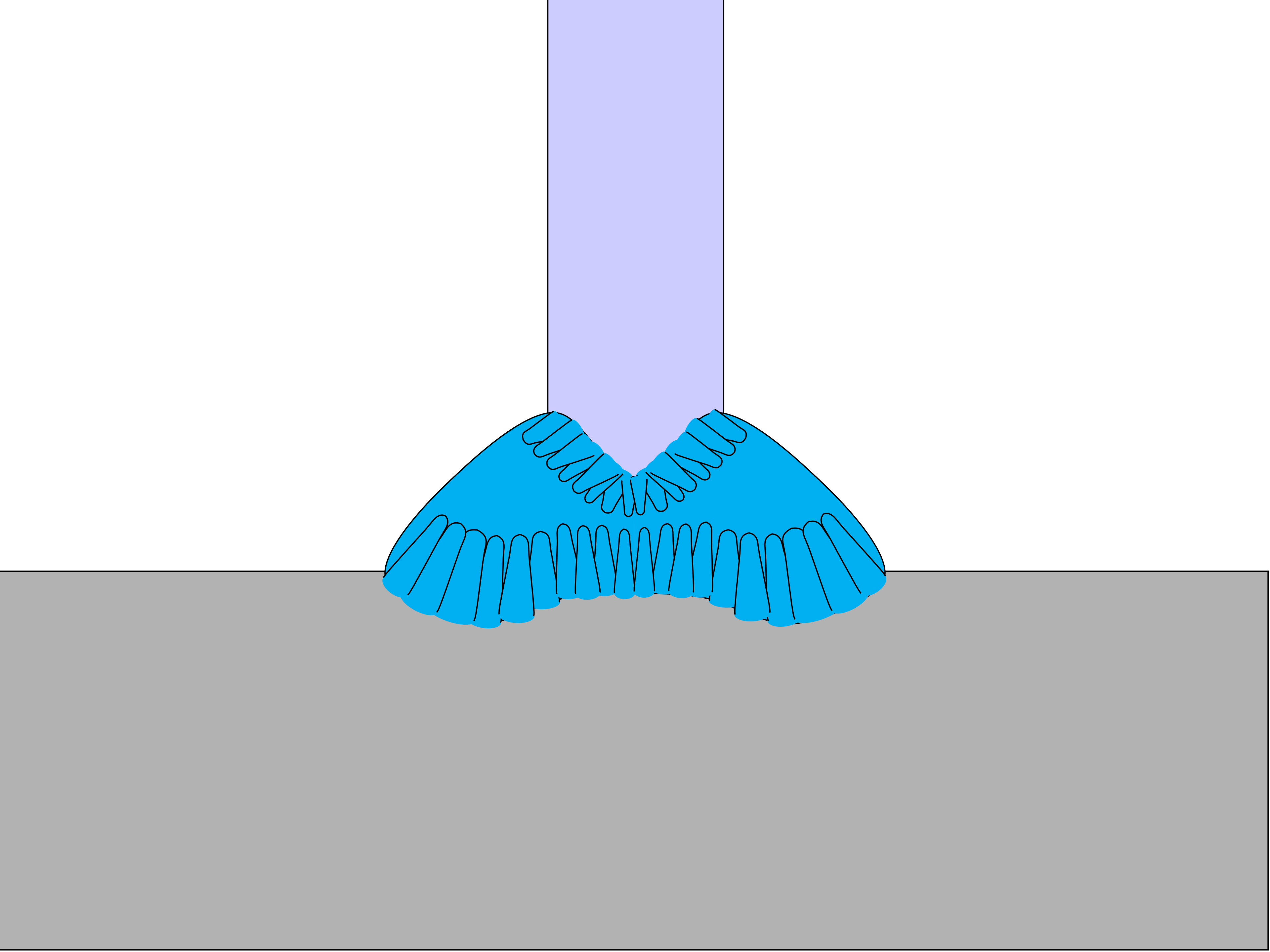


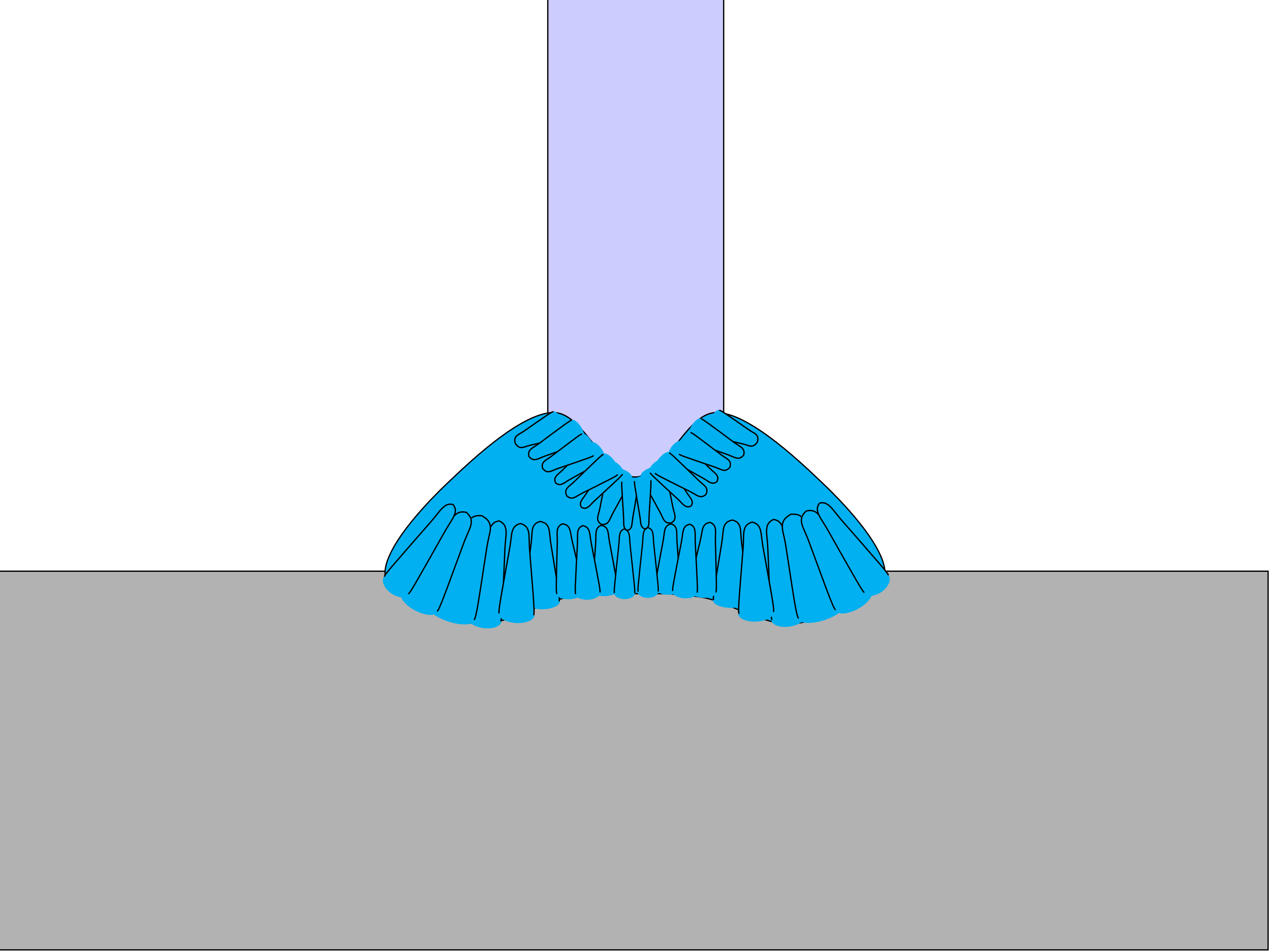


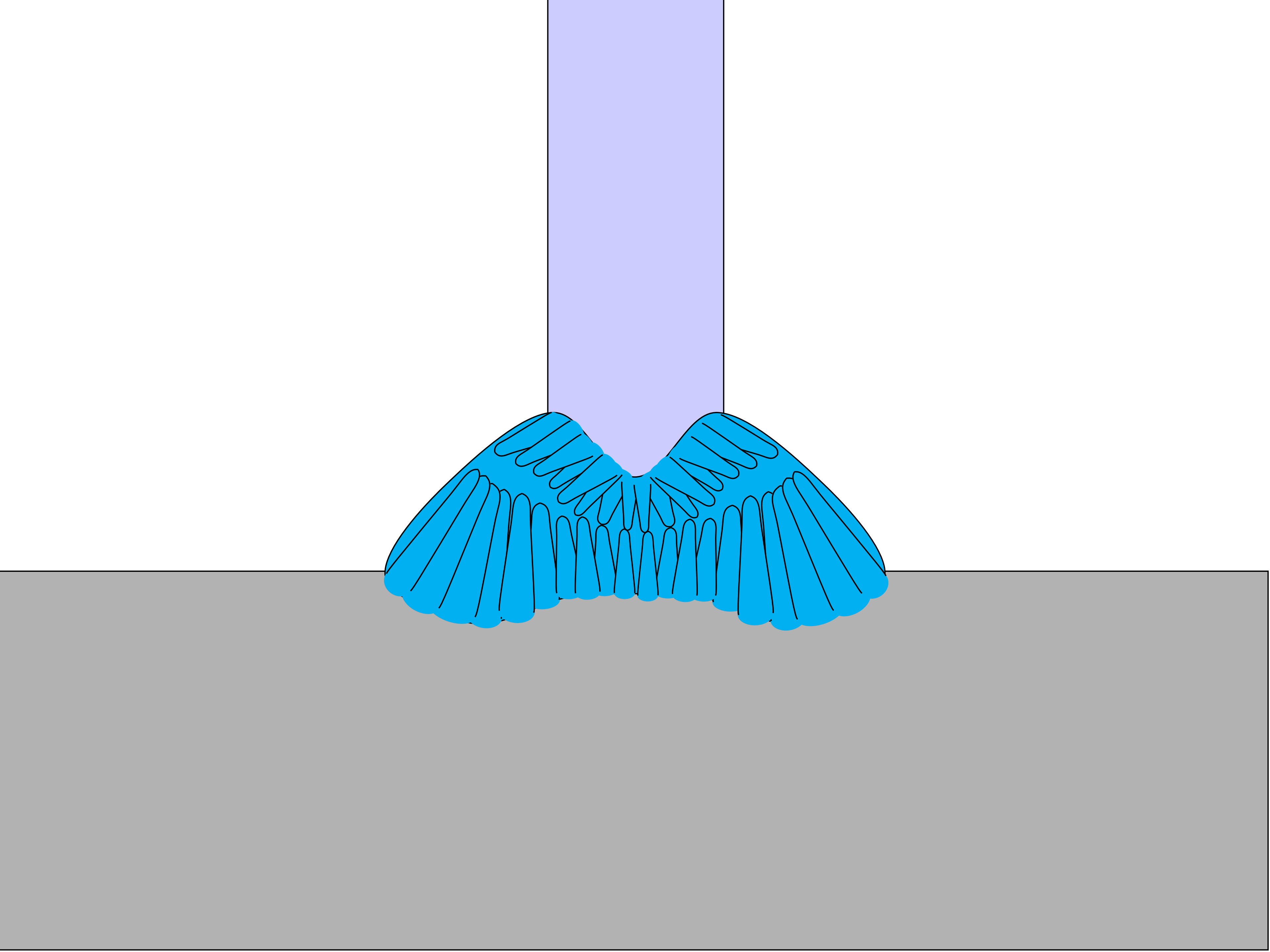


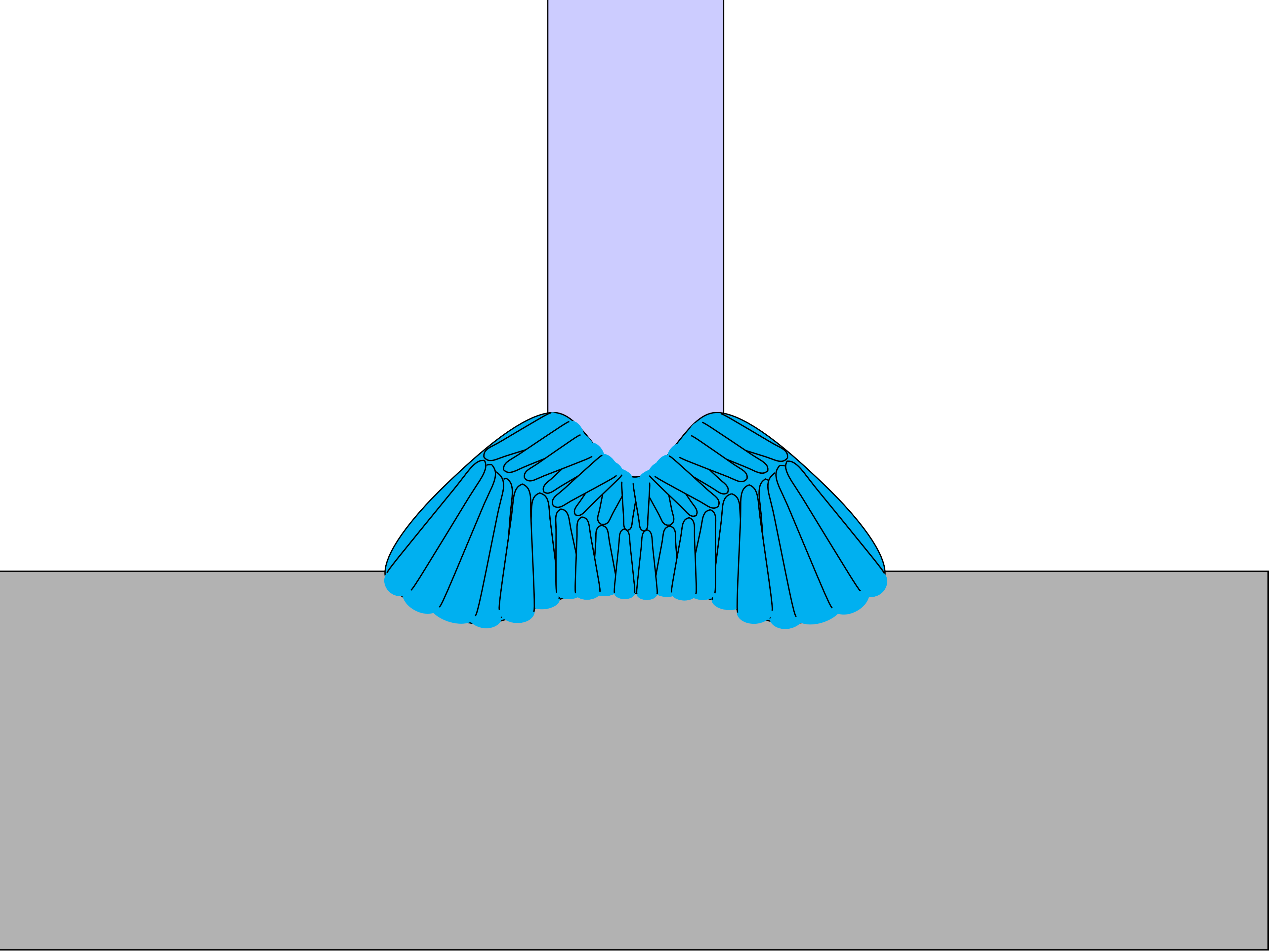


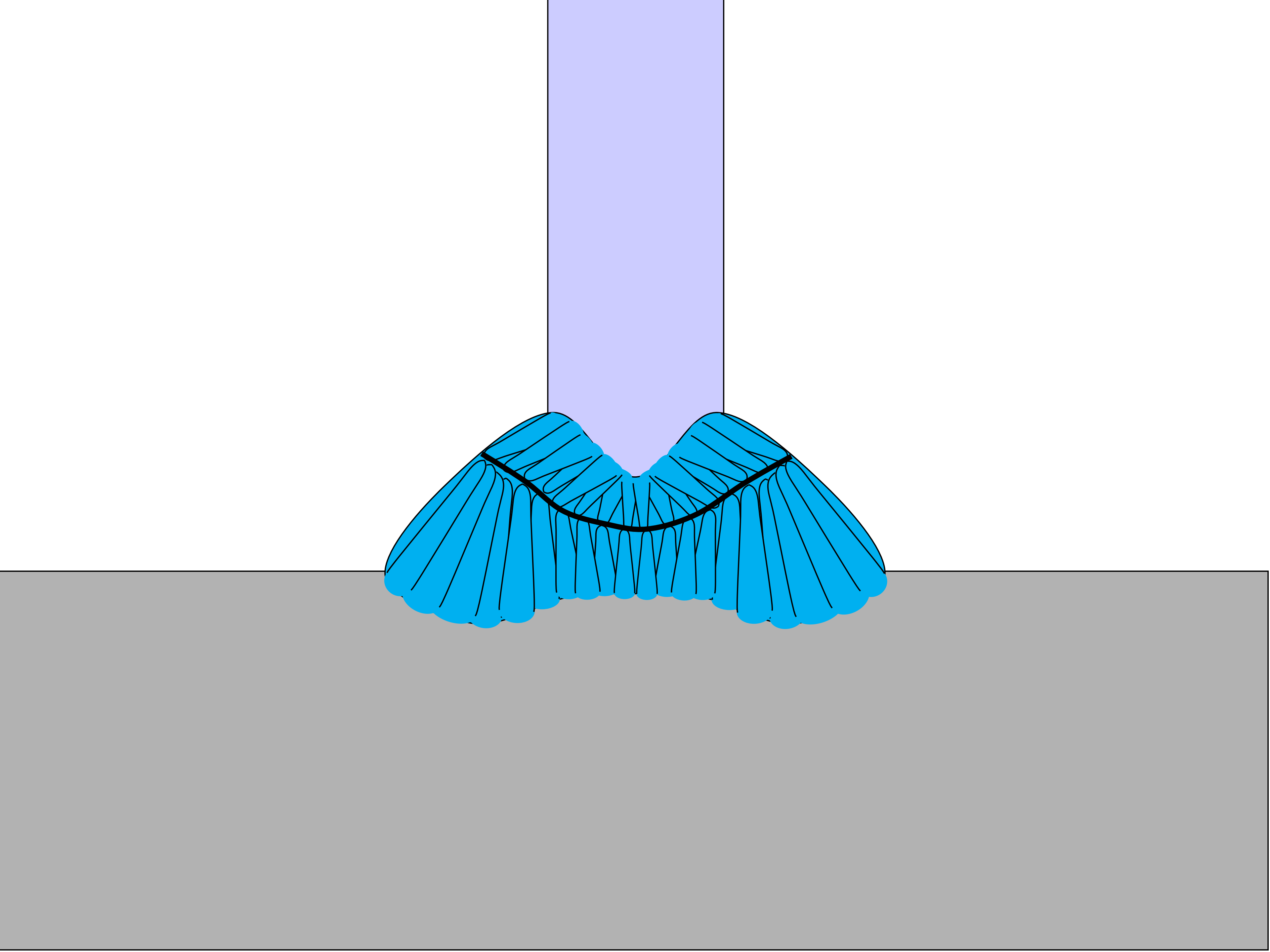


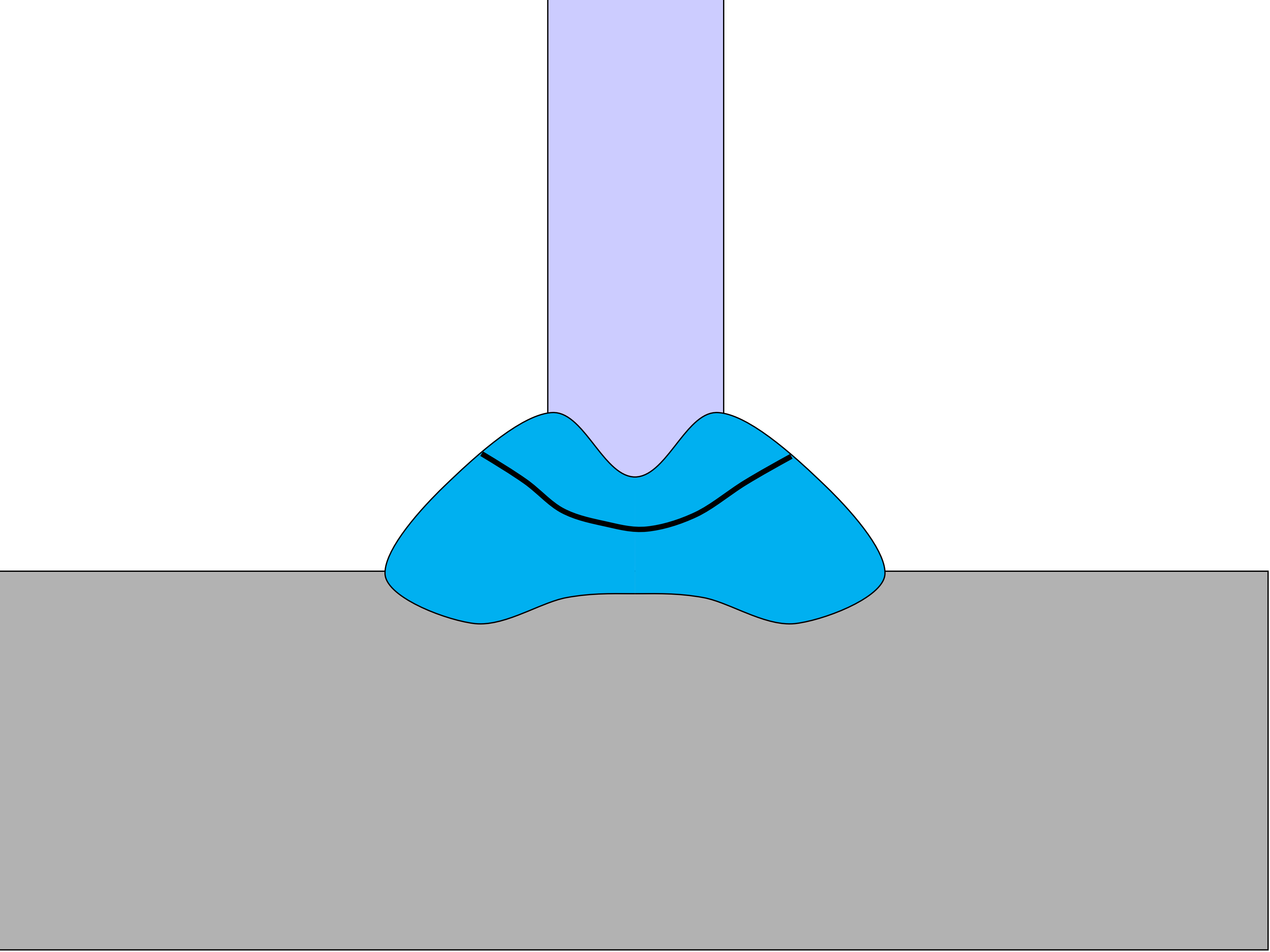


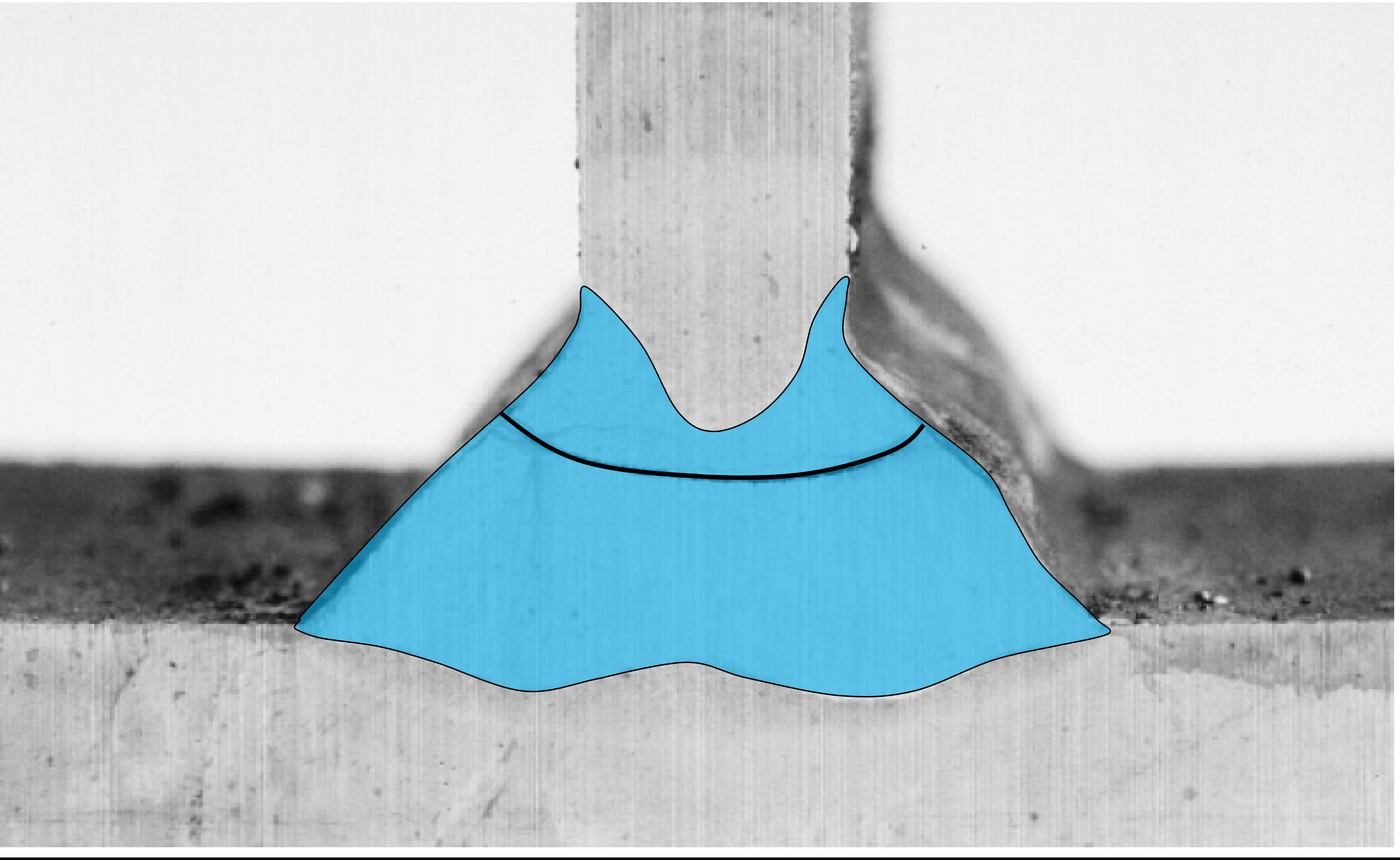


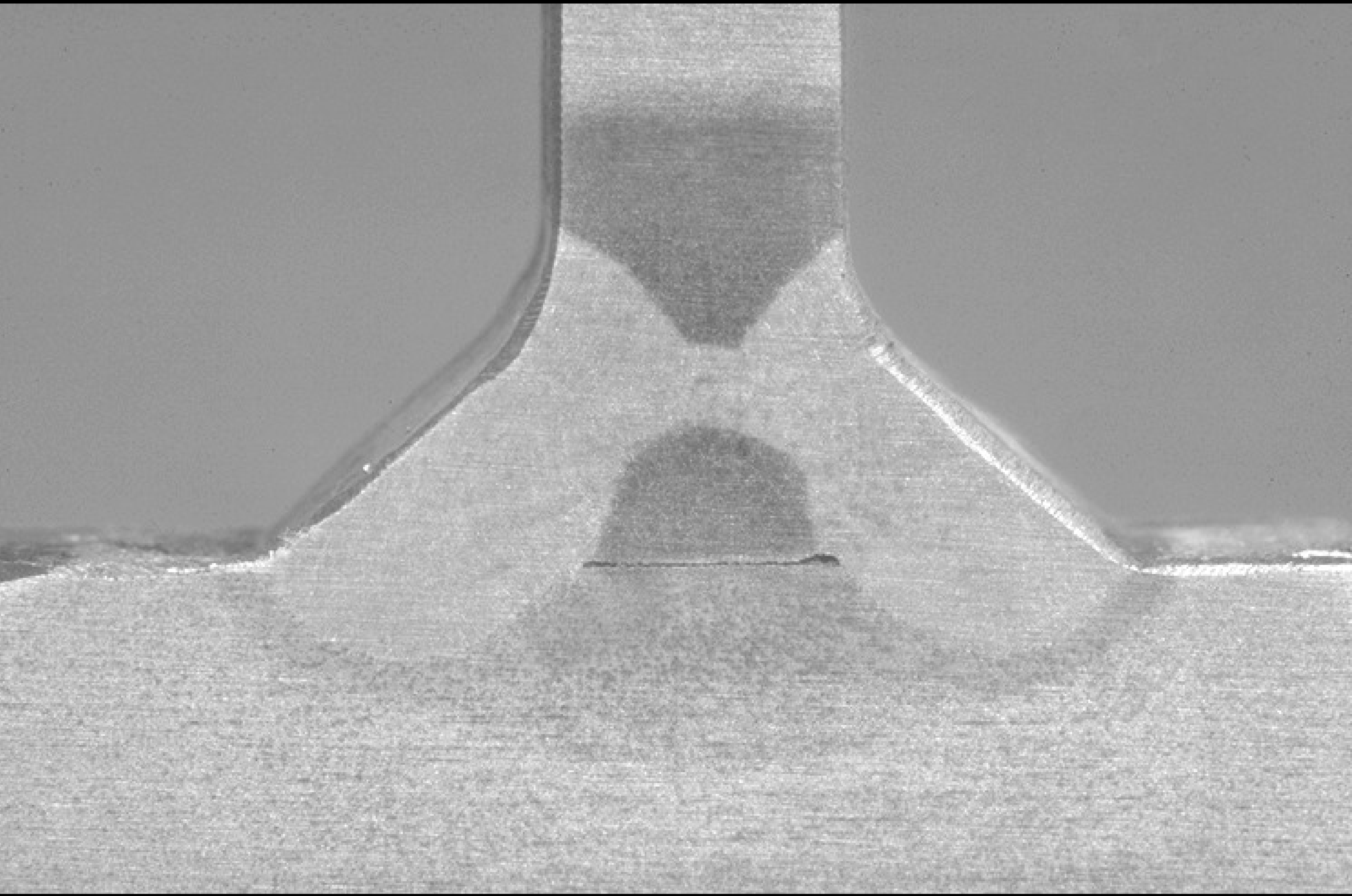


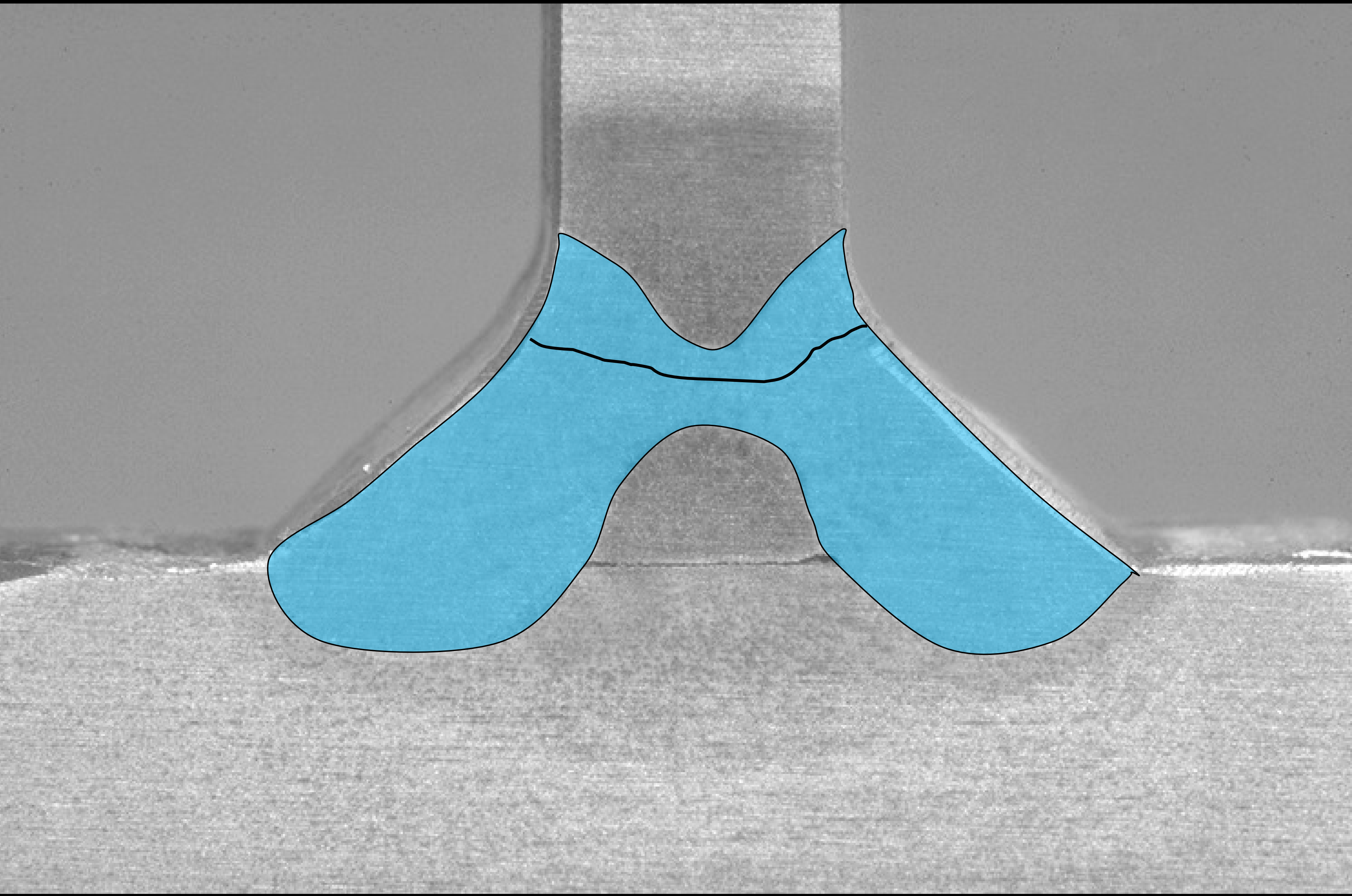


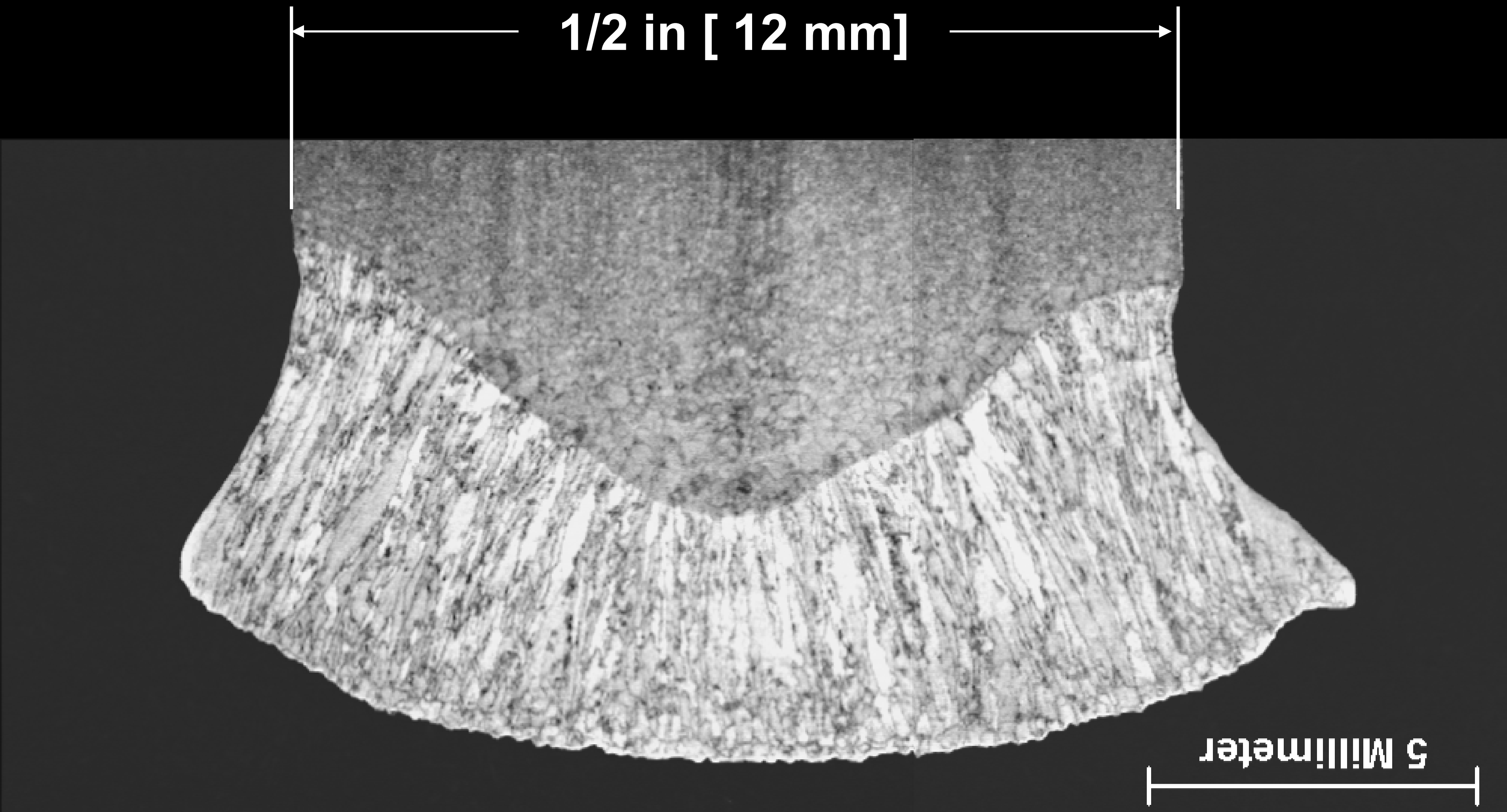




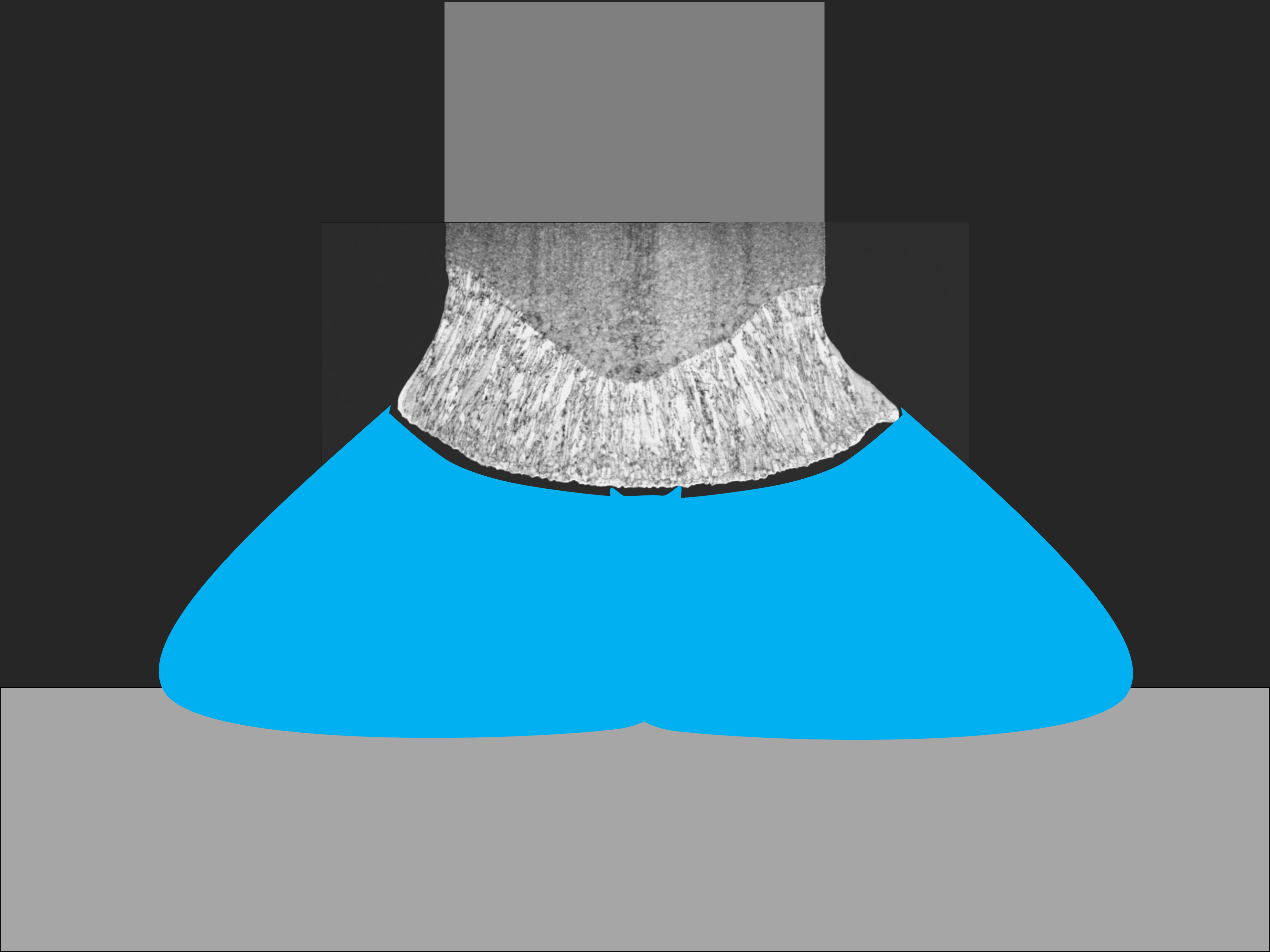








HPS70W Stiffener



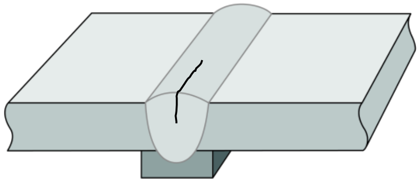
Opposed Arc Cracking

Cause: Bridging of puddle across tee joint

Solution: Eliminate the bridging

- Use thicker stiffeners (> 3/8 [10 mm])
- Cascade the arcs so they are not opposed
- Adjust welding current and current density
- Adjust torch angle and electrode placement

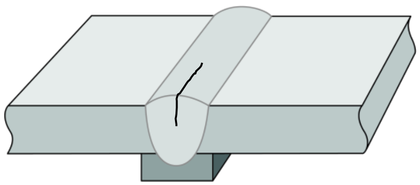
Centerline Cracking

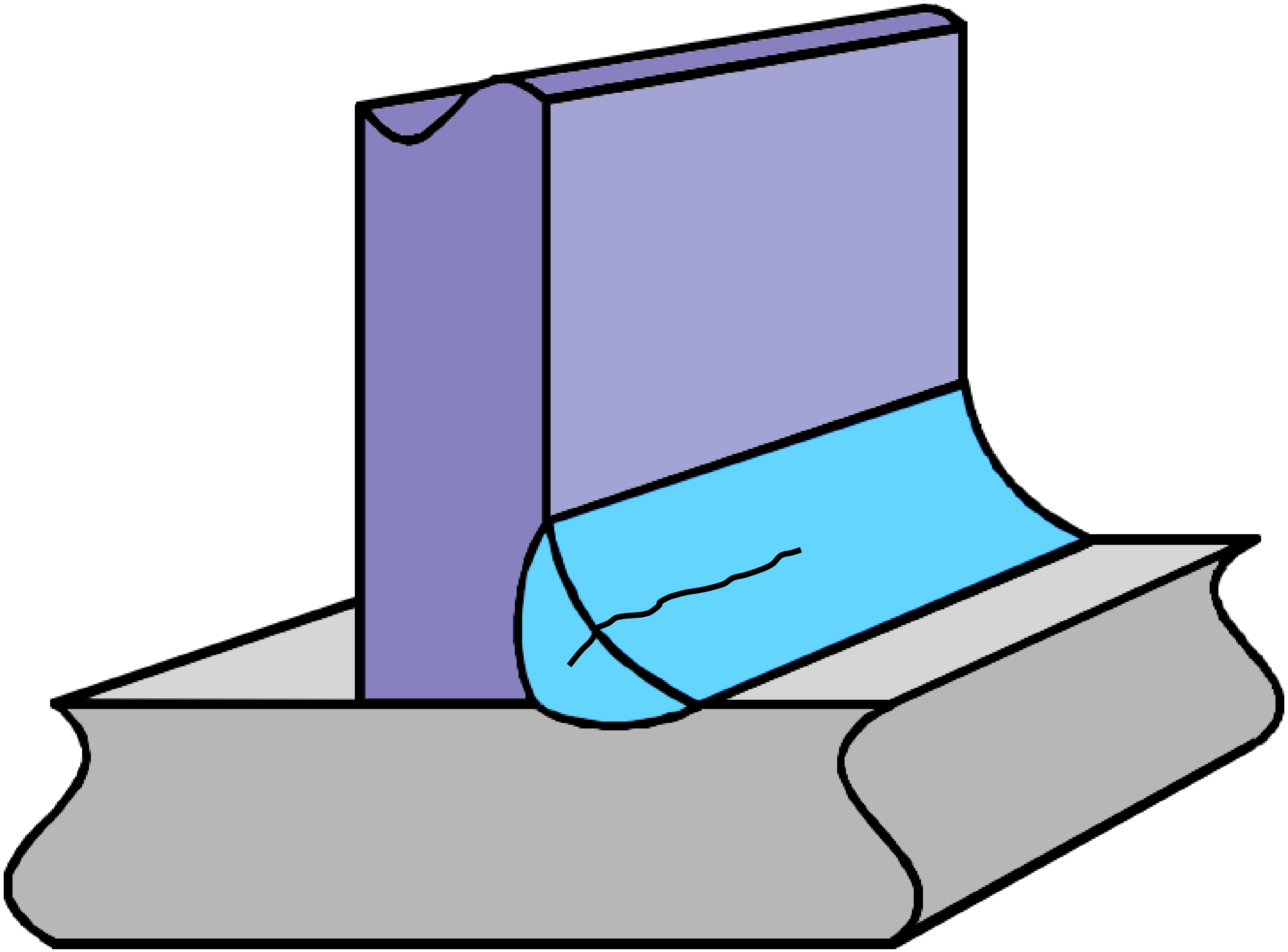


Cause 3: Surface Profile Cracking

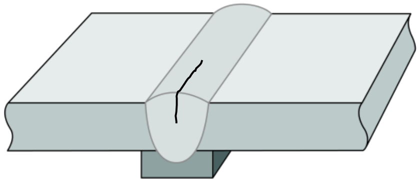
The surface of the weld is concave

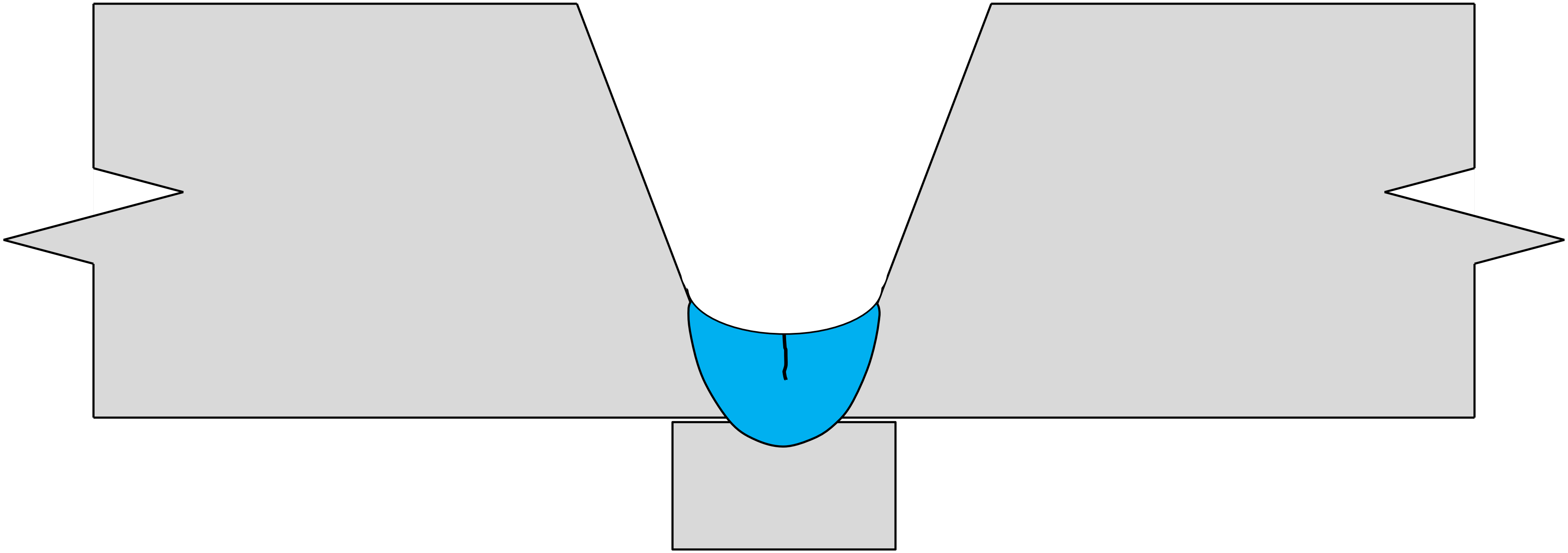
Centerline Cracking



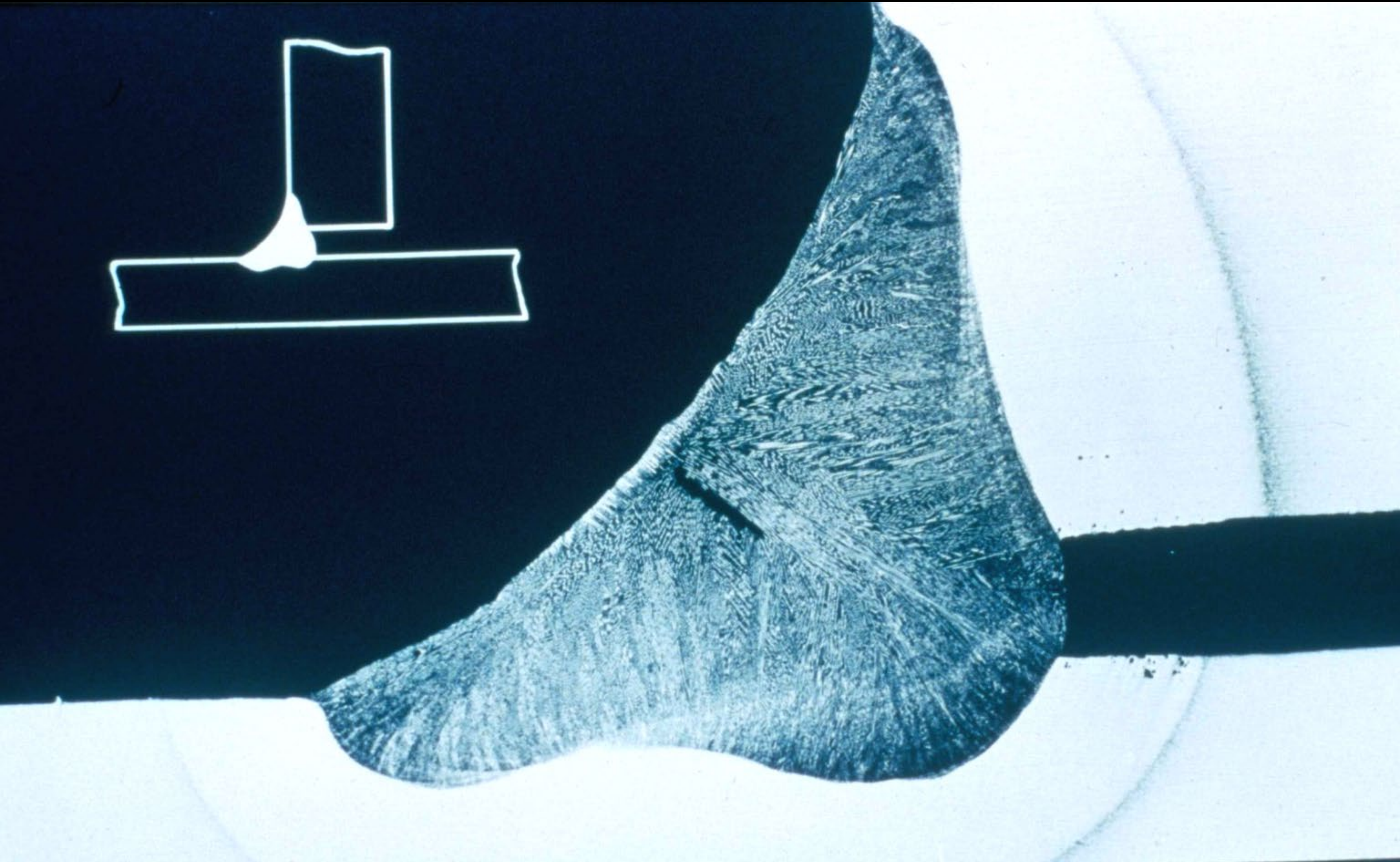


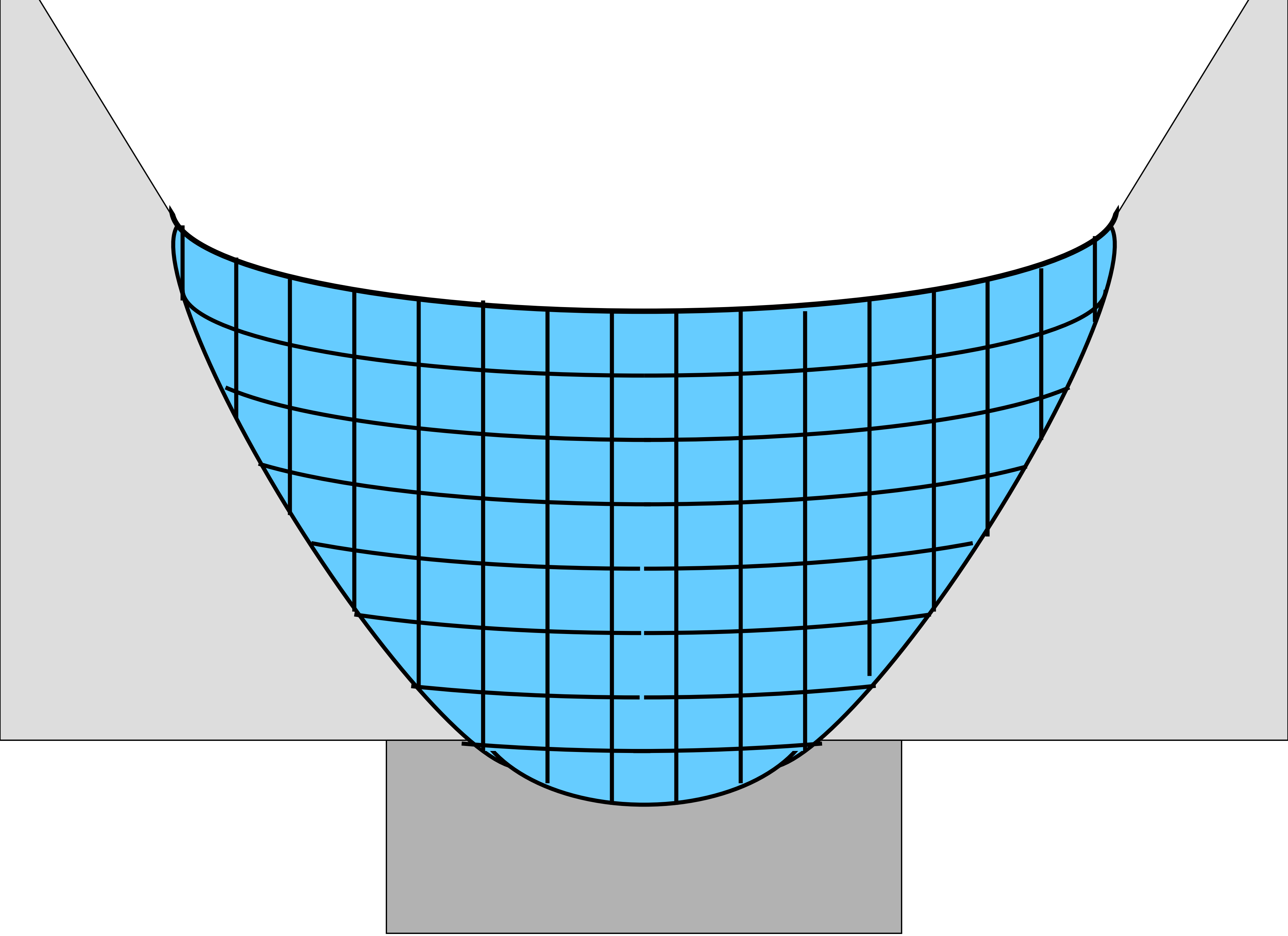
Centerline Cracking

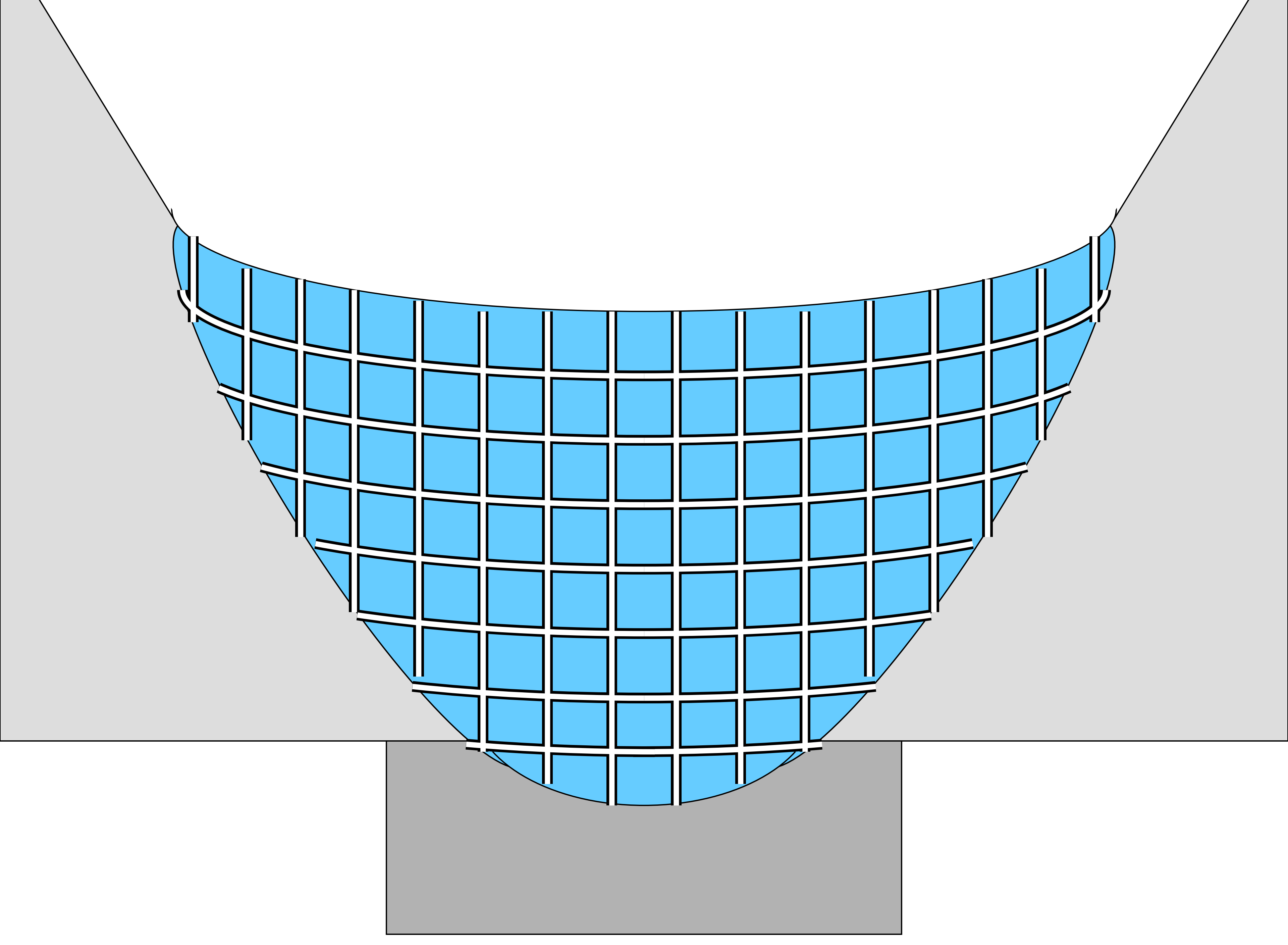


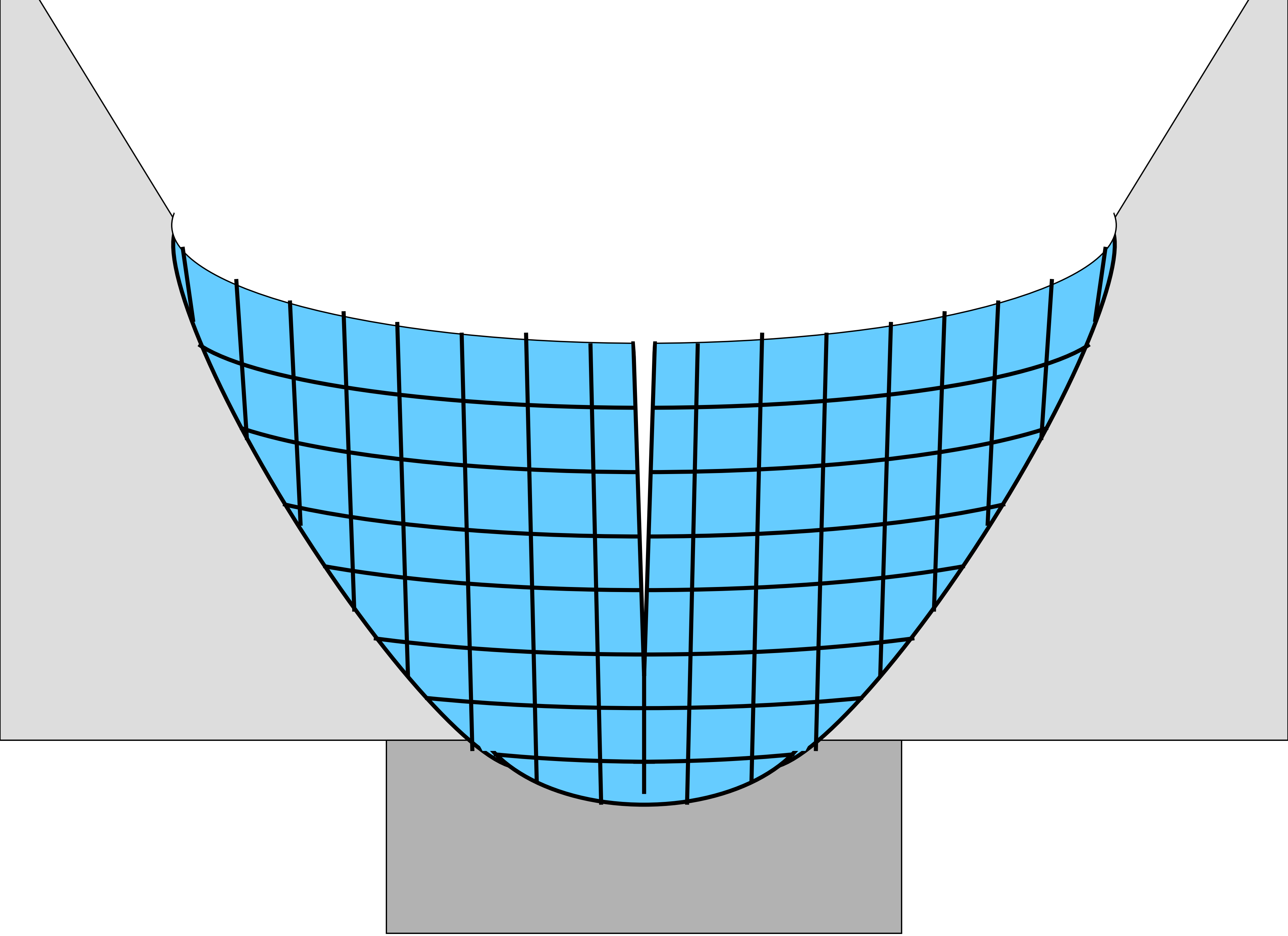


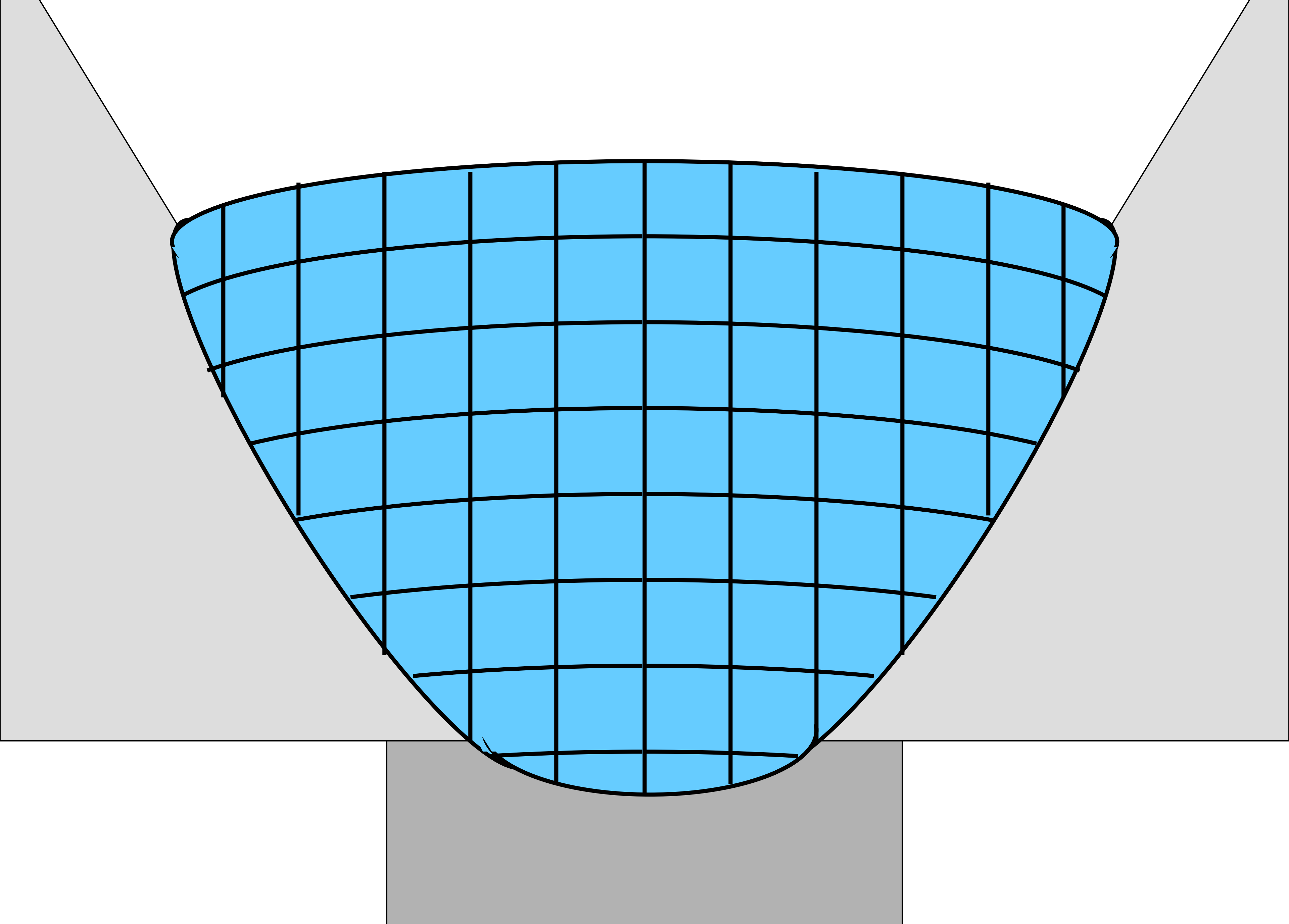
Any concave pass, especially root passes

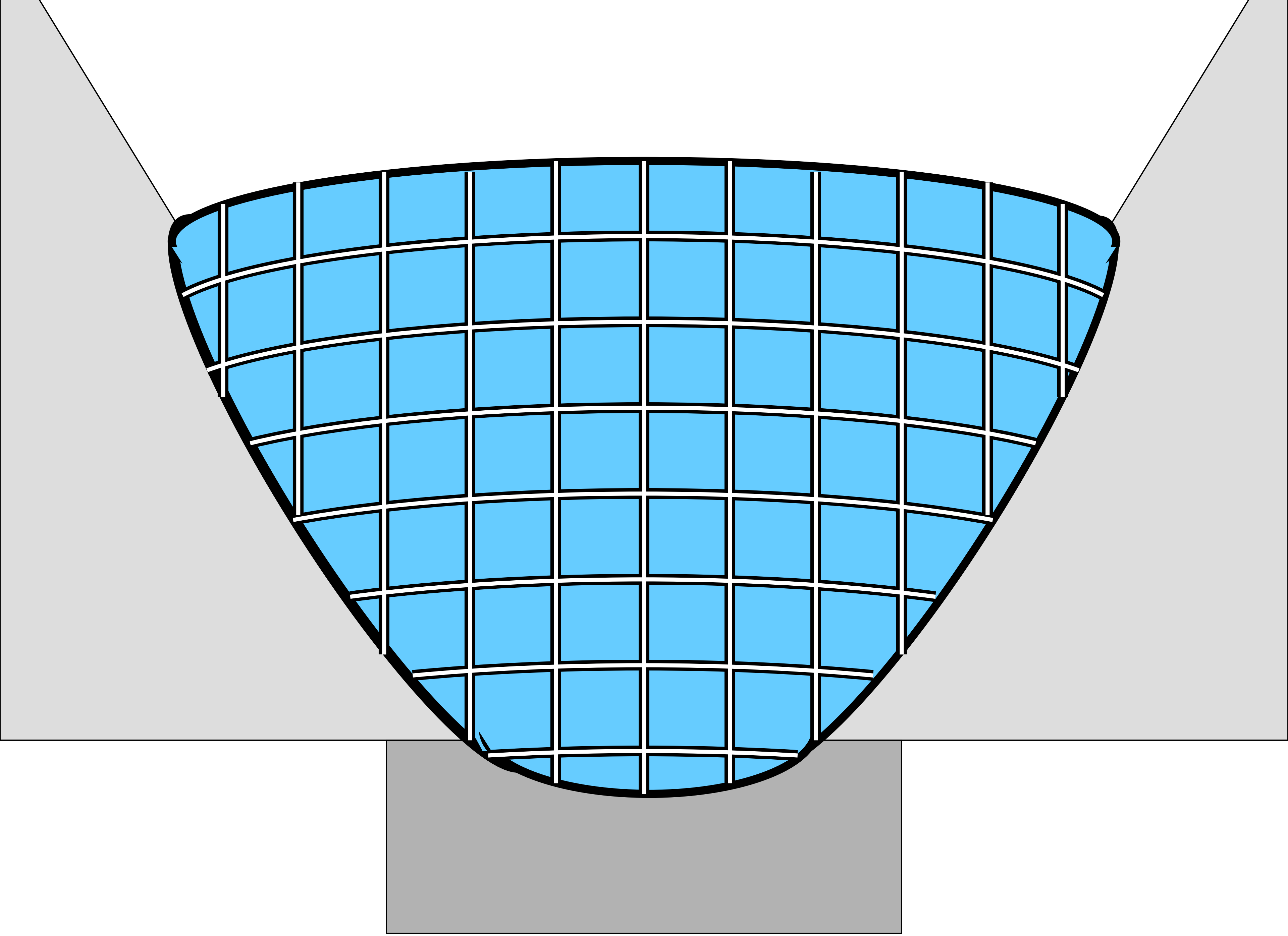


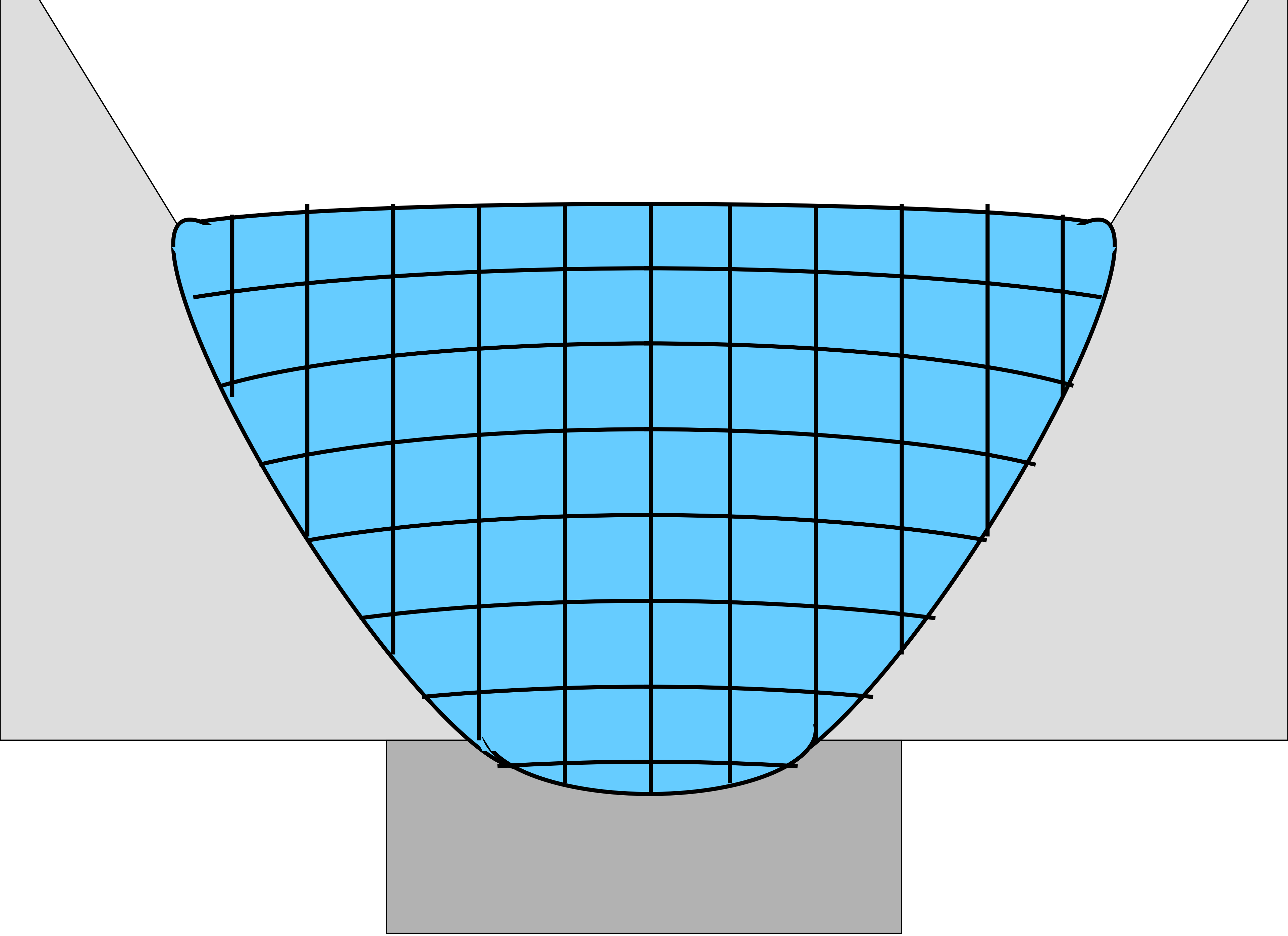






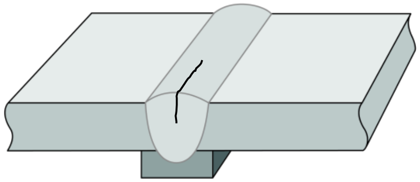






Centerline Cracking

Cause 3: Surface Profile Cracking

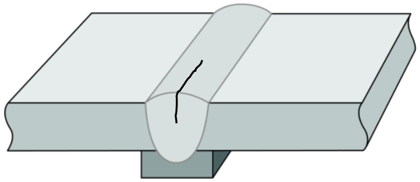


The surface of the weld is concave

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_2 combinations tend to give flatter/more convex beads
    - Vertical up (convex) versus vertical down (concave)
    - Lower voltage, amperage (“colder”)

Centerline Cracking



Cause 3: Surface Profile Cracking

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Solution: Make sure the bead surface is convex

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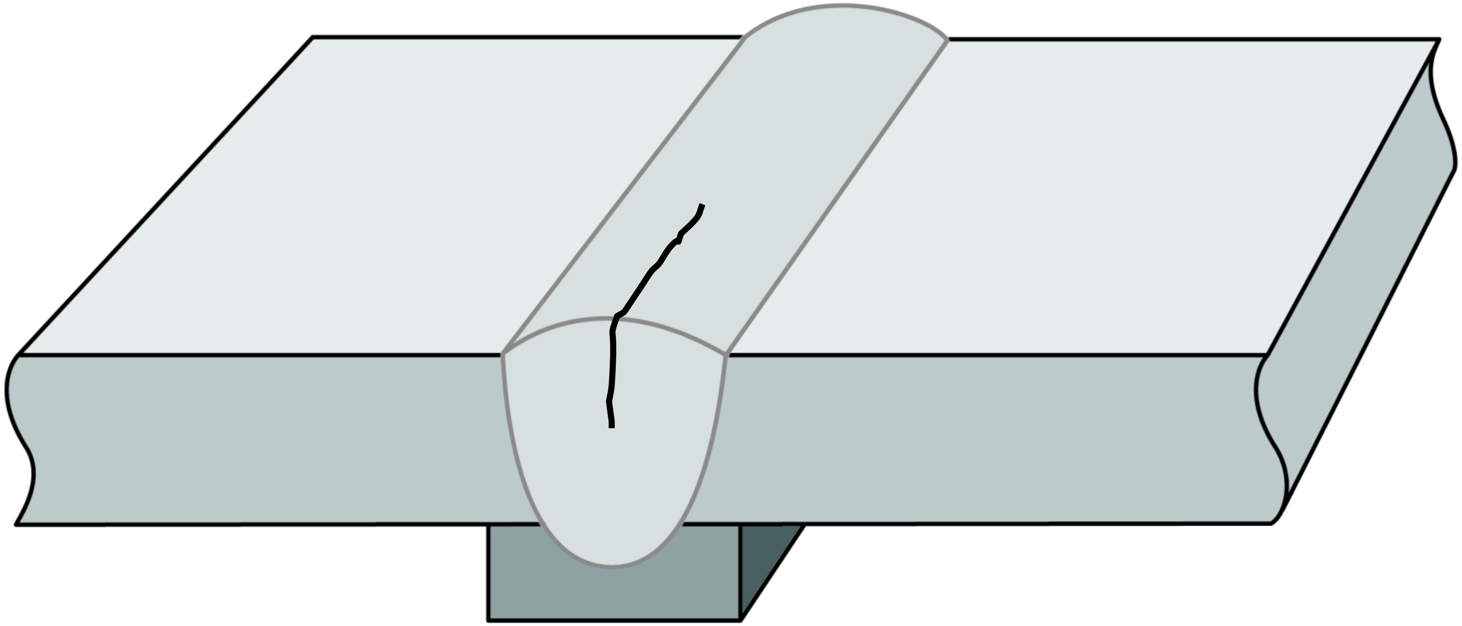
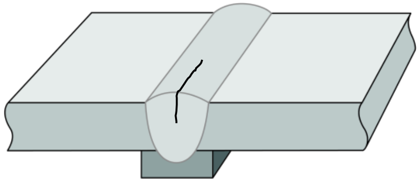
Centerline Cracking



Centerline Cracking

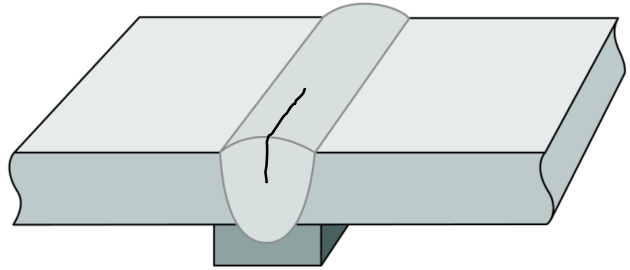


Cause 1: Segregation Cracking
Cause 2: Width-to-Depth Ratio Cracking
Cause 3: Surface Profile Cracking

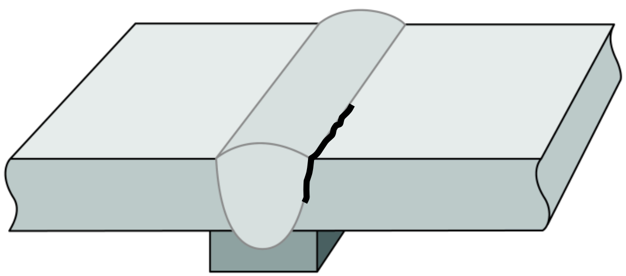
To troubleshoot, use a countdown.

- 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.

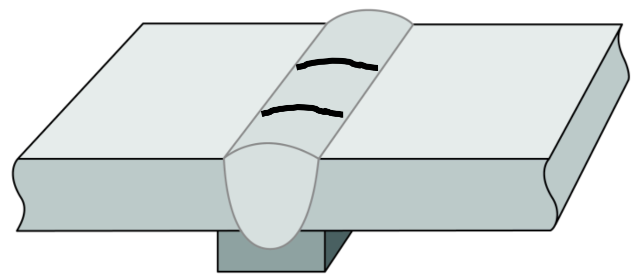
HOT CRACK



Centerline



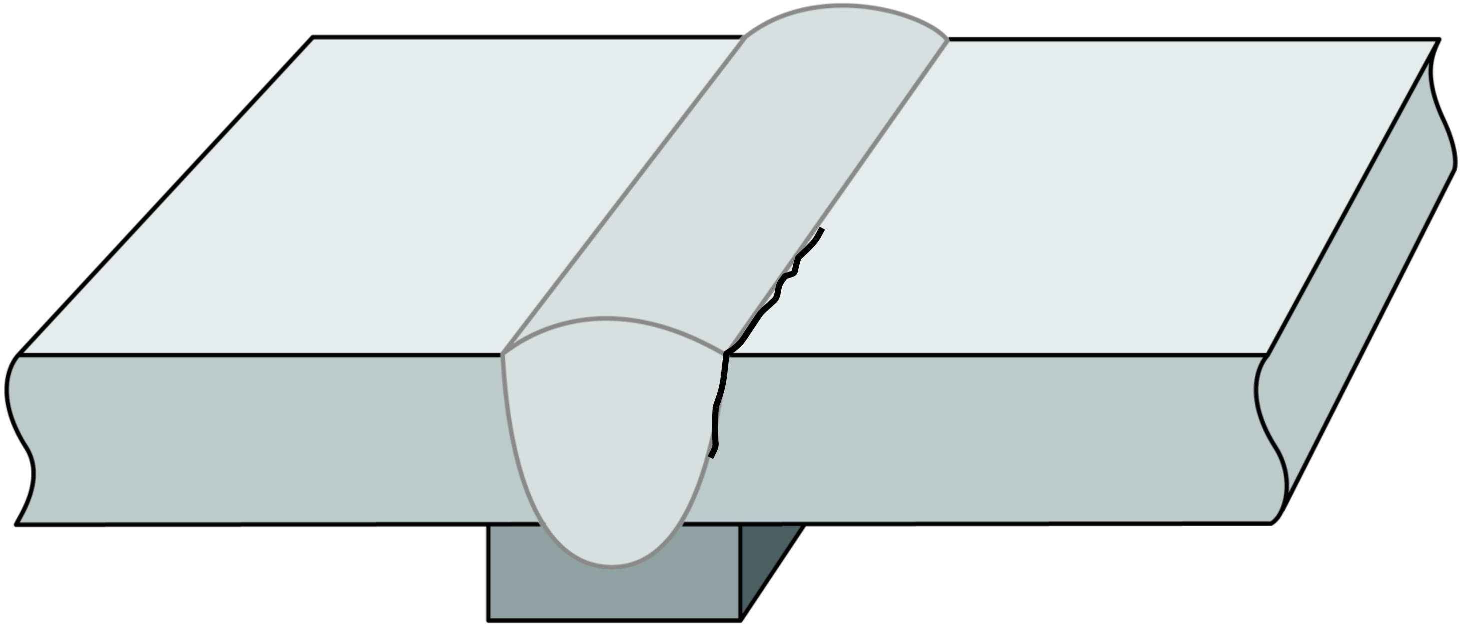
Underbead

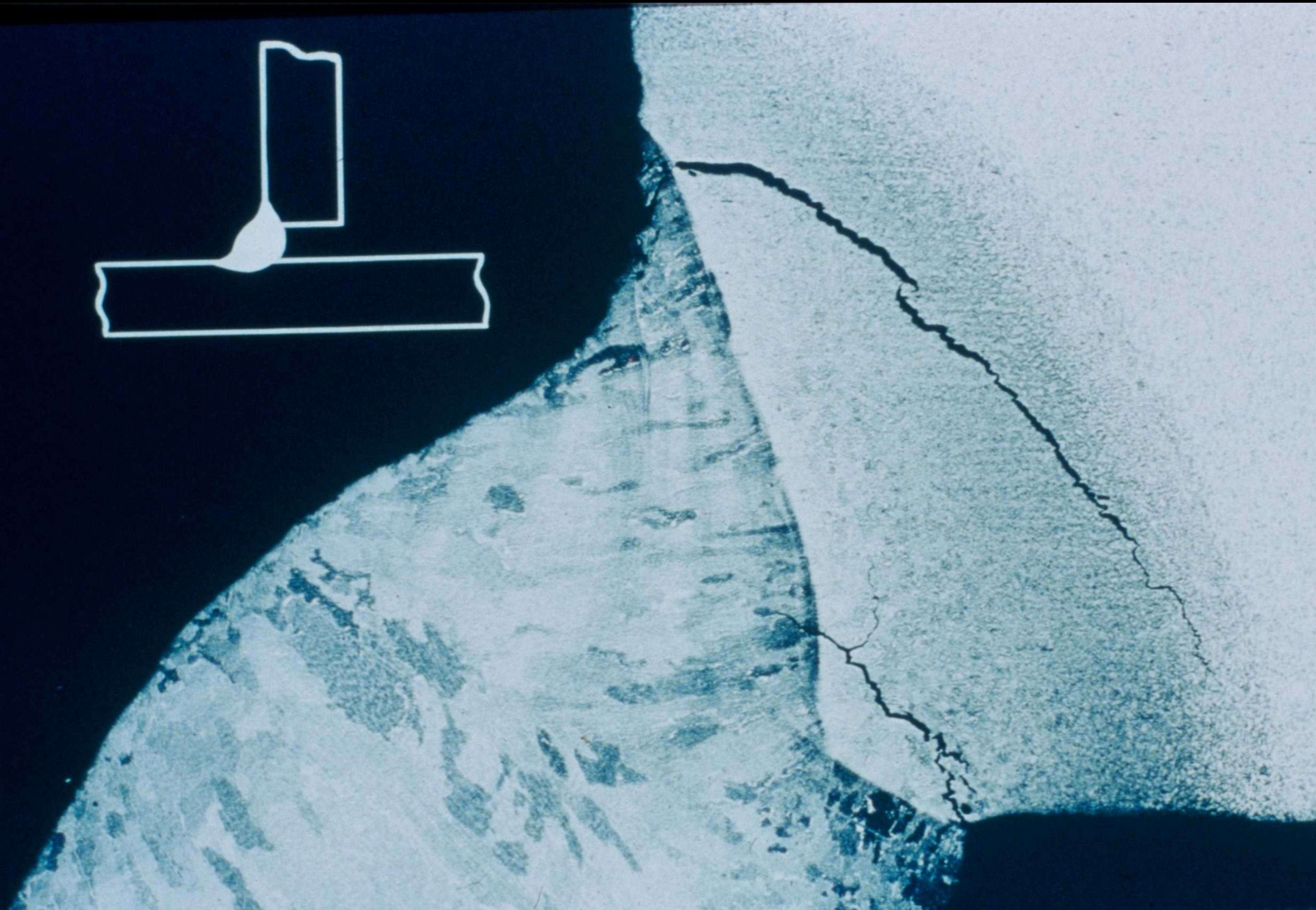


Transverse

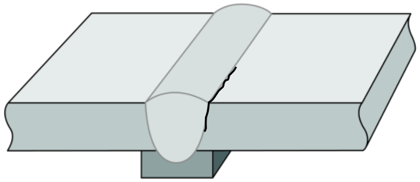
COLD CRACKS

Underbead Cracking





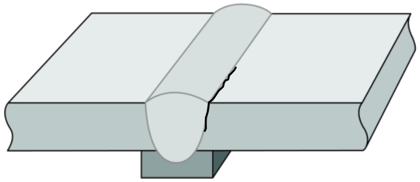
Underbead Cracking



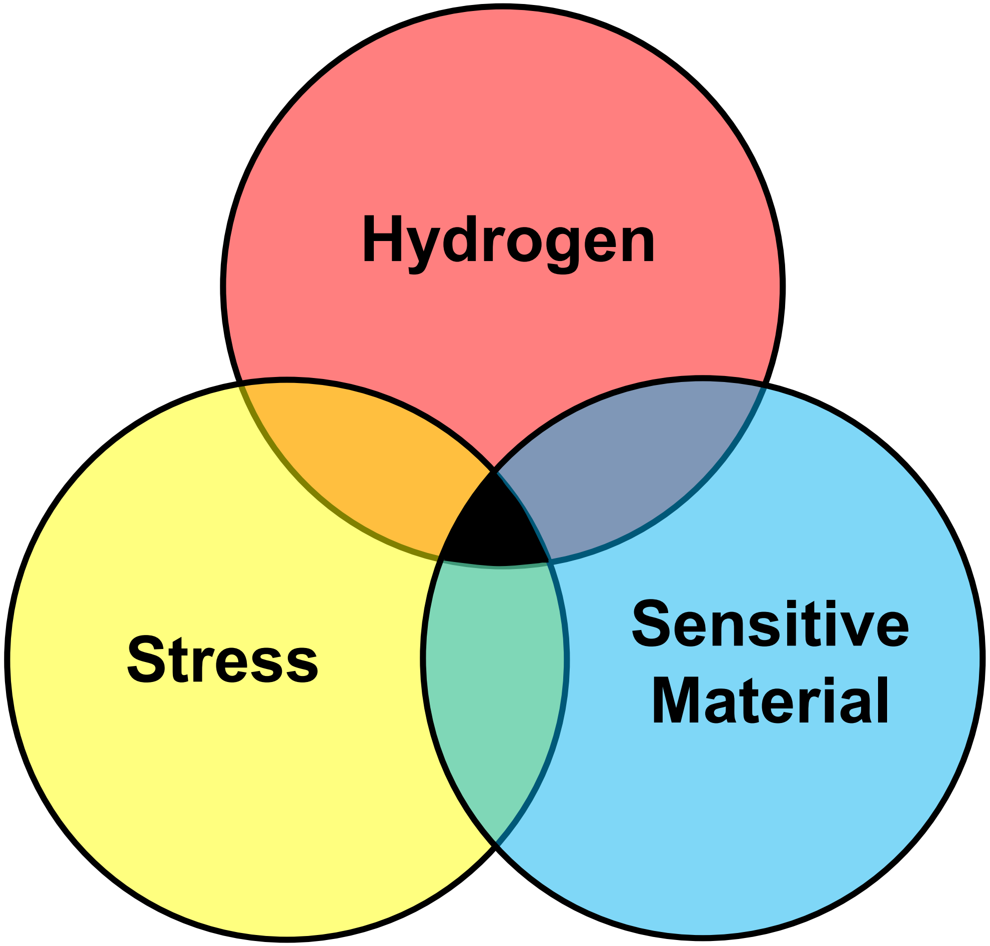
Characteristics

- 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

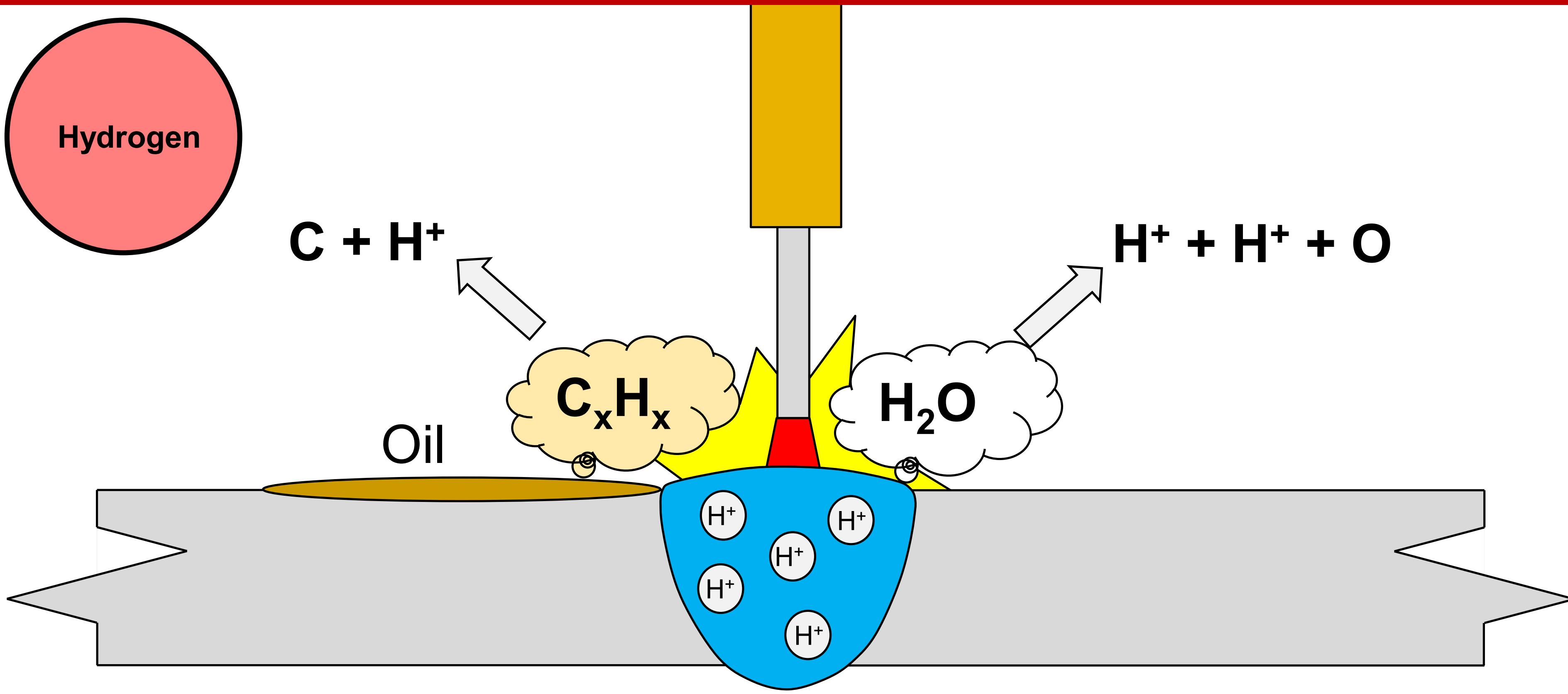
Underbead Cracking



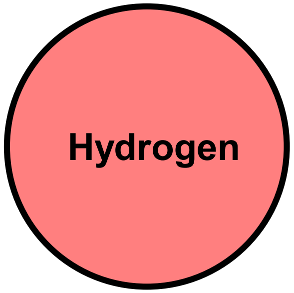
Cause: Excessive hydrogen AND an applied or residual AND a sensitive material

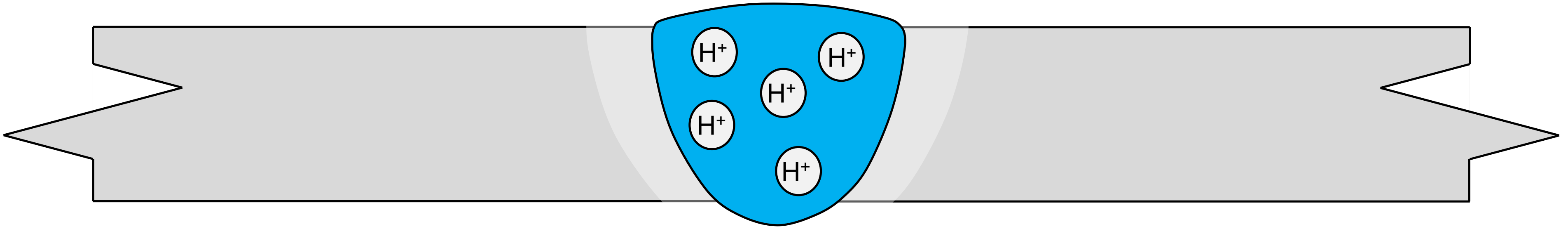


Development of atomic hydrogen

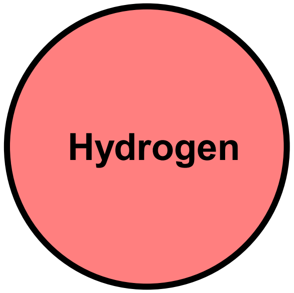


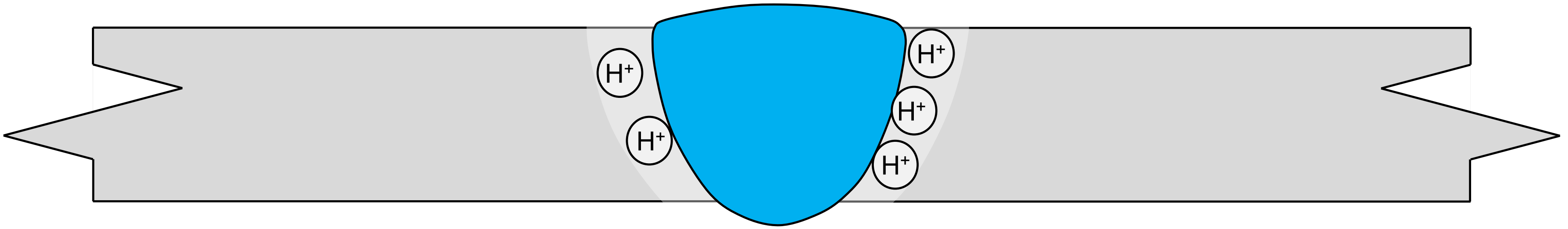
Migration of atomic hydrogen



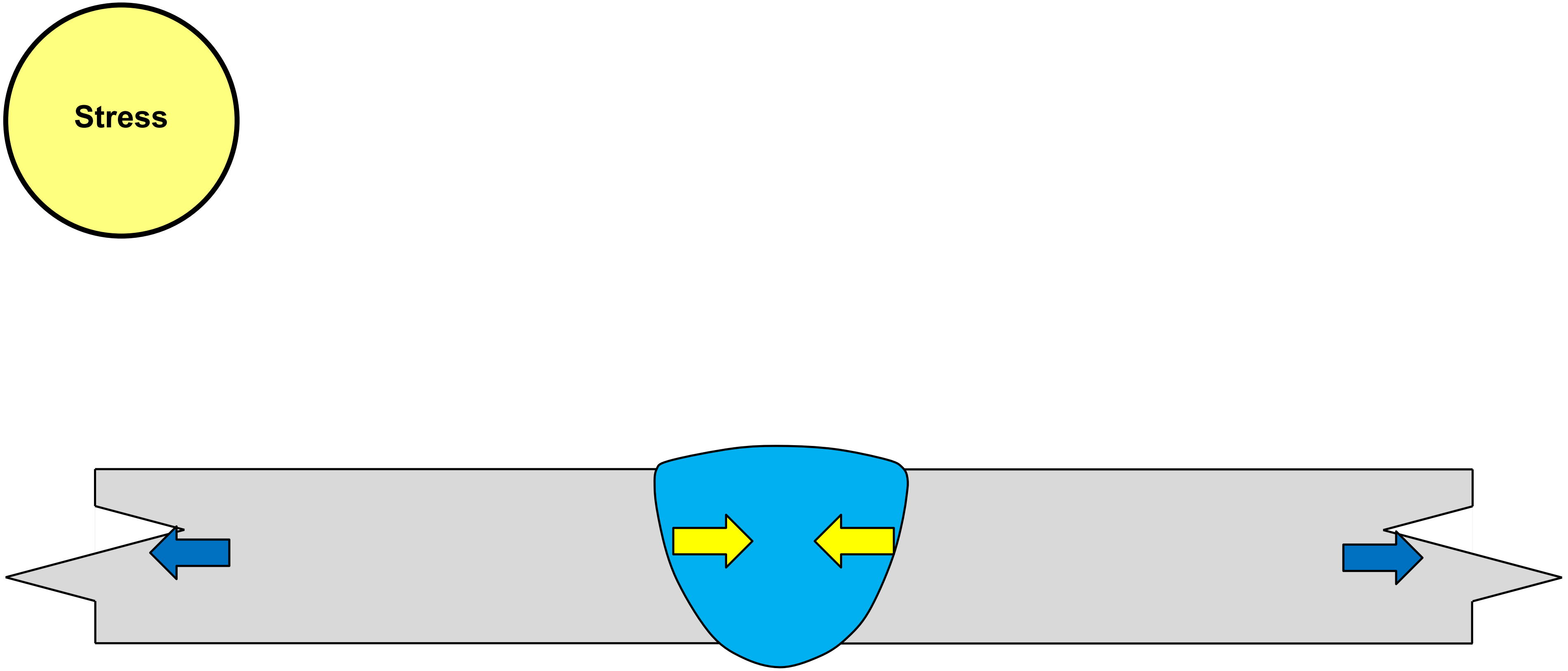


Migration of atomic hydrogen

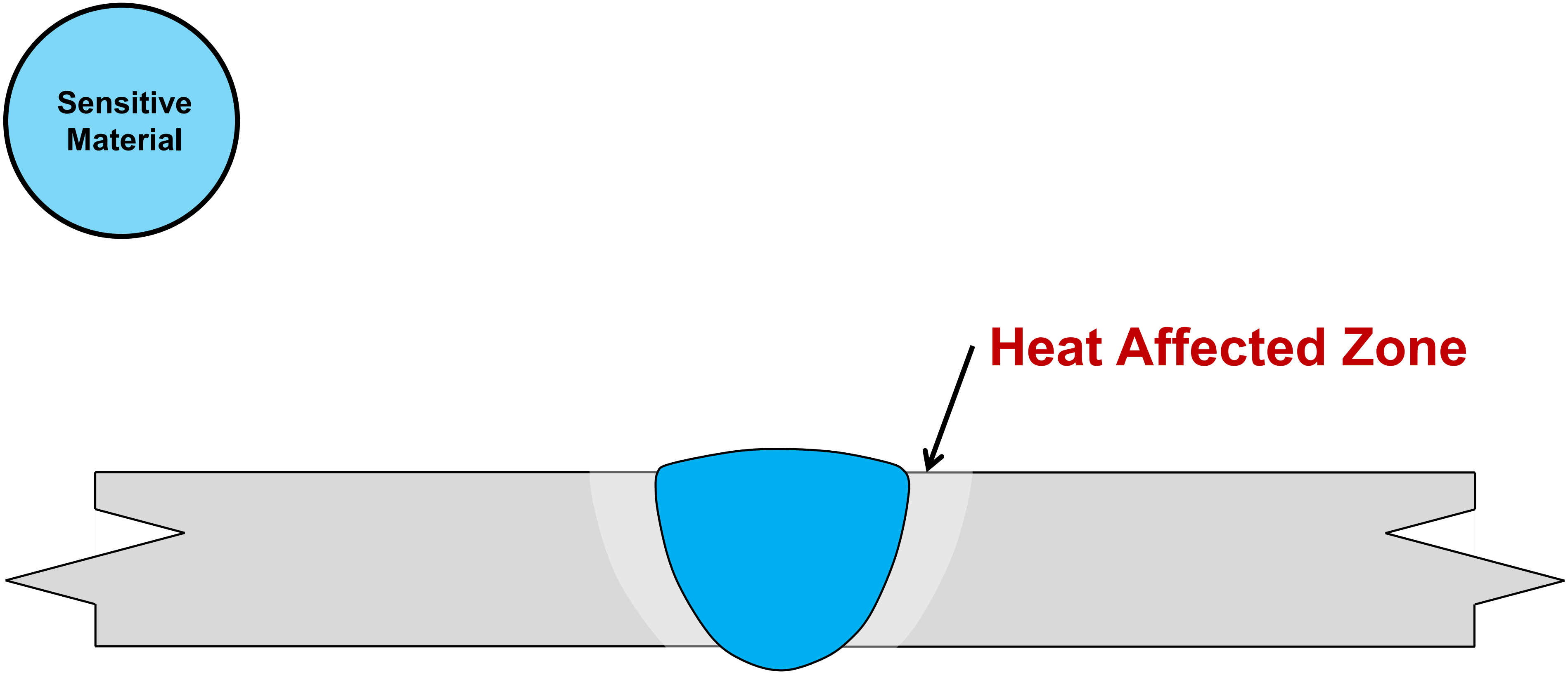




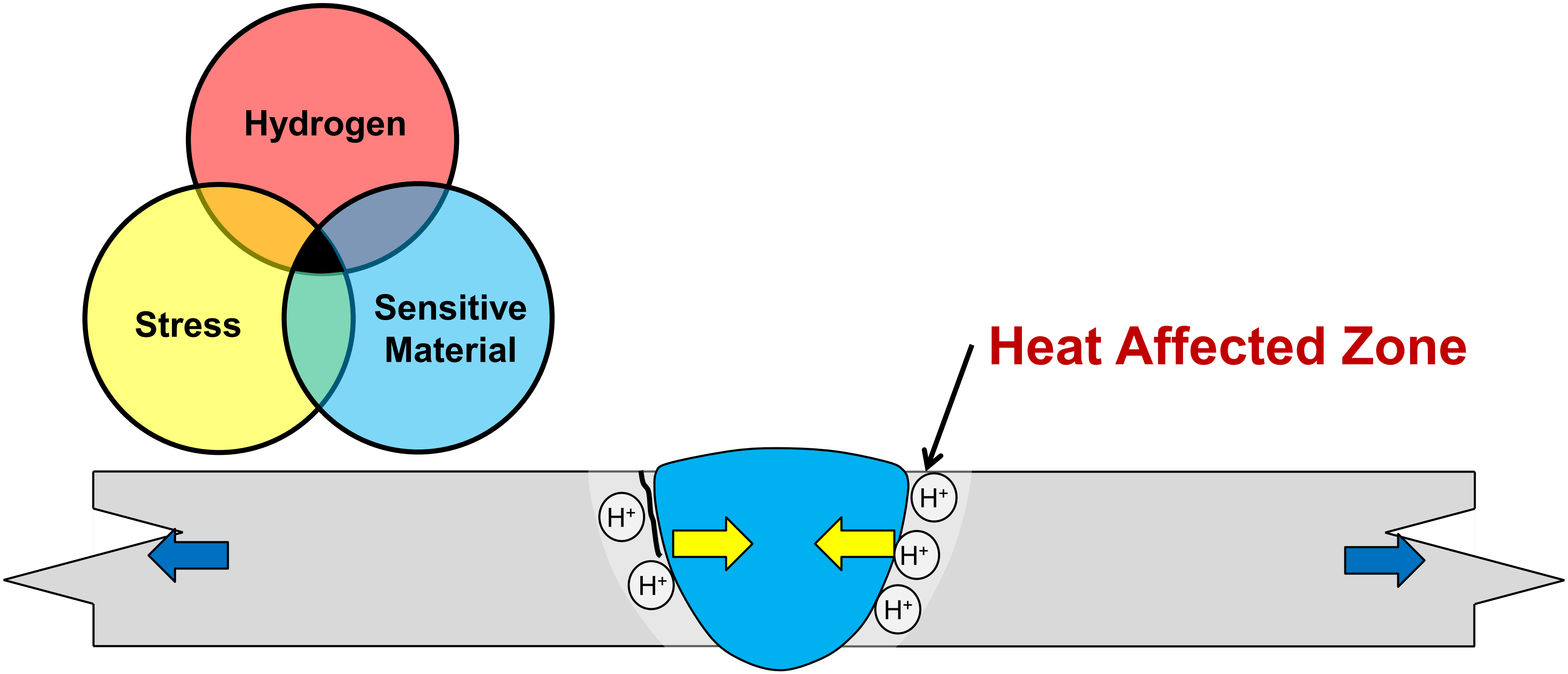
Shrinkage Stresses



Sensitive Material

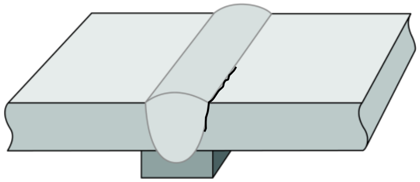


Combining all three….



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".

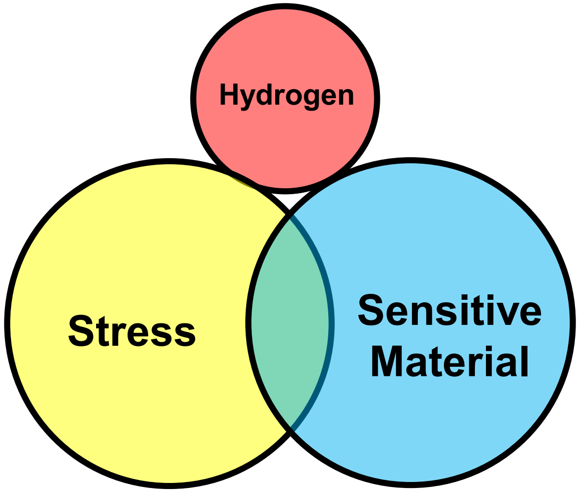
Underbead Cracking



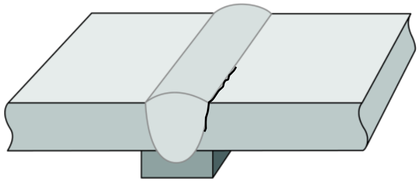
Cause: Excessive hydrogen AND a sensitive material AND an applied or residual stress

Solution:

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



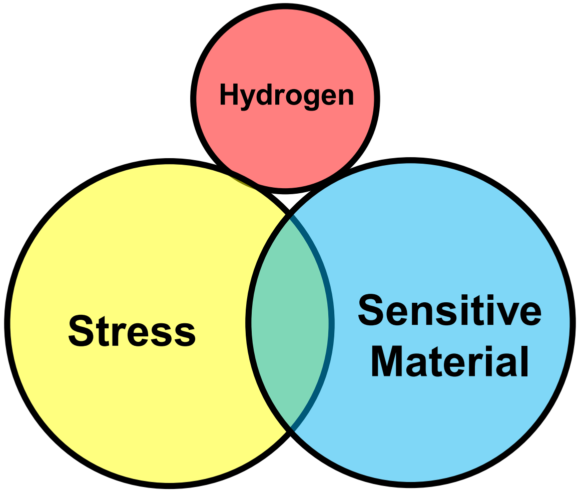
Underbead Cracking



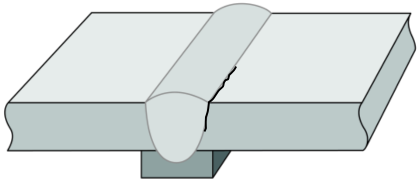
Cause: Excessive hydrogen AND
a sensitive material AND
an applied or residual stress

Solution:

- Maximize diffusion of hydrogen
  - Increased preheat
  - Increased interpass temperature
  - Higher heat input
  - Thinner weld layers
  - Increased time between passes
  - Slower cooling after welding
  - Post heat



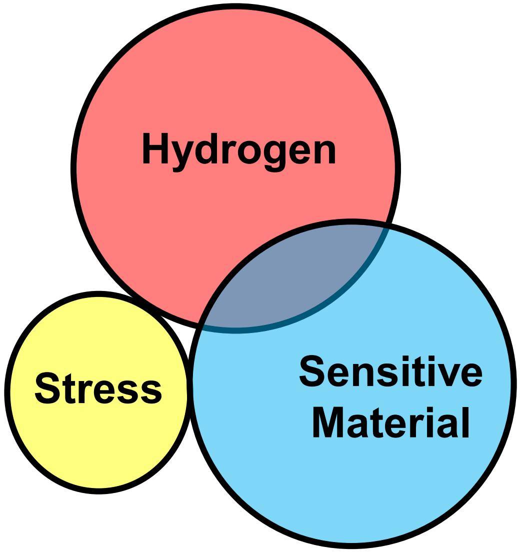
Underbead Cracking



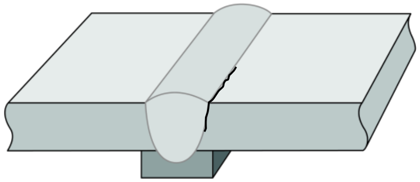
Cause: Excessive hydrogen AND
a sensitive material AND
an applied or residual stress

Solution:

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



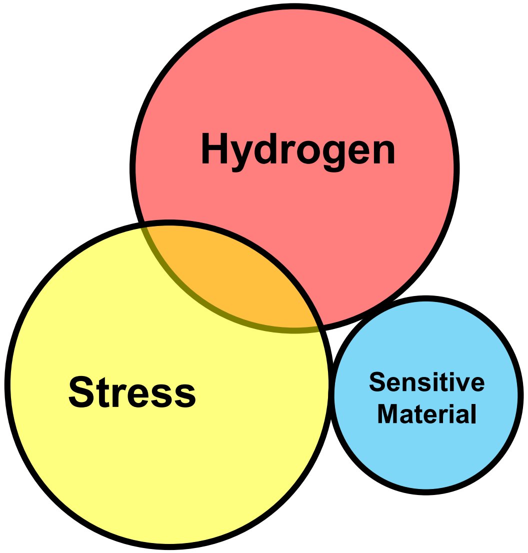
Underbead Cracking



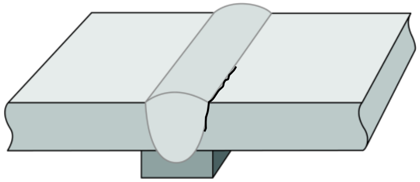
Cause: Excessive hydrogen AND a sensitive material AND an applied or residual stress

Solution:

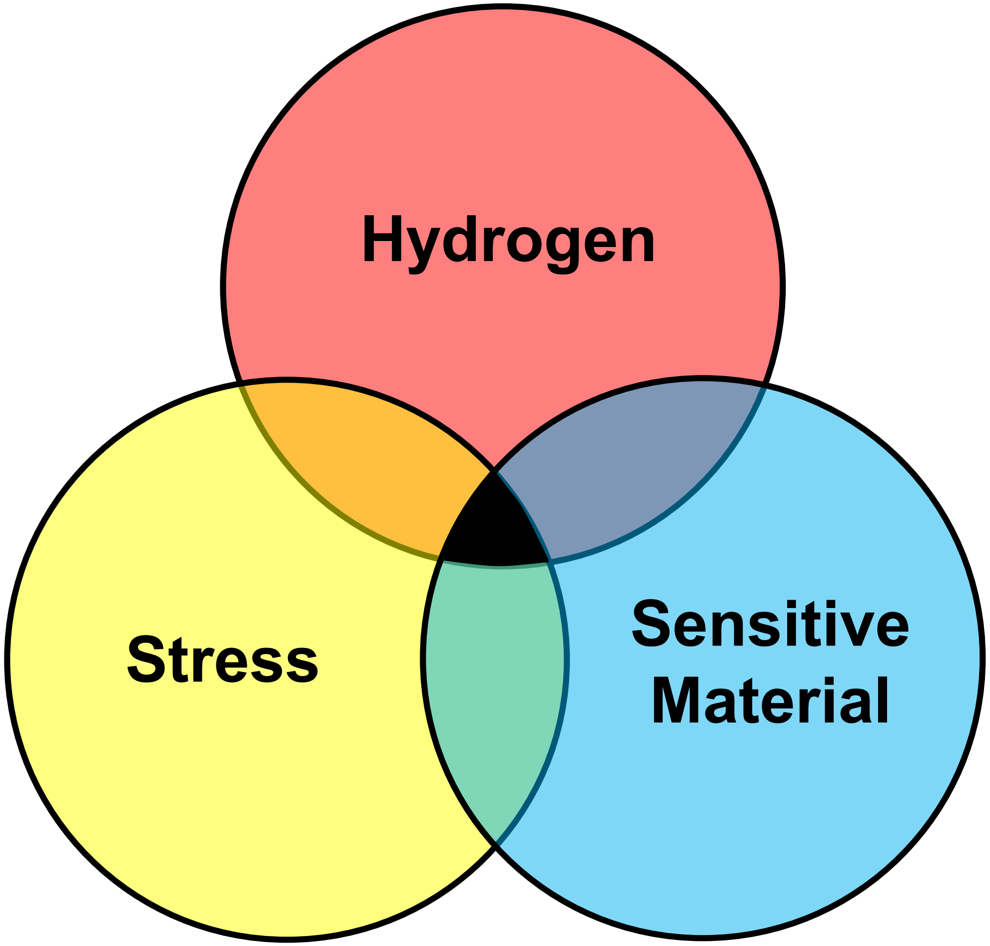
- Reduce Material (HAZ) Sensitivity
  - Selection of base metal (low hardenability—low carbon, low alloys)
  - Increased preheat
  - Higher heat input
  - Increased interpass temperature



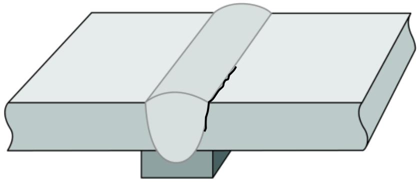
Underbead Cracking



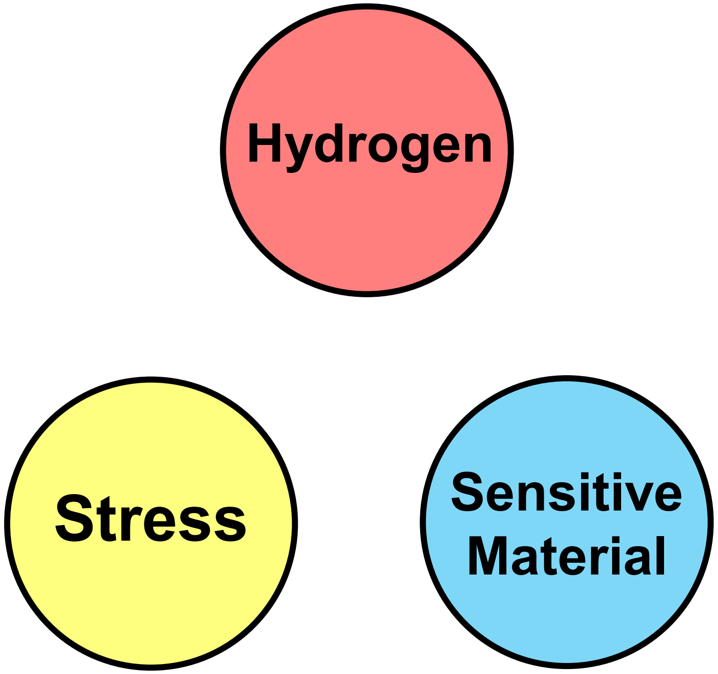
Cause: Excessive hydrogen AND an applied or residual AND a sensitive material



Underbead Cracking



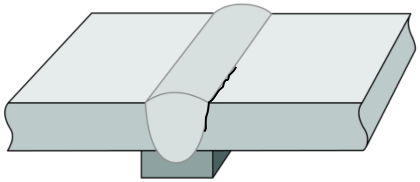
Cause: Excessive hydrogen AND an applied or residual AND a sensitive material

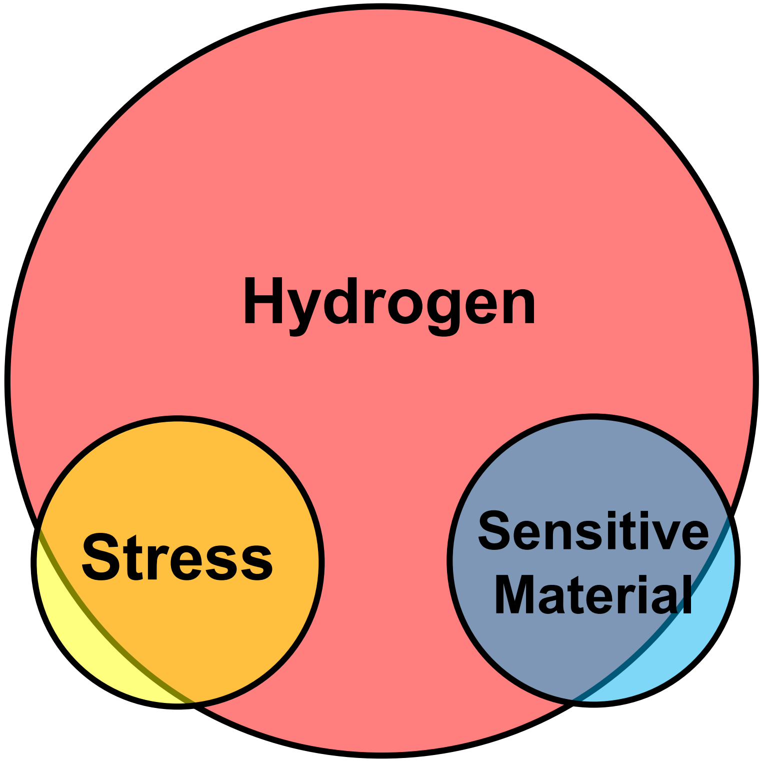


Typically, when an underbead cracking problem is encountered, all three variables are reduced.

Underbead Cracking

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





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

AASHTO/AWS D1.5:2015 Bridge Welding Code

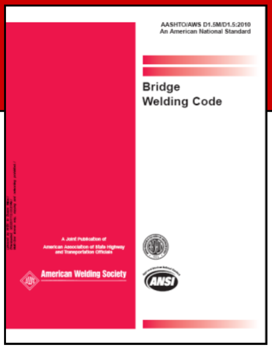


Table 4.3
Minimum Preheat and Interpass Temperature, °C [°F]

Welding Process (Base Metal)	To 20 mm [3/4 in] Incl.	Over 20 mm [3/4 in] to 40 mm [1-1/2 in] Incl.	Over 40 mm [1-1/2 in] to 65 mm [2-1/2 in] Incl.	Over 65 mm [2-1/2 in]
	Thickness of Thickest Part at Point of Welding, mm [in]			
SAW; GMAW; FCAW; SMAW (M 270M/M 270 (A709/A709M) Gr. 250 [36], 345 [50], 345S [50S], 345W [50W], HPS 345W [HPS 50W])	10 [50]	20 [70]	65 [150]	110 [225]
SAW; GMAW; FCAW; SMAW (M 270M/M 270 (A709/A709M) Gr. HPS 485W [HPS 70W] and HPS 690W [HPS 100W]	10 [50]	50 [125]	80 [175]	110 [225]

[a] See 4.2.2 for maximum preheat and interpass temperature limitations.

Note: See Annex G and Tables 12.3, 12.4, and 12.5 for alternate preheat and interpass temperatures.

AASHTO/AWS D1.5:2015 Bridge Welding Code

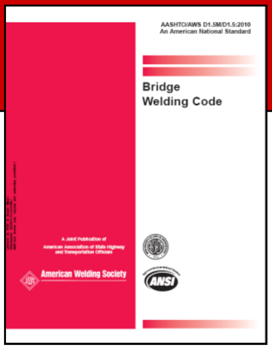
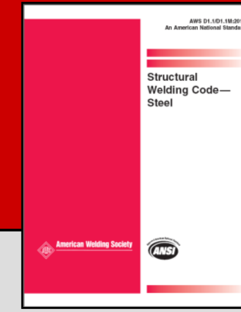


Table 12.4
M 270M/M 270 (A709/A709M) Gr. 345W [50W], HPS 345W [HPS 50W], HPS 485W [HPS 70W] Minimum Preheat and Interpass Temperatures, °C [°F] (see 12.14)

	Heat Input (as calculated by 5.12) kJ/mm [kJ/in]								
	1.2 [30] < HI ≤ 2.0 [50]			2.0 [50] < HI ≤ 2.8 [70]			HI > 2.8 [70]		
Thickness t, mm [in]	H4	H8	H16	H4	H8	H16	H4	H8	H16
t ≤ 20 [3/4]	40 [125]	60 [150]	80 [200]	40 [100]	40 [100]	60 [150]	40 [100]	40 [100]	40 [100]
20 [3/4] < t ≤ 40 [1-1/2]	100 [200]	100 [250]	120 [275]	80 [175]	100 [200]	120 [250]	60 [150]	80 [175]	100 [200]
40 [1-1/2] < t ≤ 60 [2-1/2]	140 [300]	160 [325]	180 [350]	140 [275]	140 [300]	160 [325]	120 [250]	140 [275]	160 [300]
t > 60 [2-1/2]	180 [350]	180 [350]	200 [375]	160 [325]	180 [350]	200 [350]	140 [300]	160 [325]	180 [350]

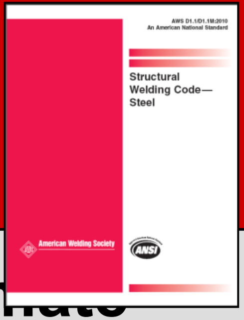
Note: H4, H8, and H16 are electrode optional supplemental designators for diffusible hydrogen.

AWS D1.1:2015 Structural Welding Code—Steel
Table 5.7 Minimum Fillet Weld Sizes



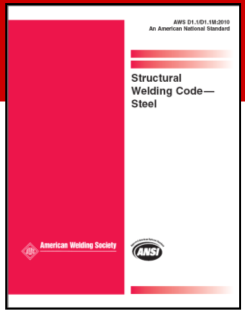
Base-Metal Thickness (T)[a] in. [mm]	Minimum Size of Fillet Weld[b] in. [mm]
$T \leq 1/4$ [6]	1/8 [3]
1/4 [6] $< T \leq$ 1/2 [12]	3/16 [5]
1/2 [12] $< T \leq$ 3/4 [20]	1/4 [6]
3/4 [20] $< T$	5/16 [8]

AWS D1.1:2015 Structural Welding Code—Steel
Table 5.7 Minimum Fillet Weld Sizes



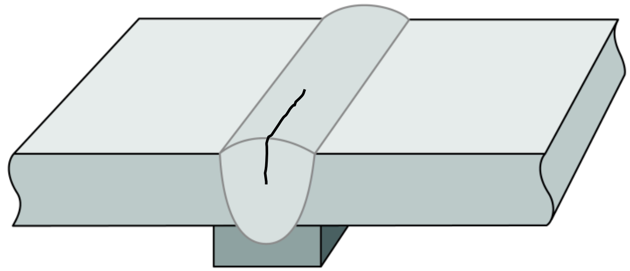
Base-Metal Thickness (T)[a] in. [mm]	Minimum Size of Fillet Weld[b] in. [mm]	Approximate Minimum Heat Input, kJ/in. [kJ/mm]
T ≤ 1/4 [6]	1/8 [3]	7 [0.3]
1/4 [6] < T ≤ 1/2 [12]	3/16 [5]	16 [0.6]
1/2 [12] < T ≤ 3/4 [20]	1/4 [6]	30 [1.2]
3/4 [20] < T	5/16 [8]	43 [1.7]

AWS D1.1:2010 Structural Welding Code--Steel

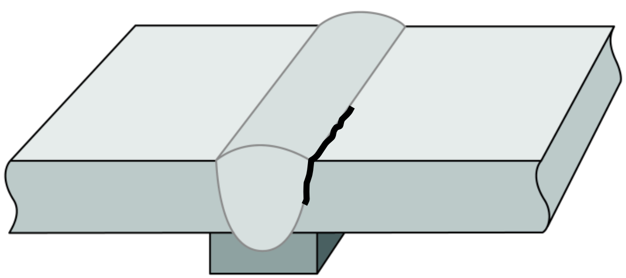


[a]For non-low hydrogen processes….T equals the thickness of the thicker part joined….For low-hydrogen processes…T equals the thickness of the thinner part….

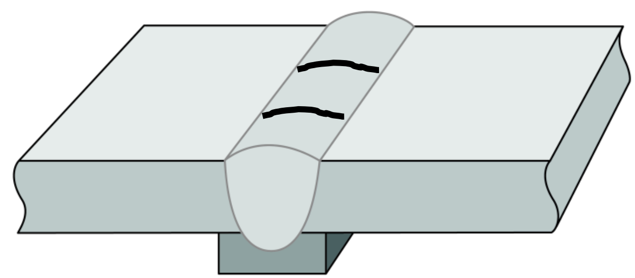
HOT CRACK



Centerline



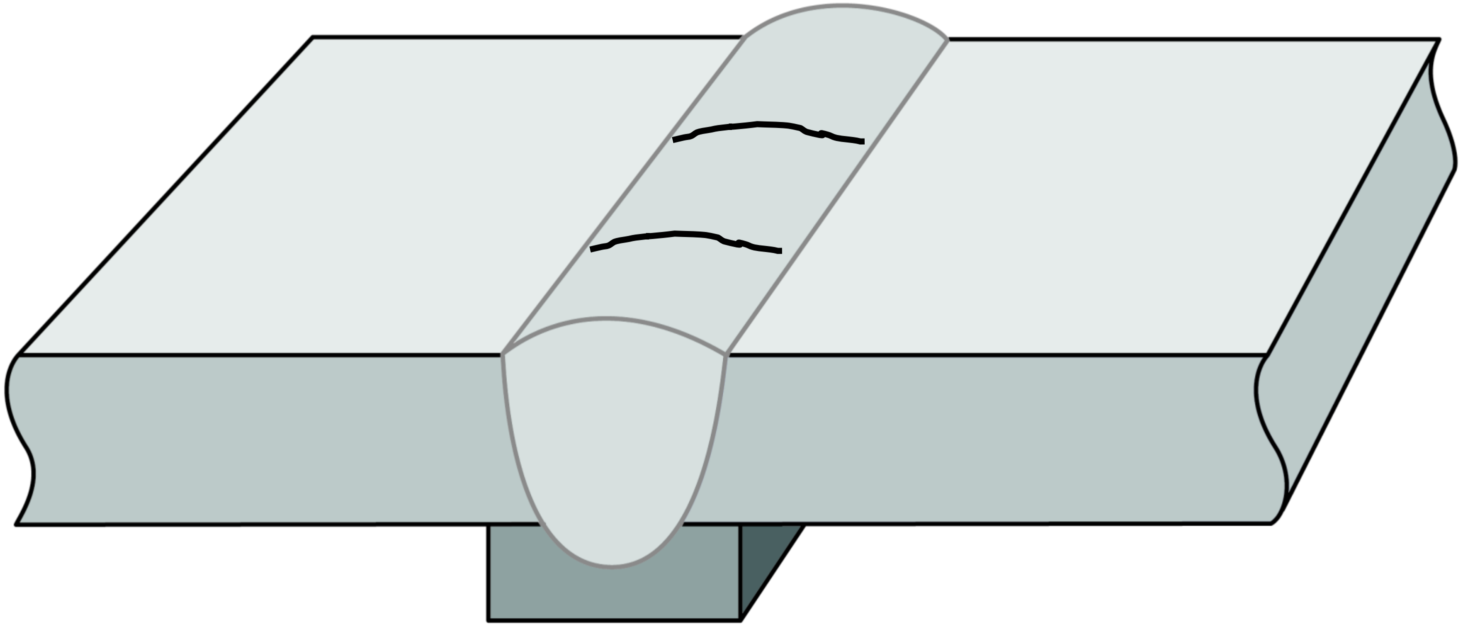
Underbead



Transverse

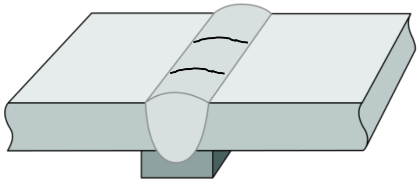
COLD CRACKS

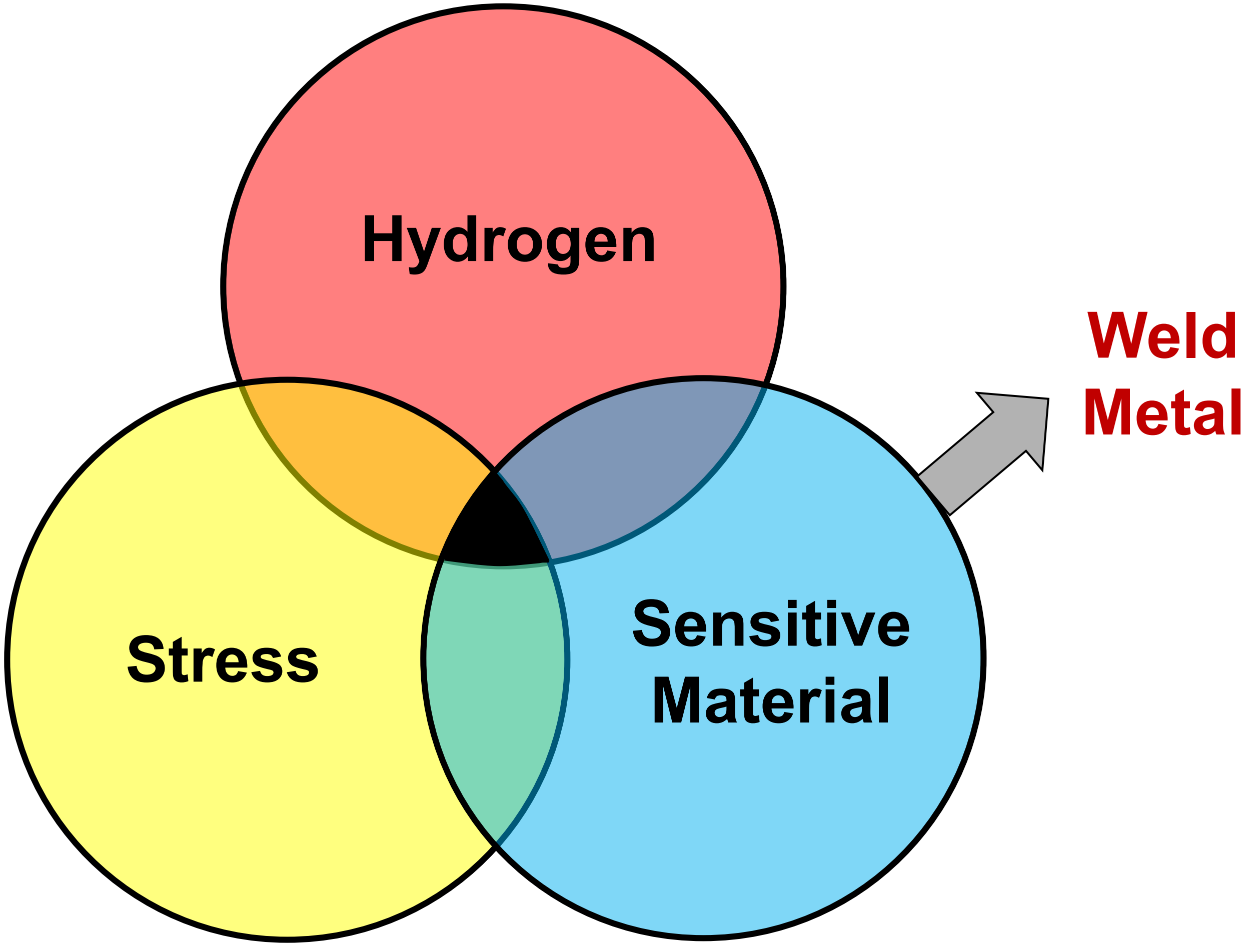
Transverse Cracking



Transverse Cracking

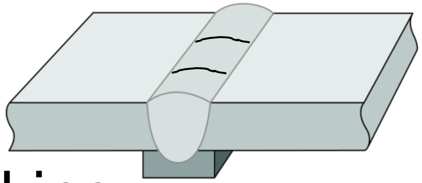
Cause: Excessive hydrogen AND an applied or residual AND a sensitive material





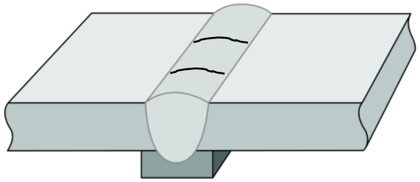
Transverse Cracking

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)
- Commonly occurs when welding on higher strength steels that require no preheat (based on the base metal composition)
- Some hardsurfacing deposits are designed to cross crack, thus relieving residual stresses and preventing spalling

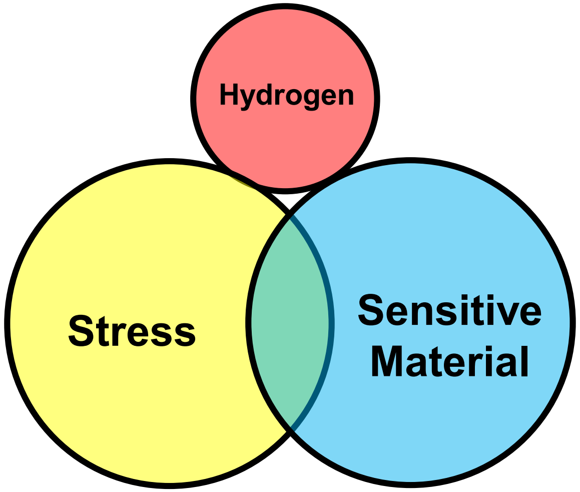
Transverse Cracking



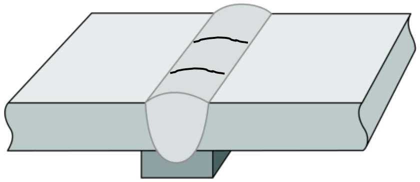
Cause: Excessive hydrogen AND an applied or residual AND a sensitive material

Solution:

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



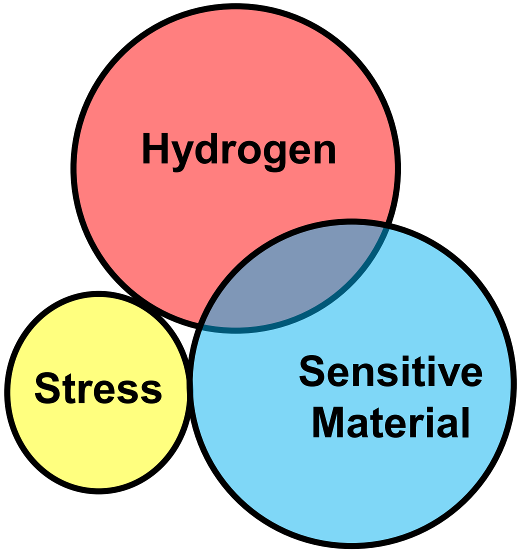
Transverse Cracking



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

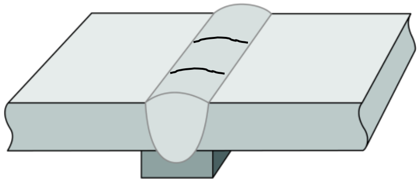
Solution:

- 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.

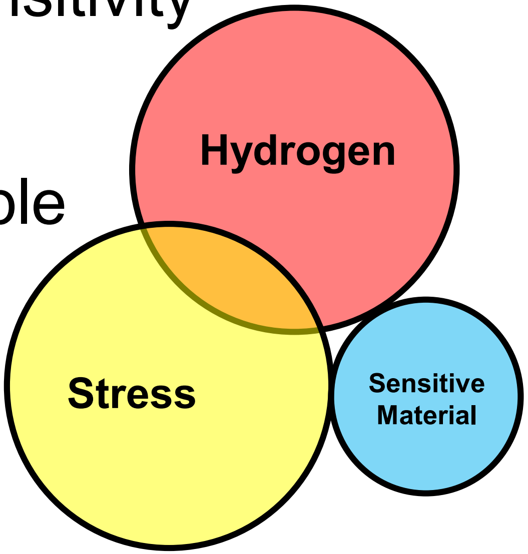
Transverse Cracking



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

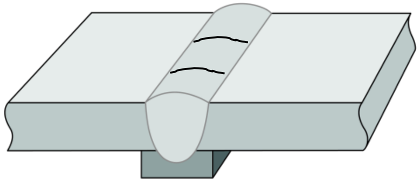
Solution:

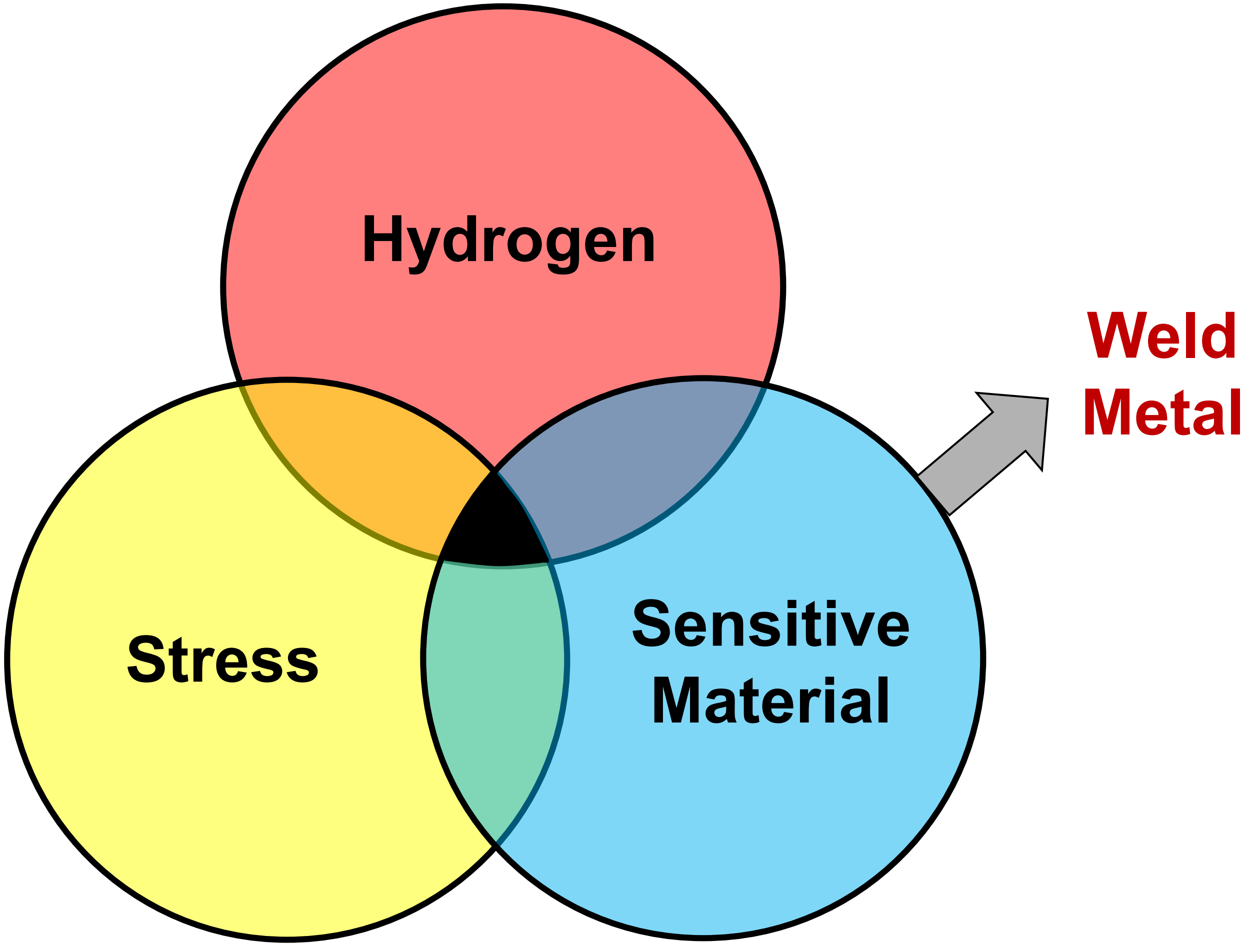
- Reduce Material (Weld Metal) Sensitivity
  - Selection of filler metal
  - Use undermatching where possible
  - Increased preheat
  - Higher heat input
  - Increased interpass temperature
  - Control admixture (pickup)



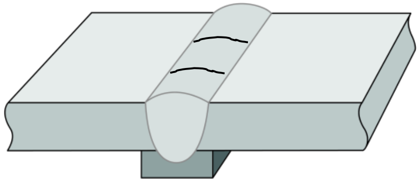
Transverse Cracking

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

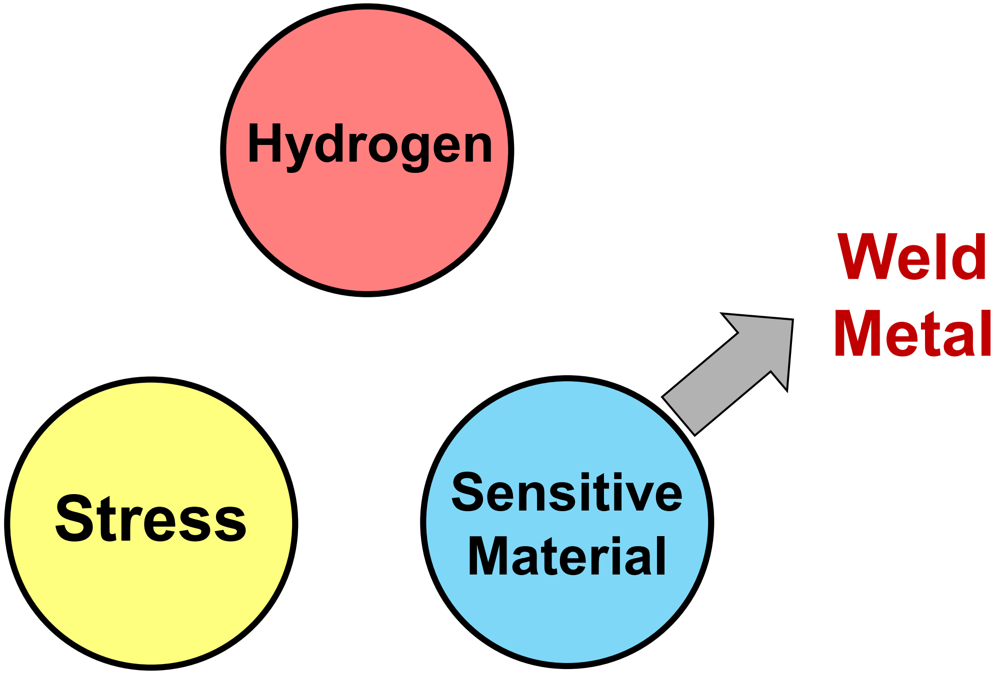




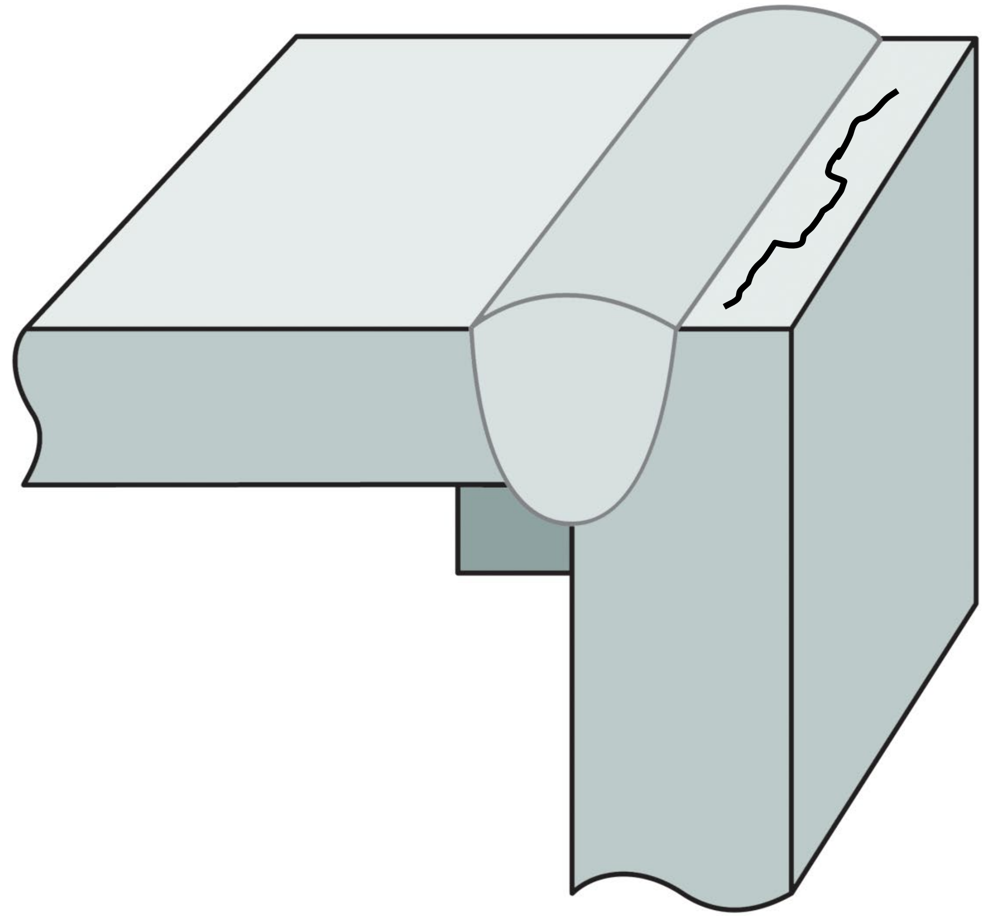
Transverse Cracking

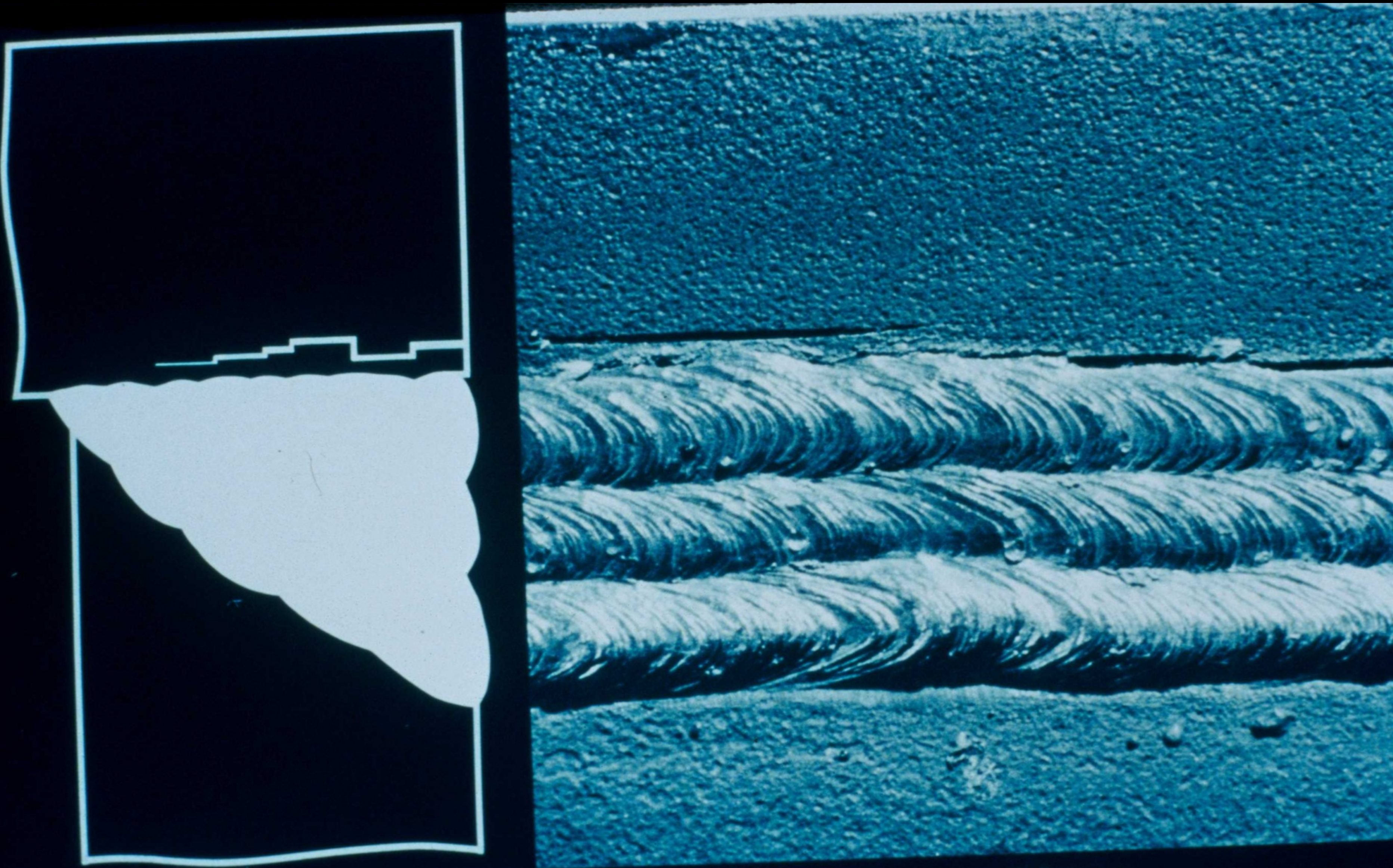


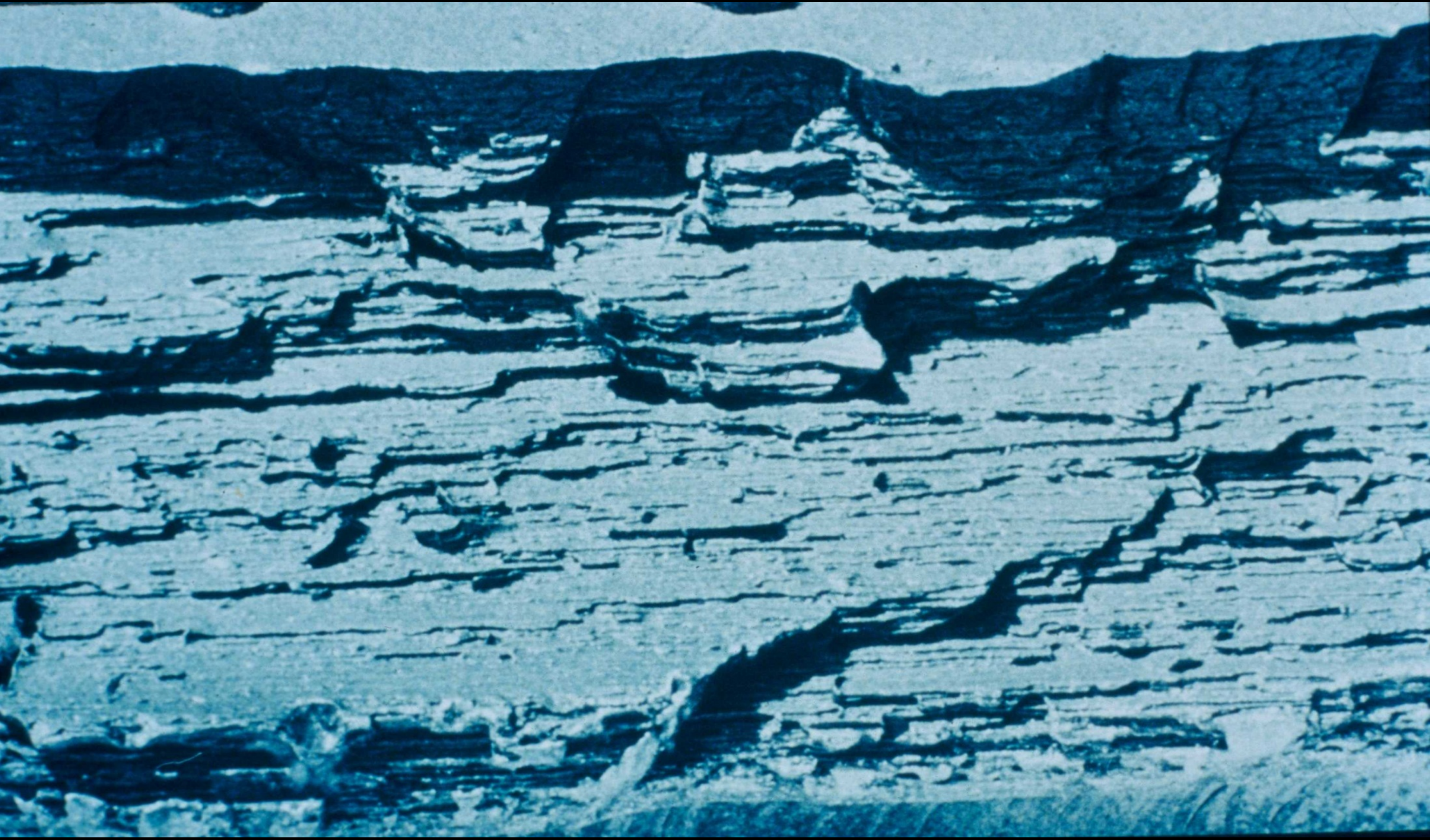
Cause: Excessive hydrogen AND an applied or residual AND a sensitive material



Lamellar Tearing

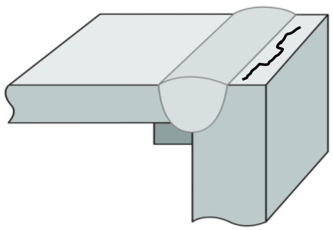






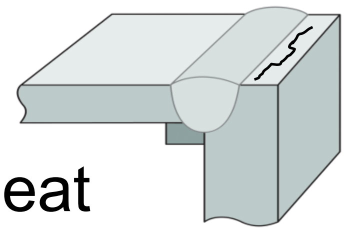
Lamellar Tearing

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



Lamellar Tearing

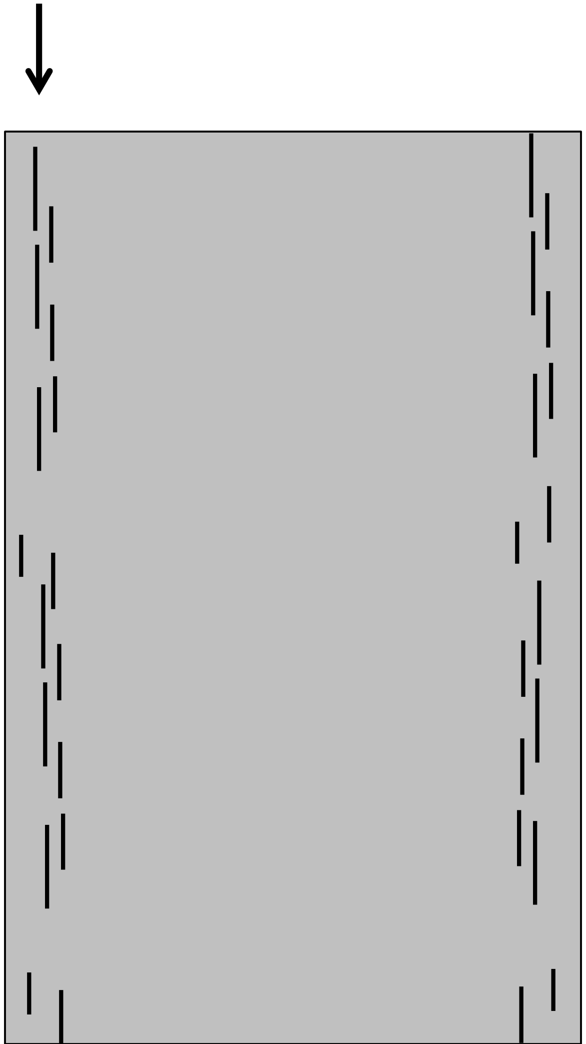
Characteristics



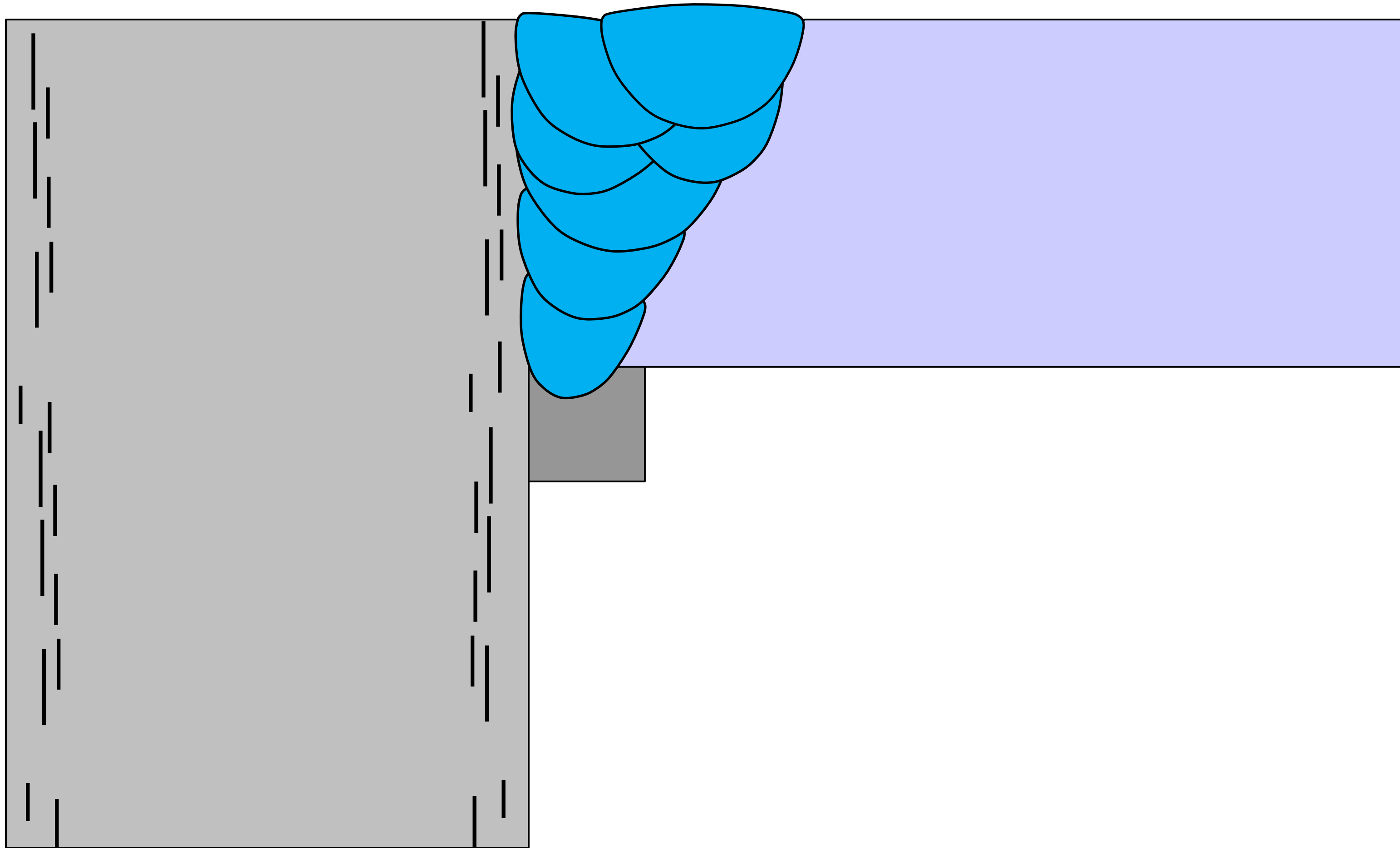
- Typically occurs immediately outside the heat affected zone
- Typically is not delayed
- Is aggravated by hydrogen (but not caused by hydrogen)
- Occurs less frequently today (2012) than it did in the past (due to improved steel making practices)
- Typically associated with steel thicknesses >3/4”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

Lamellar Tearing

Inclusions, typically
manganese sulfides

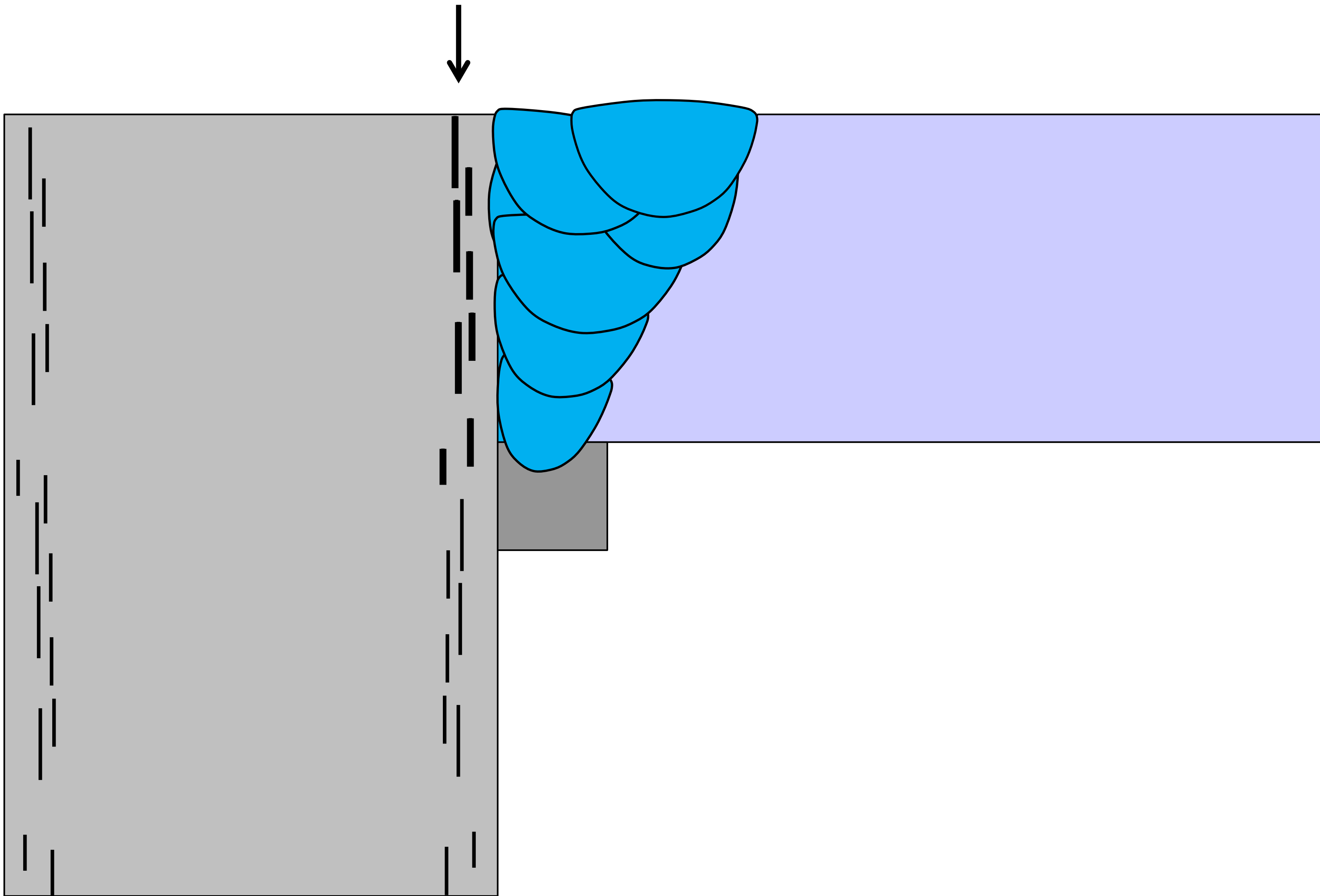


Lamellar Tearing



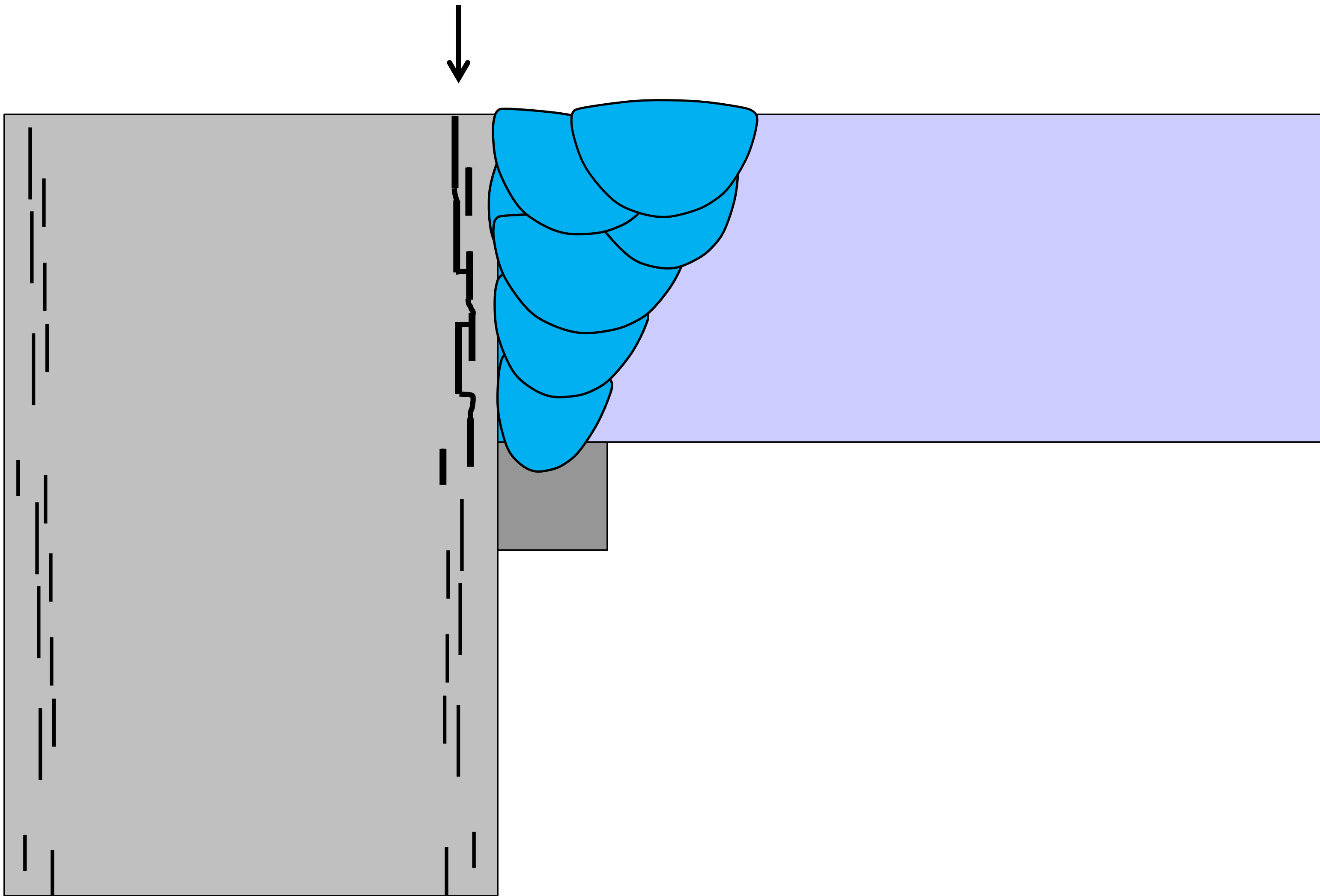
Lamellar Tearing

Step 1: Separation of the inclusions
from the surrounding steel



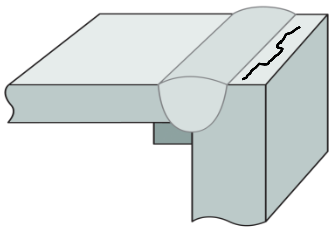
Lamellar Tearing

Step 2: Ductile tearing of the ligaments between the inclusions



Lamellar Tearing

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

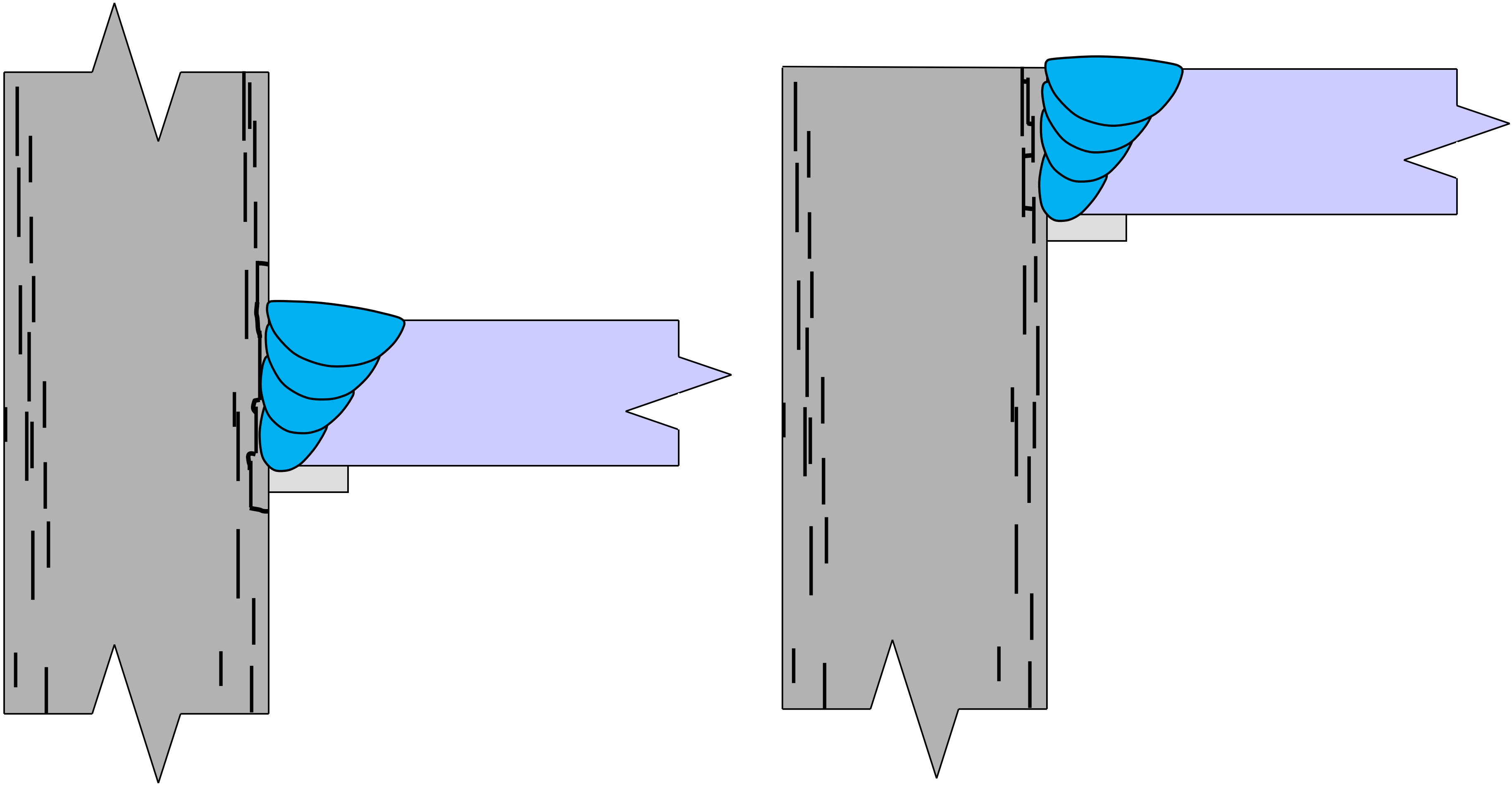


Solution:

- Use appropriate joint configurations

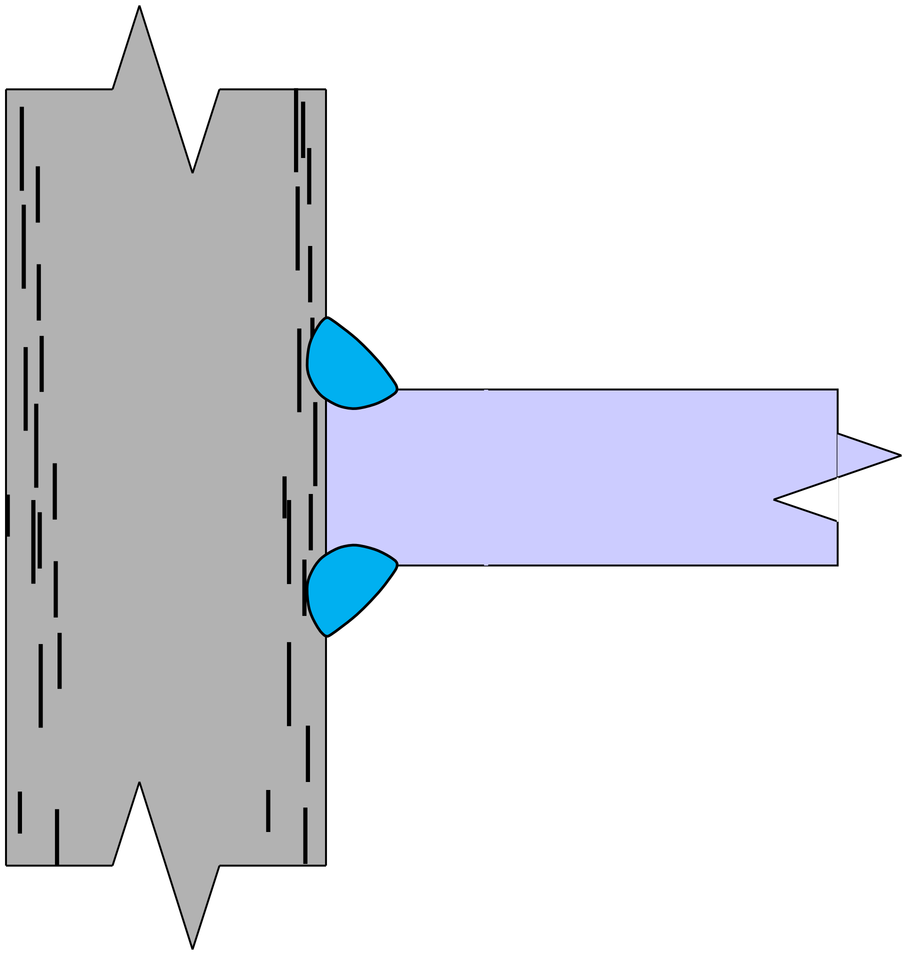
Lamellar Tearing

Non-preferred Details

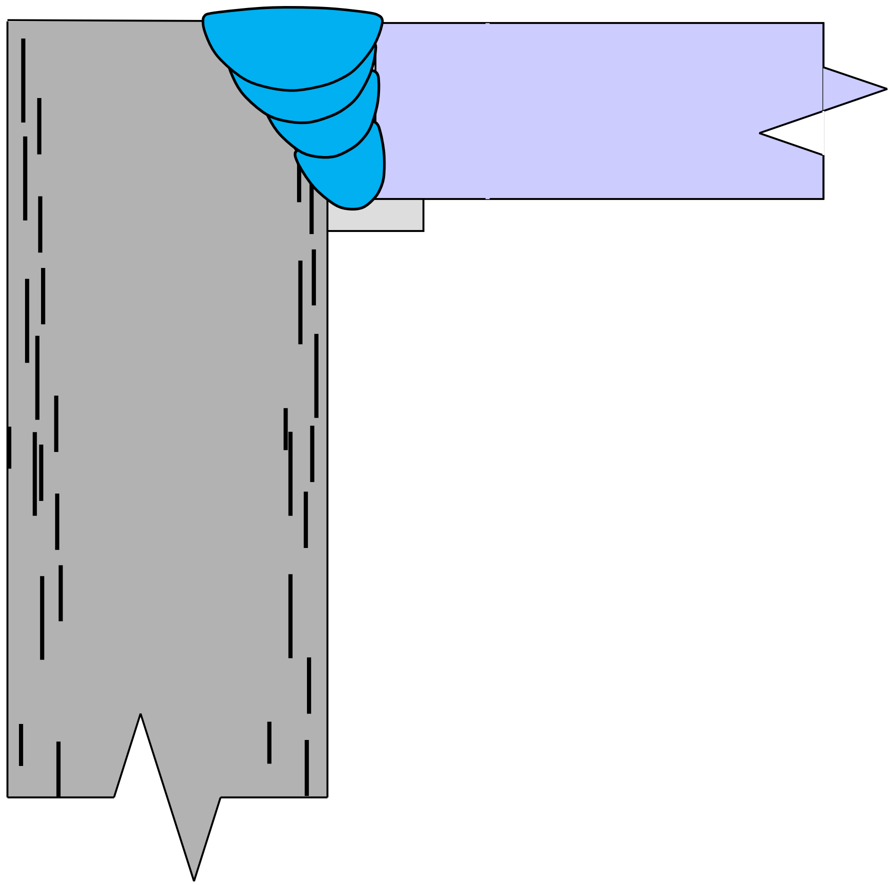


Lamellar Tearing

Preferred Details



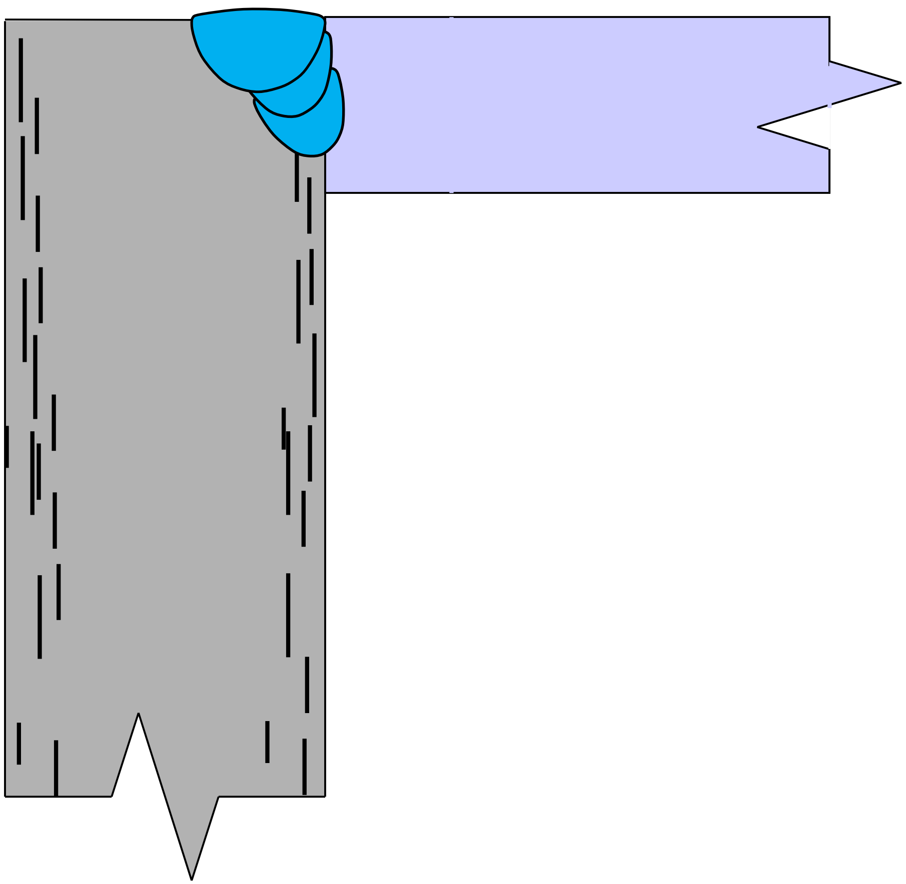
Fillets instead of CJP



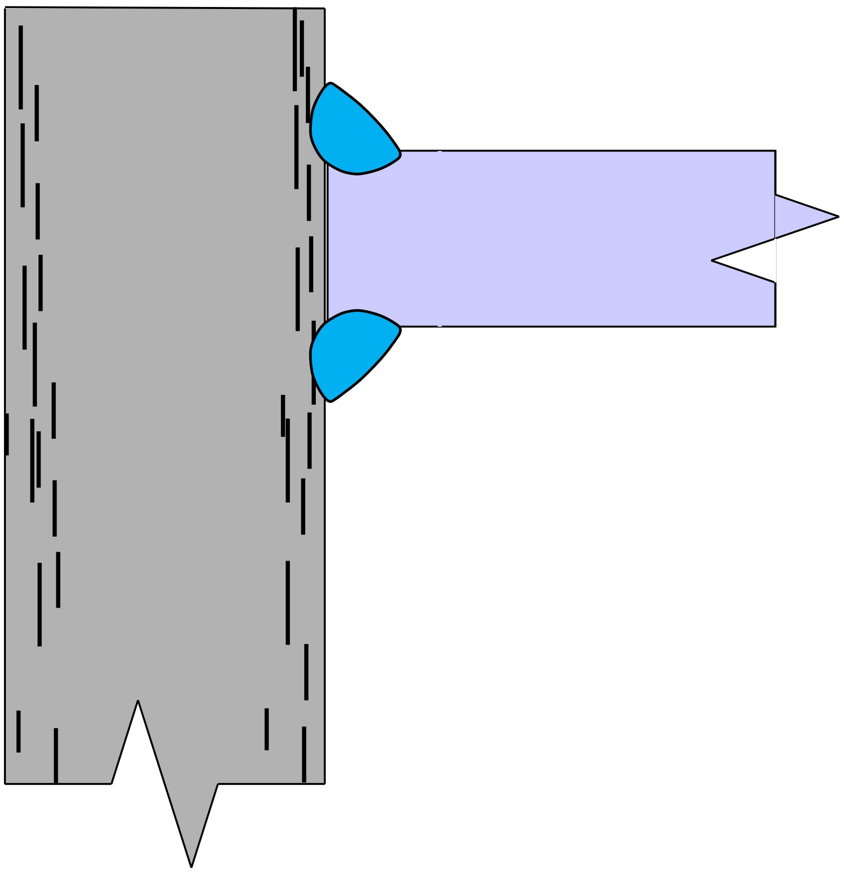
CJP with bevel on
the problematic side

Lamellar Tearing

Preferred Details



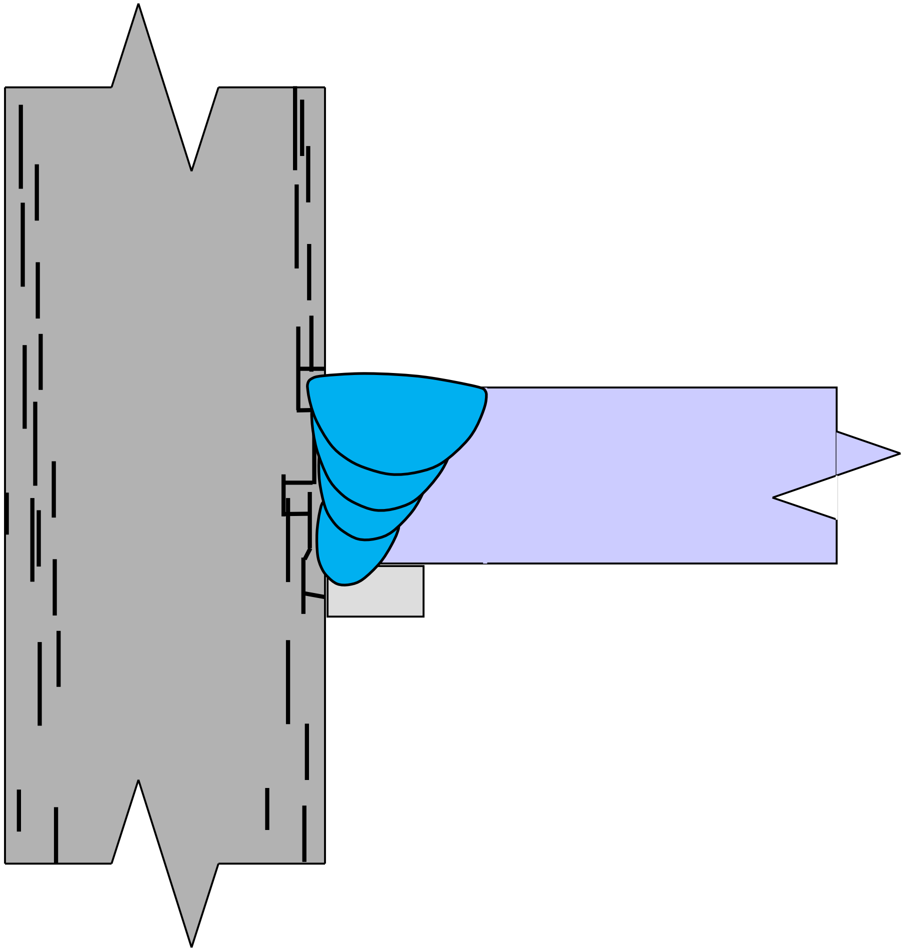
PJP instead of CJP



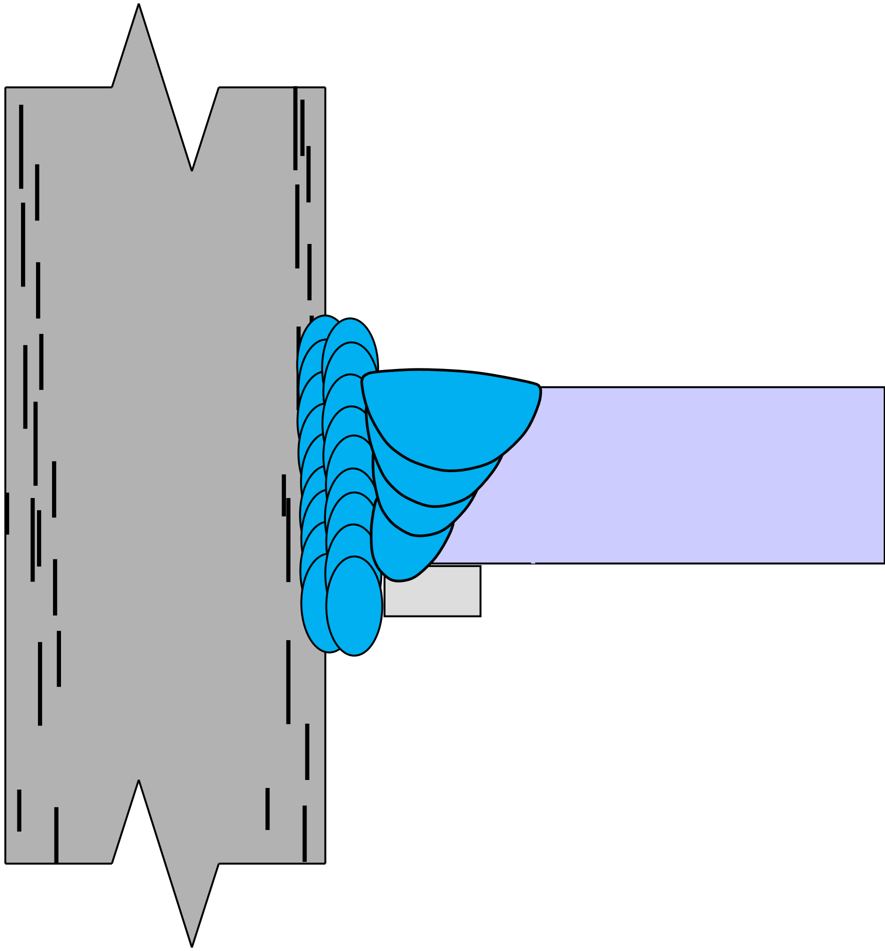
A corner-like tee joint

Lamellar Tearing

Buttering Solution



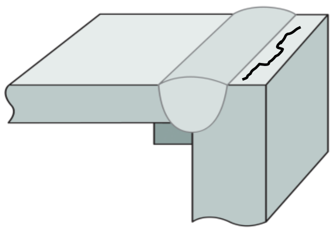
Sensitive Detail



Buttered Detail

Lamellar Tearing

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

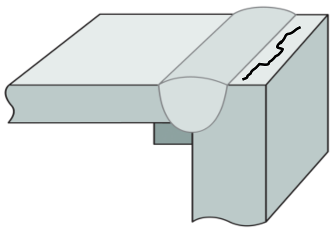


Solution: Better Material

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

Lamellar Tearing

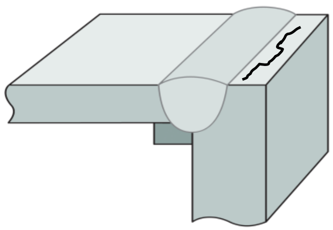
Cause: Through thickness weld shrinkage strains cause planar inclusions to join together (tear)



Solution: Better Detailing

- Bevel the sensitive member
- Minimize weld volumes: PJPs vs. CJPs
- Minimize weld volumes: Optimized details
- Butter the joint

Lamellar Tearing



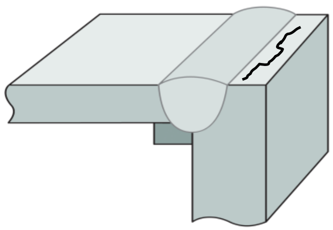
Cause: Through thickness weld shrinkage strains cause planar inclusions to join together (tear)

Solution: Better Fabrication

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

Lamellar Tearing

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

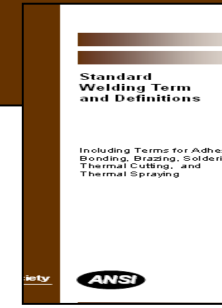


Solutions:

- Better Material
- Better Detailing
- Better Fabrication

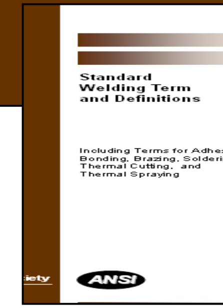
PREHEAT

AWS A3.0 Standard Welding Terms and Definitions



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.



interpass temperature

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

AASHTO/AWS D1.5:2015 Bridge Welding Code

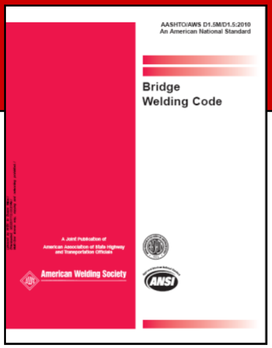
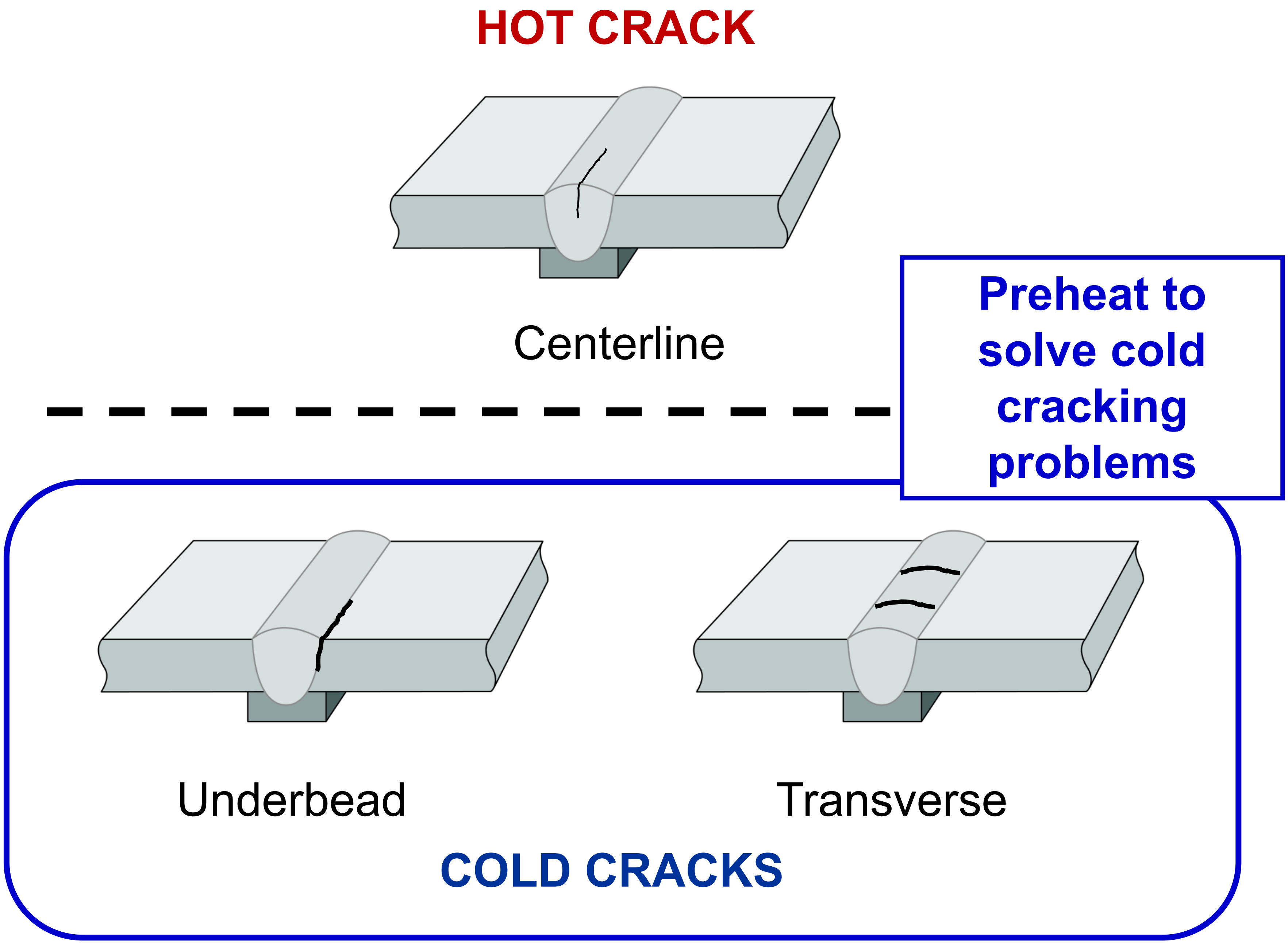


Table 12.5
M 270M/M 270 (A709/A709M) Grade HPS 690W [HPS 100W]
Minimum and Maximum Preheat/Interpass Temperature, °C [°F] (see 12.14)

	Heat Input (as calculated by 5.12) kJ/mm [kJ/in]				
Thickness t, mm [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]

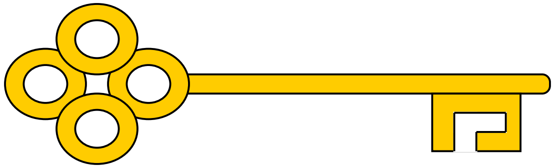
Note: The table applies to electrodes with the H4 or H8 optional supplemental designator for diffusible hydrogen limits.


HOT CRACK
Centerline
Preheat to solve cold cracking problems
Underbead
Transverse
COLD CRACKS

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

Postheat



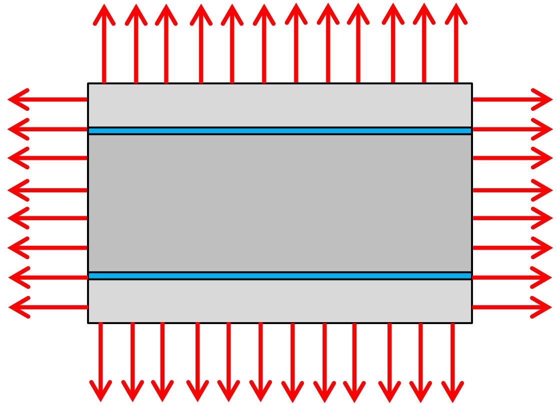
Apply post heat before cold cracking can occur (i.e., before the steel cools to below 400^{o}F).

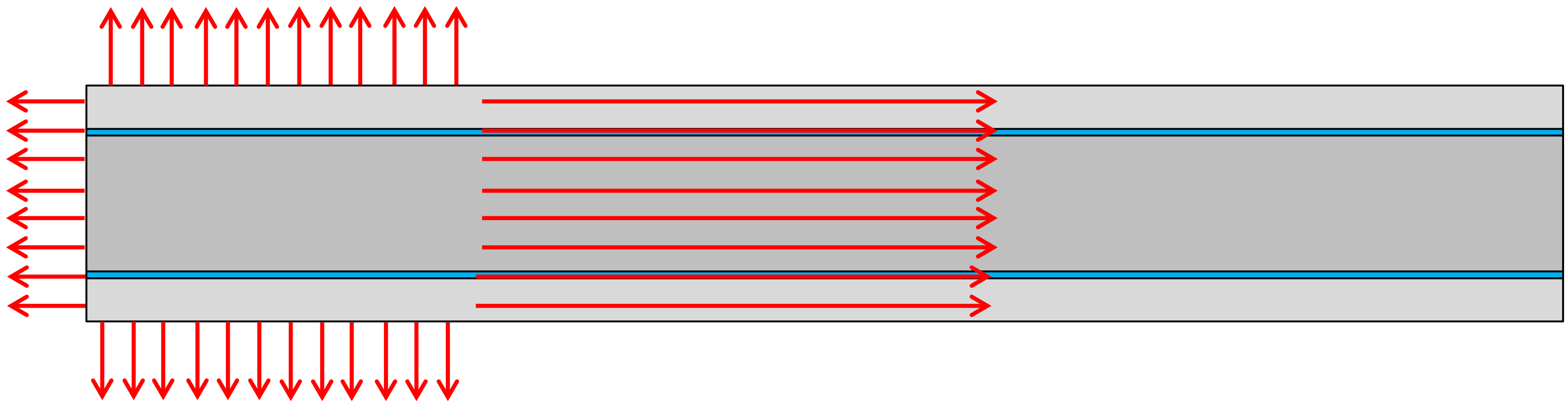
Postheat

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

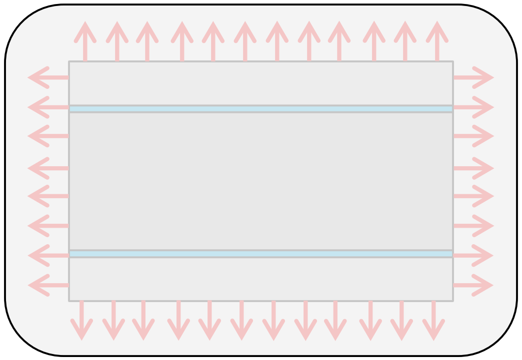
- Caveat 1: wrapping slows cooling rate, but weldment cools from interpass temperature which is often less than 400^{o}F at time weldment is wrapped.
- Caveat 2: wrapping works best when the whole weldment is at elevated temperatures

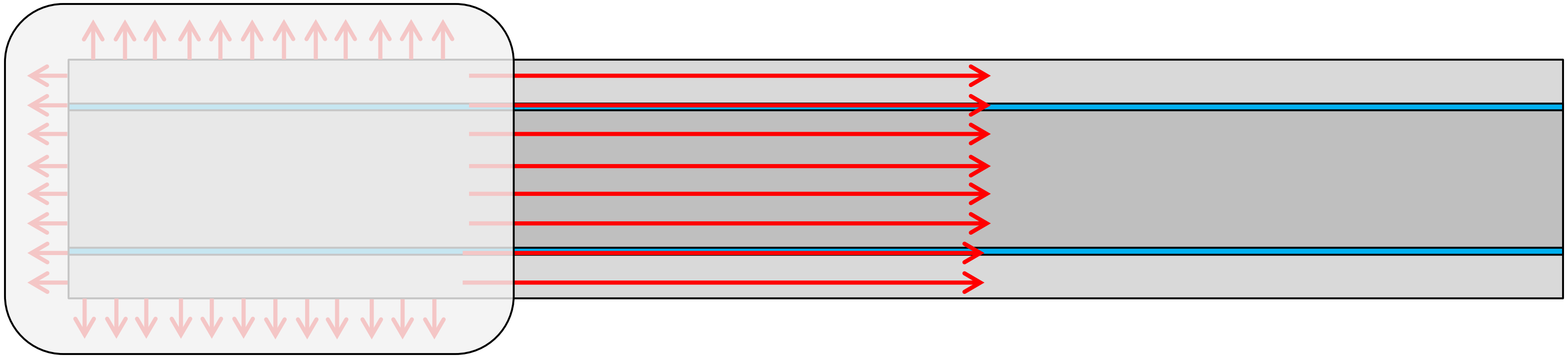
Wrapping



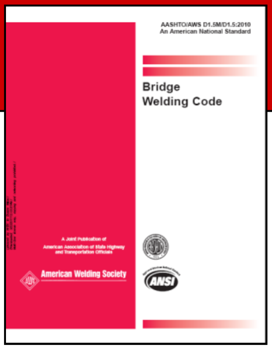


Wrapping





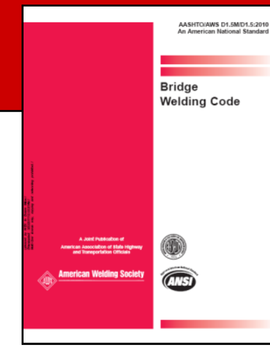
AASHTO/AWS D1.5:2015 Bridge Welding Code



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 postheat and interpass temperate before being raised to the postheat temperature.

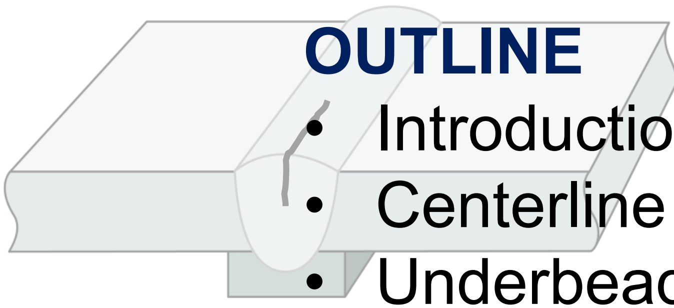
AASHTO/AWS D1.5:2015 Bridge Welding Code

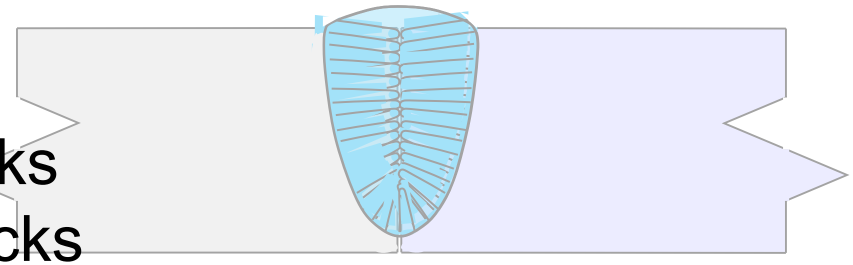


12.15.1.2 Hydrogen Diffusion Postheat Temperature Limitations.

When hydrogen diffusion postheat is required, welds and adjacent base metal shall be heated to a temperature of 230^{o}C [450^{o}F] minimum to 315^{o}C [600^{o}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 maybe used.

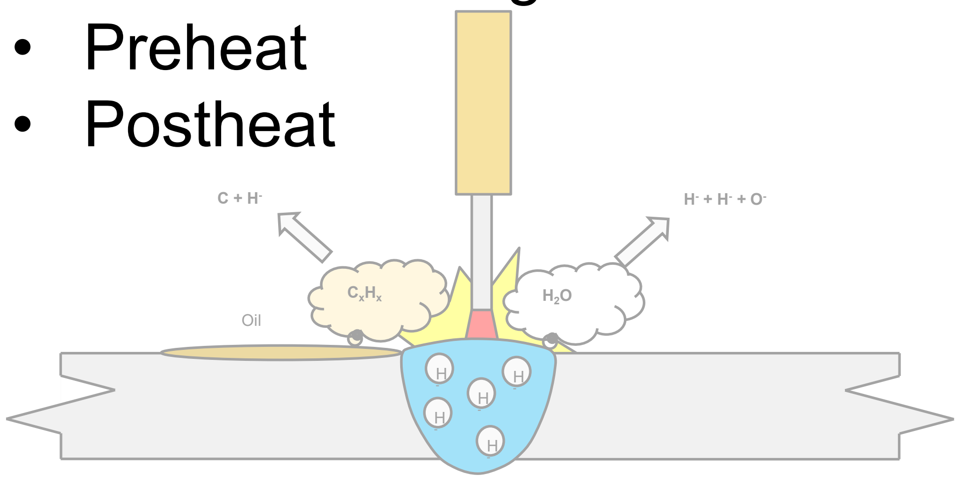
Causes and Prevention of Weld Cracking





OUTLINE

- Introduction
- Centerline cracks
- Underbead cracks
- Transverse cracks
- Lamellar tearing
- Preheat
- Postheat



2020 Mid-Atlantic Quality Assurance Workshop

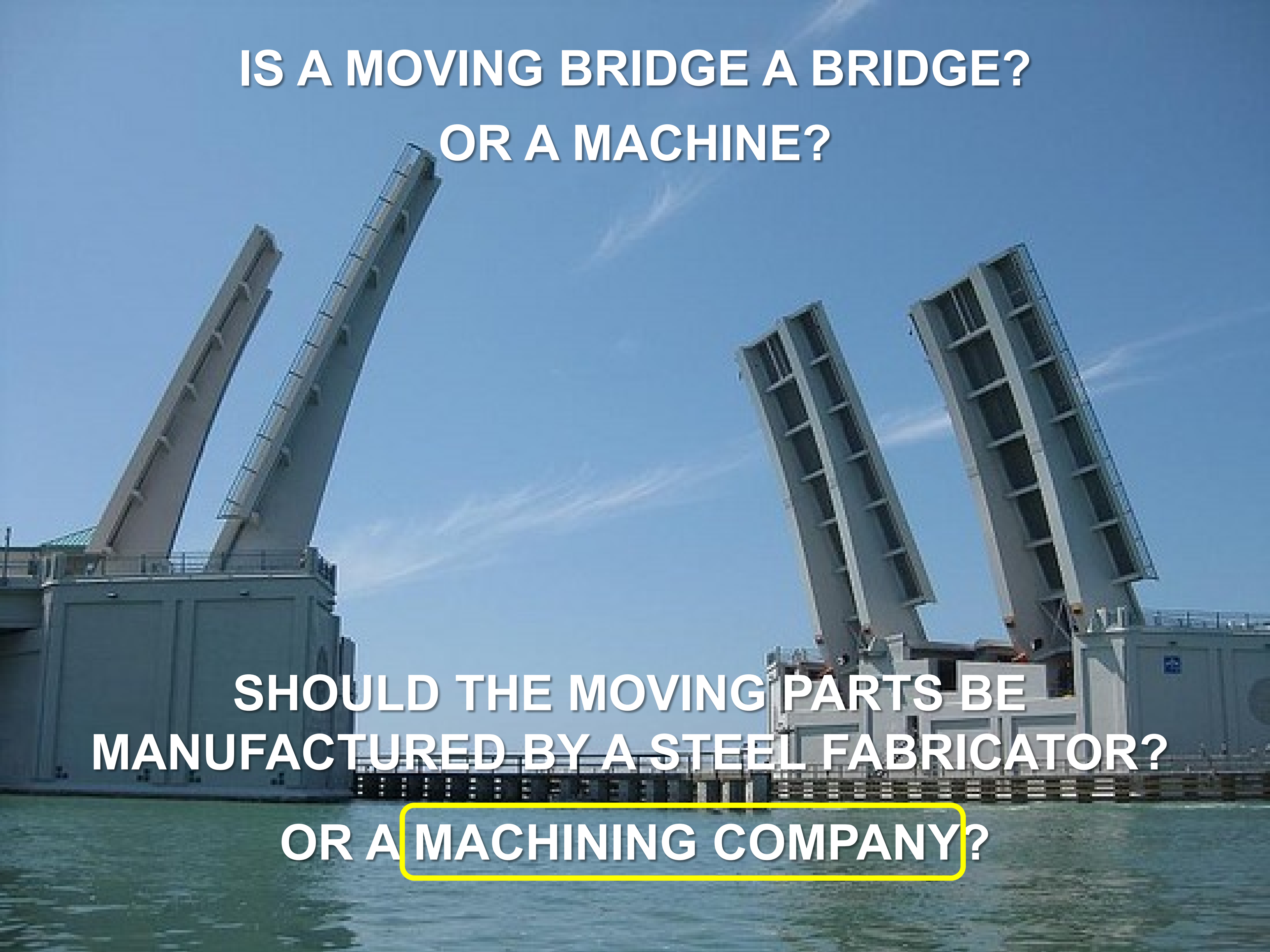
Causes and Prevention of Weld Cracking

by

Duane K. Miller, P.E., Sc.D

LINCOLN® ELECTRIC

JOHN'S PASS REPLACEMENT BRIDGE


IS A MOVING BRIDGE A BRIDGE?
OR A MACHINE?
SHOULD THE MOVING PARTS BE
MANUFACTURED BY A STEEL FABRICATOR?
OR A MACHINING COMPANY?

Ellwood City Forge
Ellwood City,PA

Sold To:		**Date:**	05/15/07
		P.O #:	49034
		Job #:	F3067
Grade and Description:	4140 Block	**Specification:**	ASTM A668 Class J Rev 04
		Drawing #:	15-1/4" x 8-3/4" x 60" LG.

Job #	Piece #	Heat/ Ingot #	Ingot Size	Ingot Weight	Product Size	Shipped Weight
F3067	09	R8242-2			8-3/4 X 15-1/4 X 60-1/4	
	10	R8242-2			8-3/4 X 15-1/4 X 190-1/8	

CHEMICAL ANALYSIS

Heat #	C	Mn	P	S	Si	Ni	Cr	Mo	Al	V	Cu	Hppm	Ti
R8242	.43	.89	.015	.025	.22	.12	.99	.22	.019	.050	.17	1.3	.0032

TENSILE TEST RESULTS: TENSILE TEST DIA. .505" **BRINELL RESULTS**

TENSILE TESTS TAKEN FROM PC 08

Piece #	Test Loc	Yield Strength .2% offset	Tensile Strength	Elong in 2"	R A %	BRINELL
08		84,573	113,196	18	49	236-240-244-245
		83,946	110,613	19	49	

IMPACT RESULTS: TEST SIZE: 10mm x 10mm

Piece#	Test Loc	Test Temp	Ft lbs.	%Shear	Lateral Expansion

HEAT TREATMENT OF PC 08 HEAT TREATED IN FURNACES CERTIFIED TO AMS –H-6875
HEAT TO 1575 DEG F 4 HRS MIN POLY QUENCH,TEMPER 1225 DEG F 9 HRS
SONIC TESTED P ASTM A 388 – REVEALED NO INDICATIONS

Signed: Kathy Carsale

Certification Clerk

ECF

Ellwood City Forge
Ellwood City, PA

Ellwood City Forge

4140

Sold To:

Date: 05/15/07
P.O.#: 49034
Job #: F3067

Grade and Description: 4140 Block

Specification: ASTM A668 Class J Rev 04
Drawing #: 15-1/4" x 8-3/4" x 60" LG.

ASTM A668 Class J
(a forging)

Job #	Piece #	Heat/ Ingot #	Ingot Size	Ingot Weight	Product Size	Shipped Weight
F3067	09	R8242-2			8-3/4 X 15-1/4 X 60-1/4	
	10	R8242-2			8-3/4 X 15-1/4 X 190-1/8	

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C	0.43
Mn	0.89
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S	0.025
Ni	0.12
Cr	0.99
Mo	0.22

TENSILE TEST RESULTS: TENSILE TEST DIA. .505" BRINELL RESULTS

TENSILE TESTS TAKEN FROM PC 08

Piece #	Test Loc	Yield Strength .2% offset	Tensile Strength	Elong in 2"	R A %	BRINELL
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		83,946	110,613	19	49	

IMPACT RESULTS: TEST SIZE: 10mm x 10mm

Piece#	Test Loc	Test Temp	Ft lbs.	%Shear	Lateral Expansion

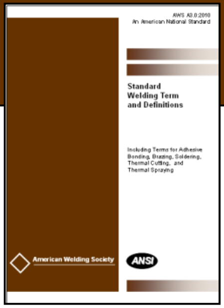
HEAT TREATMENT OF PC 08 HEAT TREATED IN FURNACES CERTIFIED TO AMS -H-6875
HEAT TO 1575 DEG F 4 HRS MIN POLY QUENCH, TEMPER 1225 DEG F 9 HRS
SONIC TESTED P ASTM A 388 – REVEALED NO INDICATIONS

Yield	84
Tensile	110

Signed: Kathy Carsale

Certification Clerk

AWS A3.0 Standard Welding Terms and Definitions

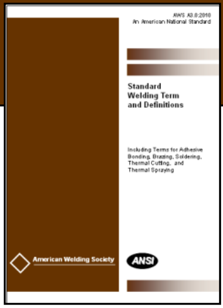


Weldability: The capacity of a material to be welded under the imposed fabrication conditions into a specific, suitably designed structure, and to perform satisfactorily in the intended service.

ASTM A6/A6M, Section X3

Weldability: A term that usually refers to the relative ease with which a metal can be welded using conventional practice.

AWS A3.0 Standard Welding Terms and Definitions



Weldability: The capacity of a material to be welded under the imposed fabrication conditions into a specific, suitably designed structure, and to perform satisfactorily in the intended service.

WELDABILITY DOES NOT MEAN "ABLE TO BE WELDED" BUT IS A RELATIVE TERM TO DESCRIBE HOW EASY OR DIFFICULT IT WILL BE TO SUCCESSFULLY WELD THE MATERIAL.

ANALOGOUS TO "READABILITY"

4140

- A weldable material
- Poor weldability

Ellwood City Forge
Ellwood City, PA

Sold To:	JC Industrial Mfg. Corp. 5700 N.W., 32 CT Miami, FL 33142	**Date:** **P.O.#:** **Job #:**	05/15/07 49034 F3067
Grade and Description:	4140 Block	**Specification:** **Drawing #:**	ASTM A668 Class J Rev 04 15-1/4" x 8-3/4" x 60" LG.

Job #	Piece #	Heat/ Ingot #	Ingot Size	Ingot Weight	Product Size	Shipped Weight
F3067	09	R8242-2			8-3/4 X 15-1/4 X 60-1/4	
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TENSILE TEST RESULTS: TENSILE TEST DIA. .505" **BRINELL RESULTS**

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Piece #	Test Loc	Yield Strength .2% offset	Tensile Strength	Elong in 2"	R A %	BRINELL
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		83,946	110,613	19	49	

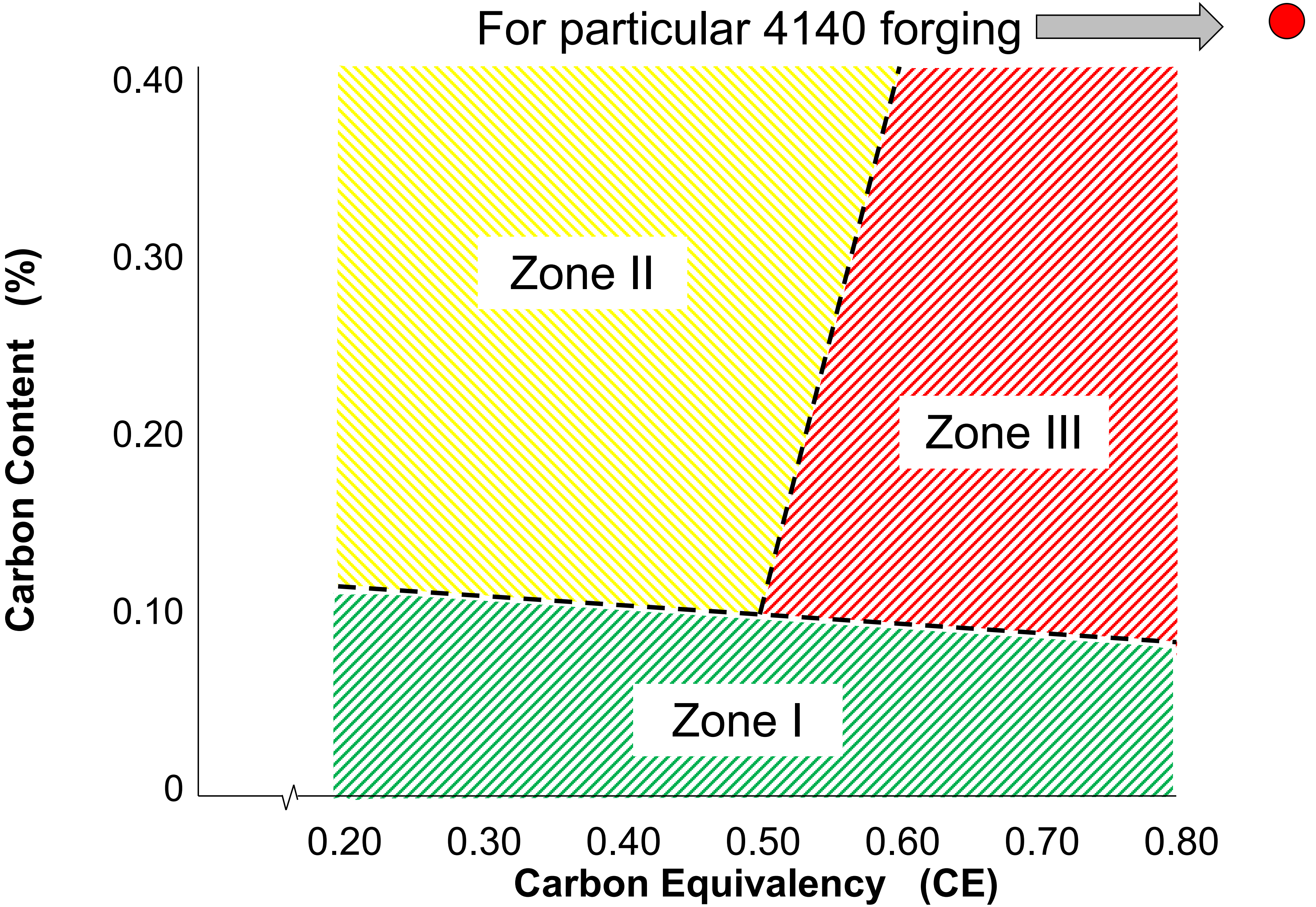
IMPACT RESULTS: TEST SIZE: 10mm x 10mm

Piece#	Test Loc	Test Temp	Ft lbs.	%Shear	Lateral Expansion

HEAT TREATMENT OF PC 08 HEAT TREATED IN FURNACES CERTIFIED TO AMS –H-6875
HEAT TO 1575 DEG F 4 HRS MIN POLY QUENCH,TEMPER 1225 DEG F 9 HRS
SONIC TESTED P ASTM A 388 – REVEALED NO INDICATIONS

Signed: Kathy Carsele

Certification Clerk



$$CE = C + \frac{(Mn + Si)}{6} + \frac{(Cr + Mo + V)}{5} + \frac{(Ni + Cu)}{15}$$

“Tools” that were used:

- A large scale mock up
- Procedure qualification
- Preheat
- Interpass temperature
- Postheat
- Stress Relief
- Buttering
- DC- buttering procedures
- Decarburizing flux
- E7018 tack welding
- Careful supervision
- A fabricator willing to do whatever was best for the project
- A cooperative Owner

SAW

TAMPA TANK INC -FLORIDA STRUCTURAL STEEL

Welding Procedure Specification

JOB SPECIFIC (5252)

Material Spec. ASTM A668 CLASS J FORGING

Welding Process(es) SAW

Position of Welding FLAT (CLADDING)

Manual ☐ Machine ☐ Semi-Automatic ☒ Automatic ☐

Cladding ("buttering")

Filler Metal Specification 5.17

Filler Metal Classification EM12K LINCOLN L-61

Flux F7A2 LINCOLN 860

L61/860

Shielding Gas N/A Gas Flow Rate N/A

DCEN: direct current, electrode negative

Welding Current DC

Polarity: AC ☐ DCEP ☐ DCEN ☒ Pulsed ☐

Welding Progression Up ☐ Down ☐

Preheat: 450ºF
Max. Interpass: 650ºF

Root Treatment N/A

Preheat Temperature 450 DEGREES (F) Interpass Temperature 650 DEGREES (F)

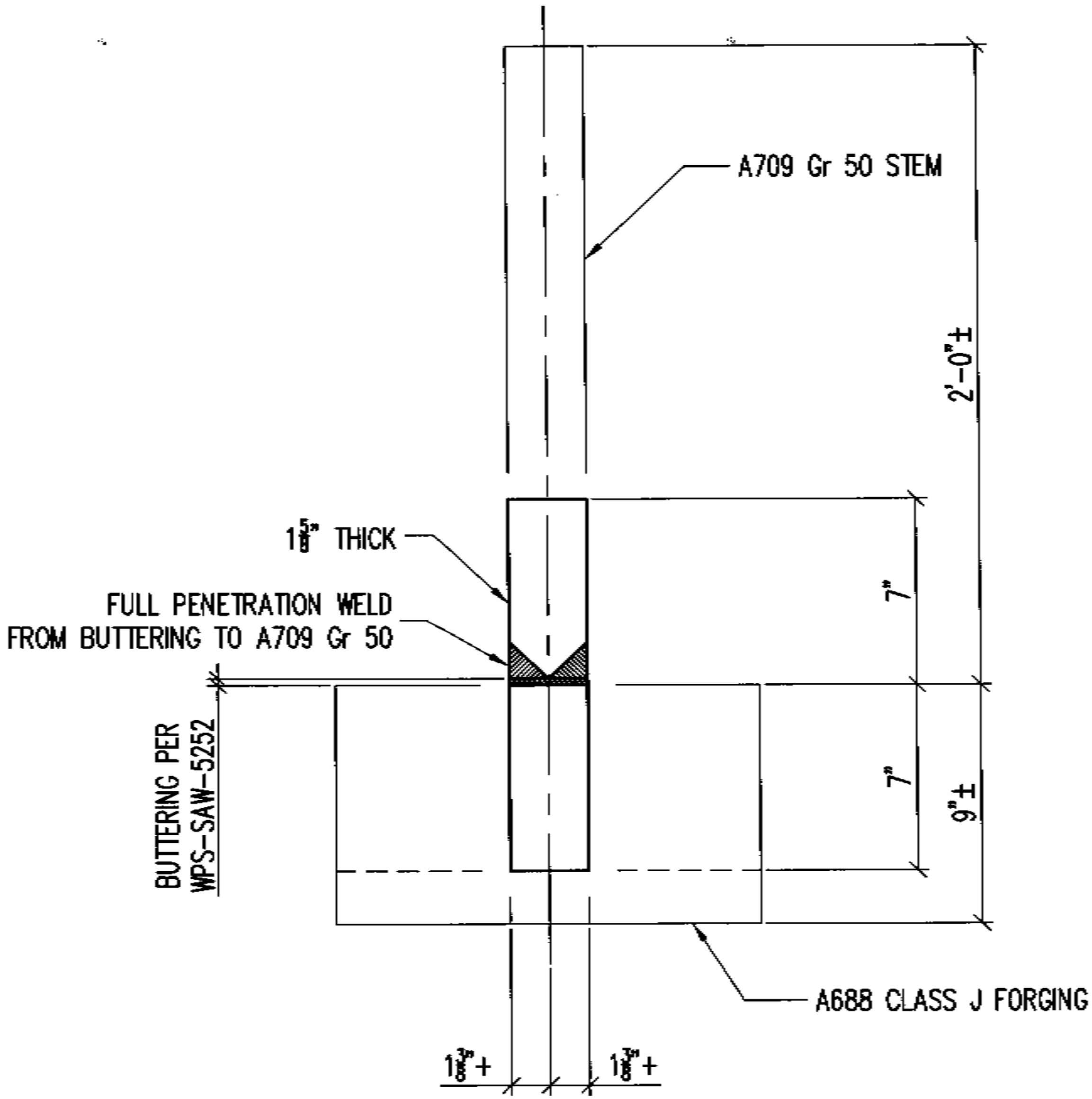
Postheat Treatment N/A

Heat Input Min 37 Max 59.4


LOCKER
PIPE+
DIES
07/10/2007


LINCOLN
ARC WELDER
07/10/2007


LOCKER
Pipe + DIES
ARC WELDER
07/10/2007



REDUCED SECTION TENSION SPECIMEN FROM MOCK-UP

(2) REQUIRED


08/23/2007


09/27/2007


Lufkin
P.R. APP'D
254Tc
8m/26'CME
inches
centimeters

2020 Mid-Atlantic Quality Assurance Workshop

Causes and Prevention of Weld Cracking

by

Duane K. Miller, P.E., Sc.D