# NDE, Welding and Metallurgy

## *Essential Tools in Supporting the Safe and Efficient Operation of Aging High Energy Piping*

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HRSG Forum
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ATC Applied Thermal Coatings
CES Combustion Engineering Solutions a Division of ATC

# Discussion Points

- Metallurgy & Welds
  - Operation at Elevated Temperatures – Creep Damage
  - Structure of Welds
  - Damage in Welds at Elevated Temperatures
- NDE
  - Characterizing Indications Found in Welds
    - Size and Orientation of Indications
    - Nature of Indications – e.g., single continuous discontinuity, multiple discrete discontinuities, a continuous or semi-continuous damage field
- Weld Repair
  - Understanding Repair Objective
  - Proper Excavation of Damage

# Discussion Objective

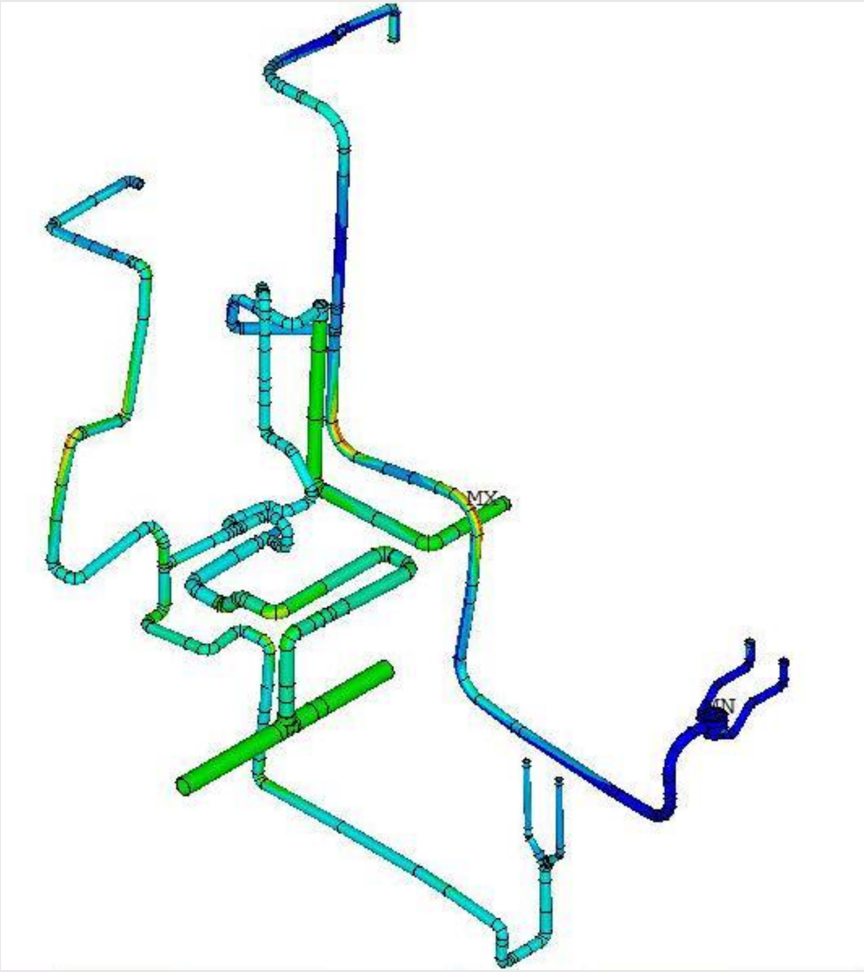
- **With a basic understanding of how damage develops in welded components operating at high temperatures:**
  - **NDE specialists will better understand where to look for damage, how to look for damage and, when damage is found, how to interpret that damage relative to the reliability of the component**
  - **Welding engineers will better understand what an appropriate repair strategy will look like in a given operating situation**

# High Energy Piping

- Piping systems in industrial-type plants that operate within the "time-dependent regime"
- These systems pose a particular problem for engineers concerned with the safe and reliable operation of a plant.
- In most cases the mode of damage that will cause failure will involve **Creep**

# High Energy Piping (HEP) in Power Plants

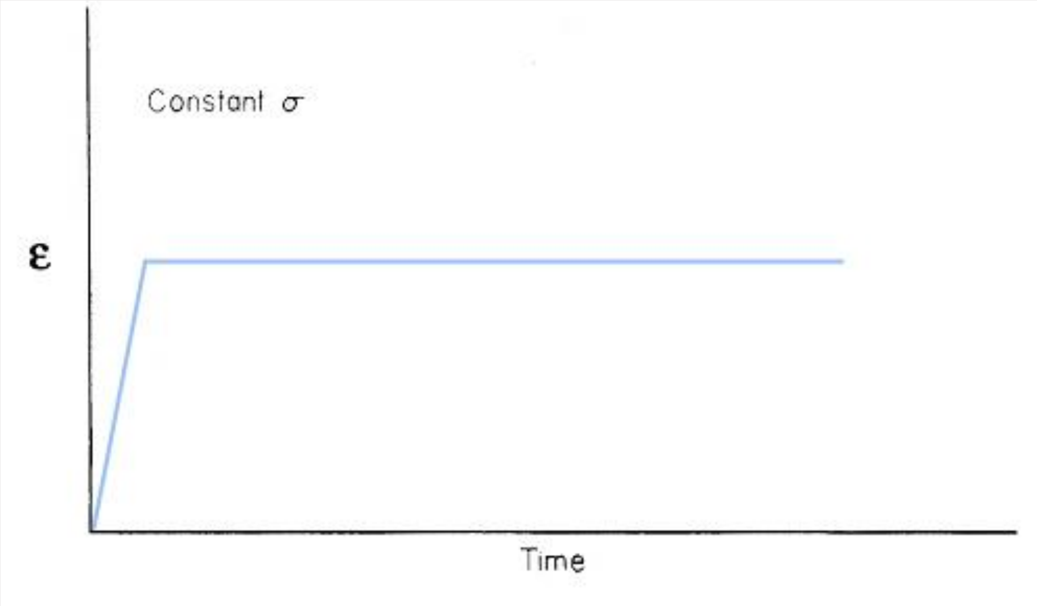
- In utility-type power plants, the two piping systems that operate within the “time-dependent regime” are the **Main Steam** piping system and the **Hot Reheat Steam** piping system
- Both systems are designed to transport high temperature steam from the steam generator to the turbine
- Operating temperature typically range **from 950-1100°F** at pressures ranging from **550-5000 psig**



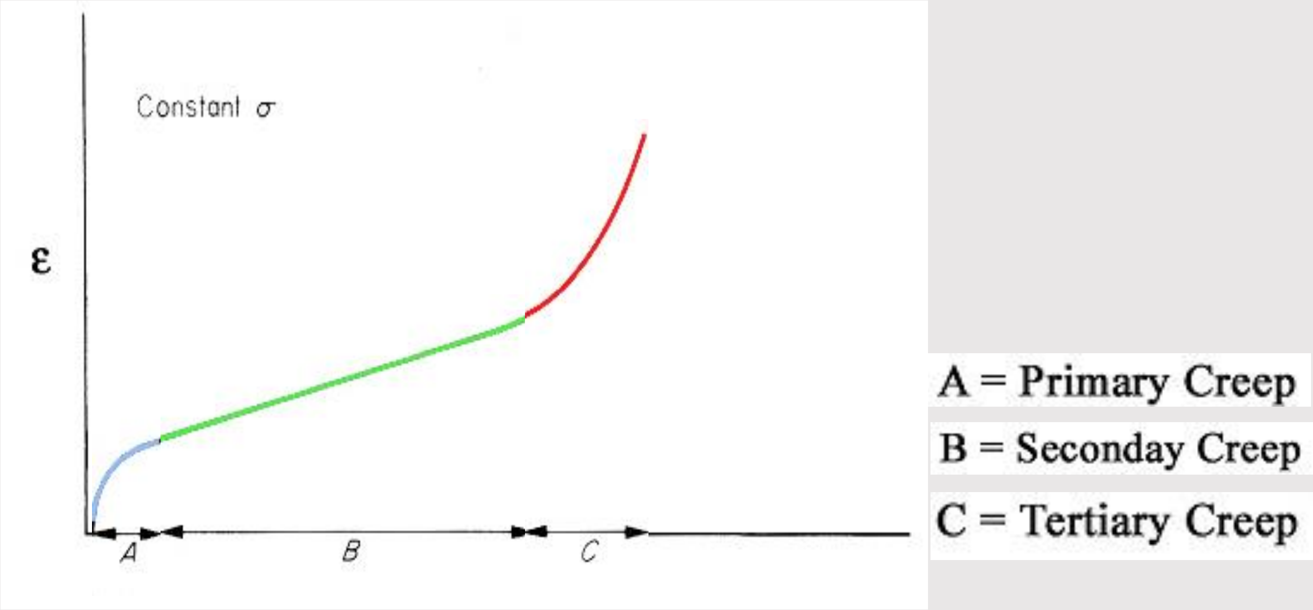
# Creep – The Principal Damage Mechanism in High Temperature Components

- **Definition**: Time-dependent strain occurring under a stress which is lower than the material's yield point at the elevated temperature

Room Temp

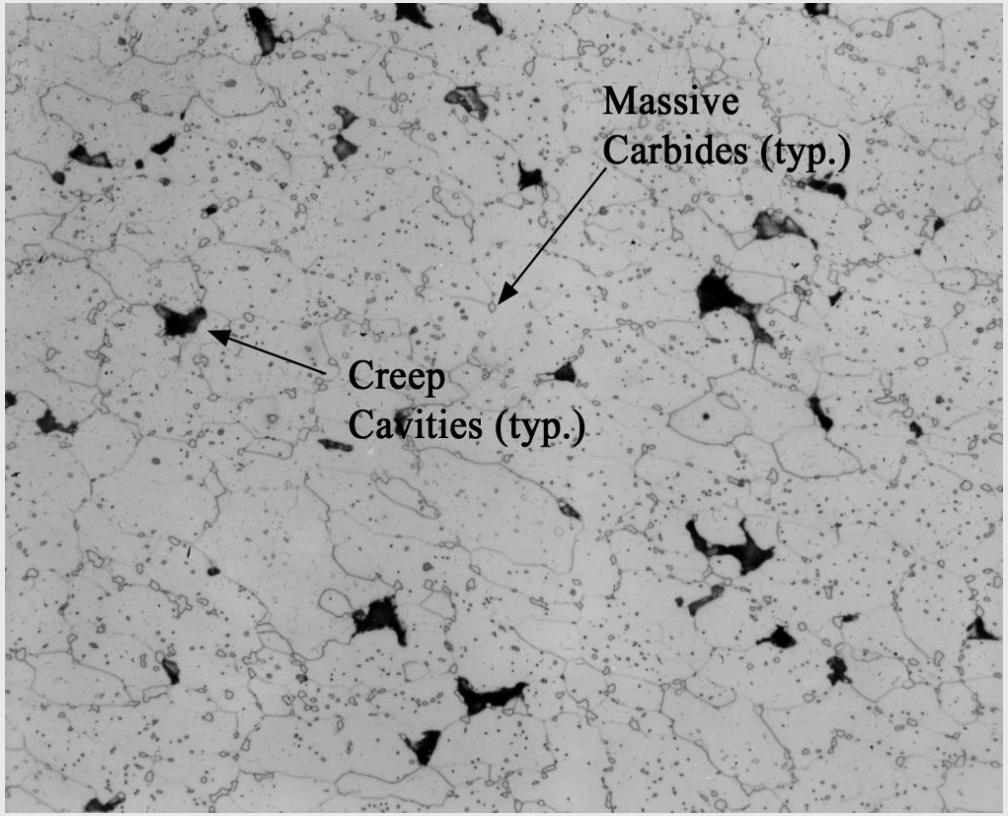



Elevated Temp

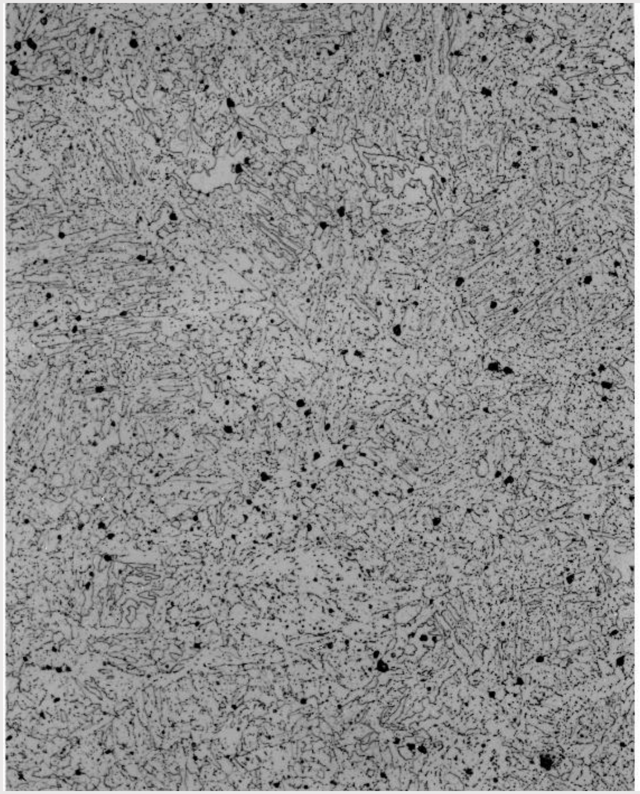


# Tertiary Creep – The Onset of Detectable Damage

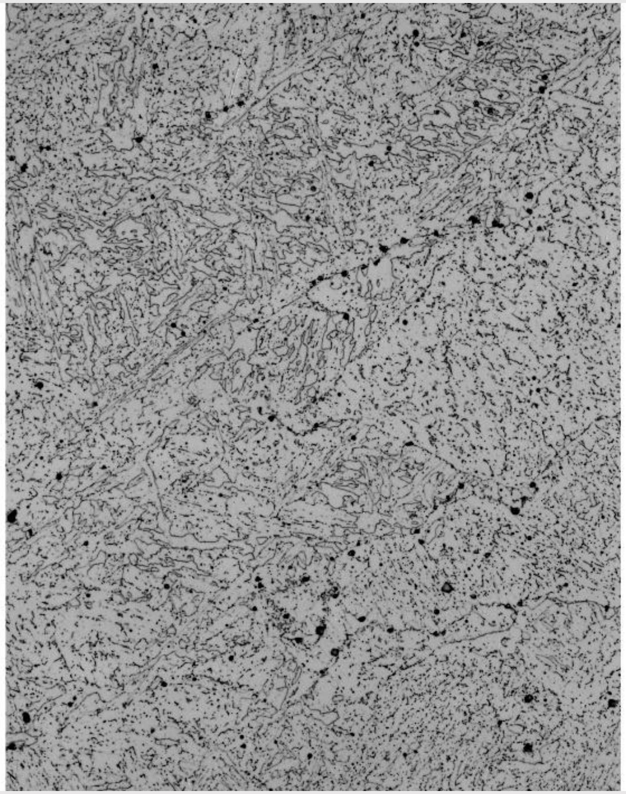
- Creep cavities are holes that form in the material as the material accumulates strain
- Creep cavity formation– diffusion controlled
- Formation is favored at higher temperatures and lower stresses
- Common damage mechanism in HEP



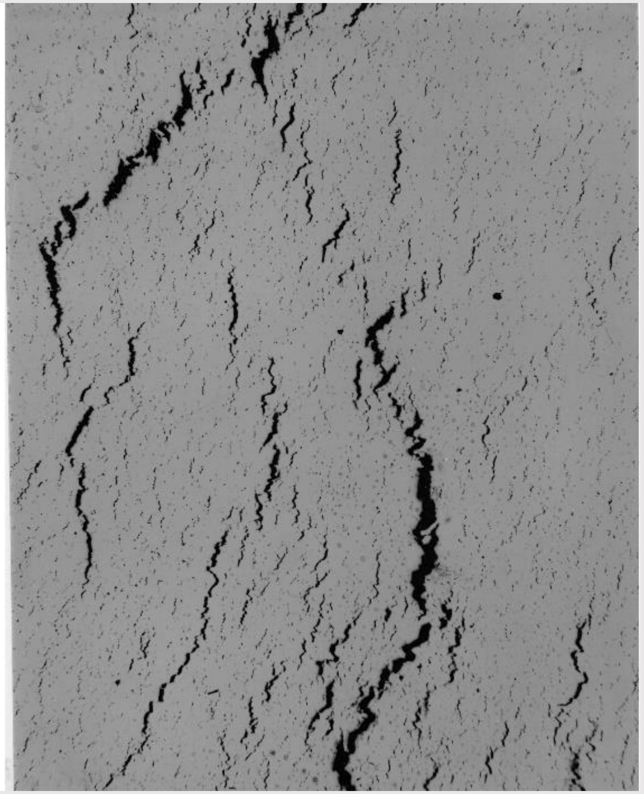
# Tertiary Creep: Stages in the Evolution of Creep Damage



Non-aligned cavities –
e.g., FG HAZ



Aligned cavities –
e.g., CG HAZ, Weld



Microcracks &
macrocracking

# HEP Designed to ASME Boiler & Pressure Vessel Code

- For HEP designed in accordance with the rules of the ASME B&PV Code (Sections I or B31.1), piping should operate reliably for > 250K hours, assuming:

a. Support of the piping system is properly maintained

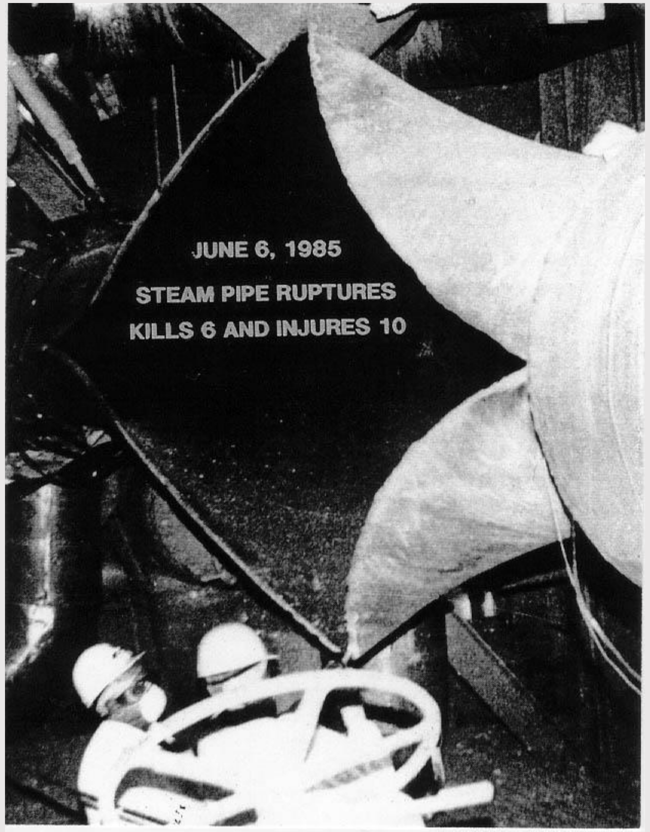
b. Steam generator is operated within design limits

c. Material is properly produced and components are properly fabricated and installed (particularly for the CSEF steels)

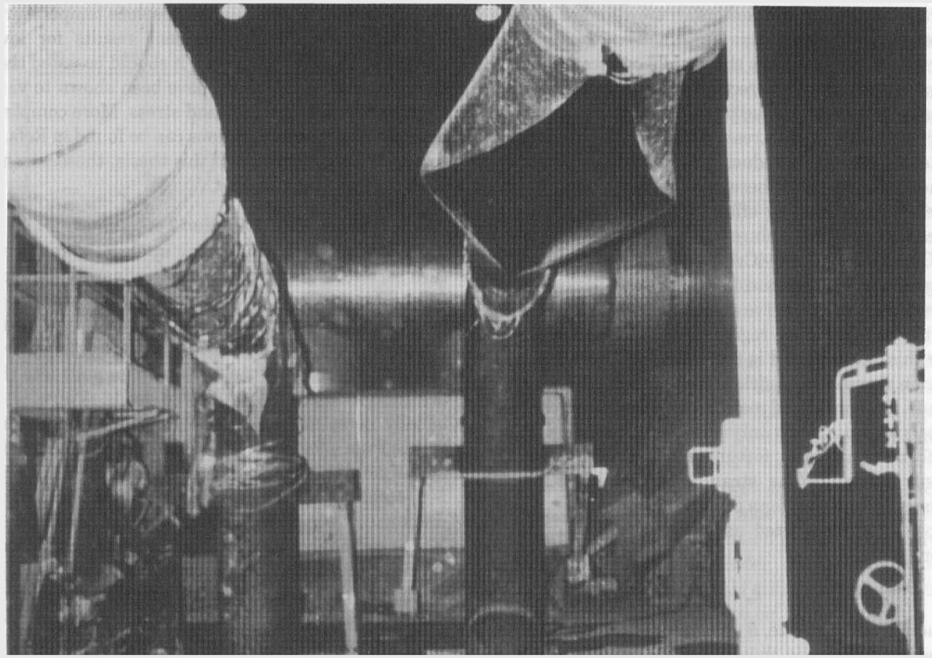
# End of Life – Pressure Part Base Metal

- In pressure parts, the gradual accumulation of creep damage can manifest itself in several different ways
- In base metal failures, the creep damage typically occurs as general swelling – for the "traditional" low alloy steels, such as Grades 11 or 22, 8-12% swelling at rupture is not uncommon
- Detection of this damage is relatively straightforward – simply measure the outside diameter

# Most Failures in HEP Occur at Welds




***Mohave***



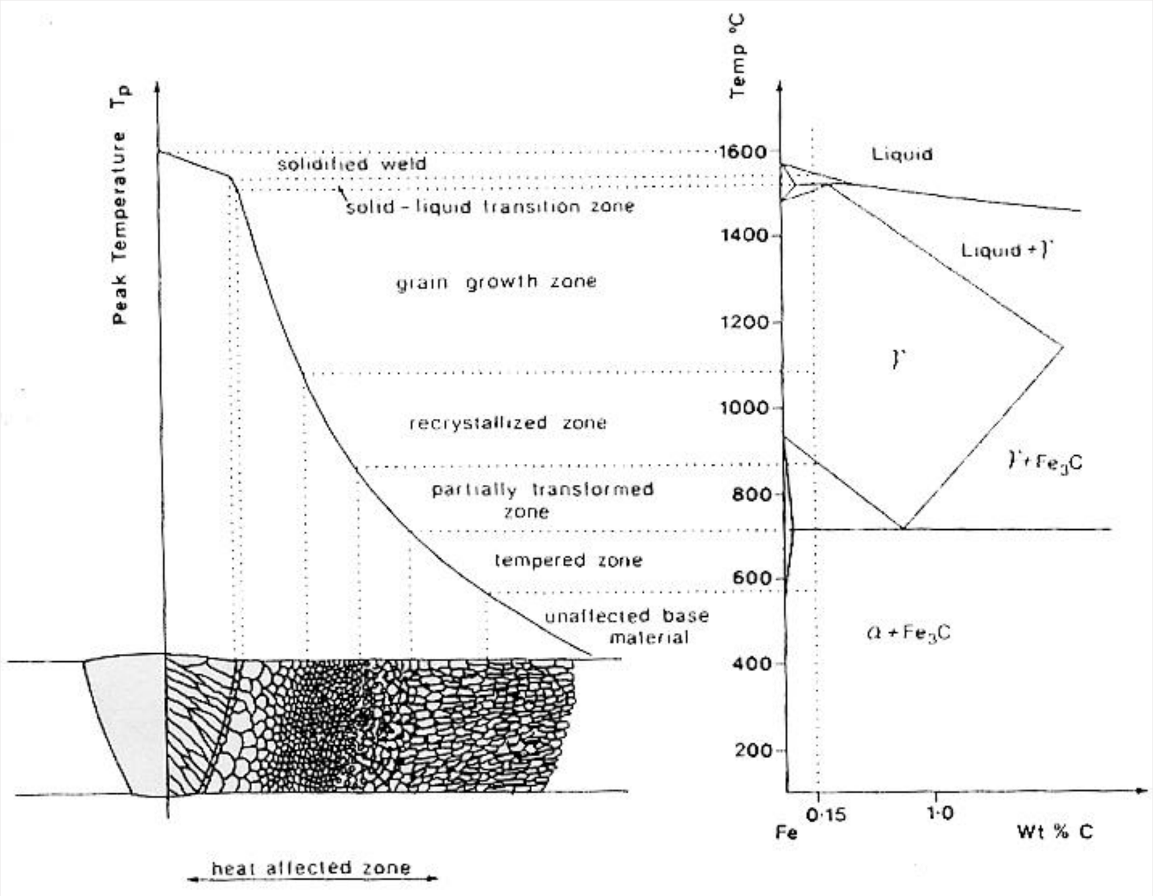
***Monroe***

In These Cases, Failures Occurred in Weld Metal Immediately Adjacent to the Weld Fusion Boundary – *There Was No Gross Swelling of the Pipe and Failure Occurred at Fraction of "Expected" Life*

# Welds in HEP

- All HEP systems contain welds
  - *Girth seam welds*
  - *Longitudinal seam welds*
  - Pipe-to-Pipe saddle welds
  - Lug attachment welds
  - Radiograph plug welds


# The Structure of Welds



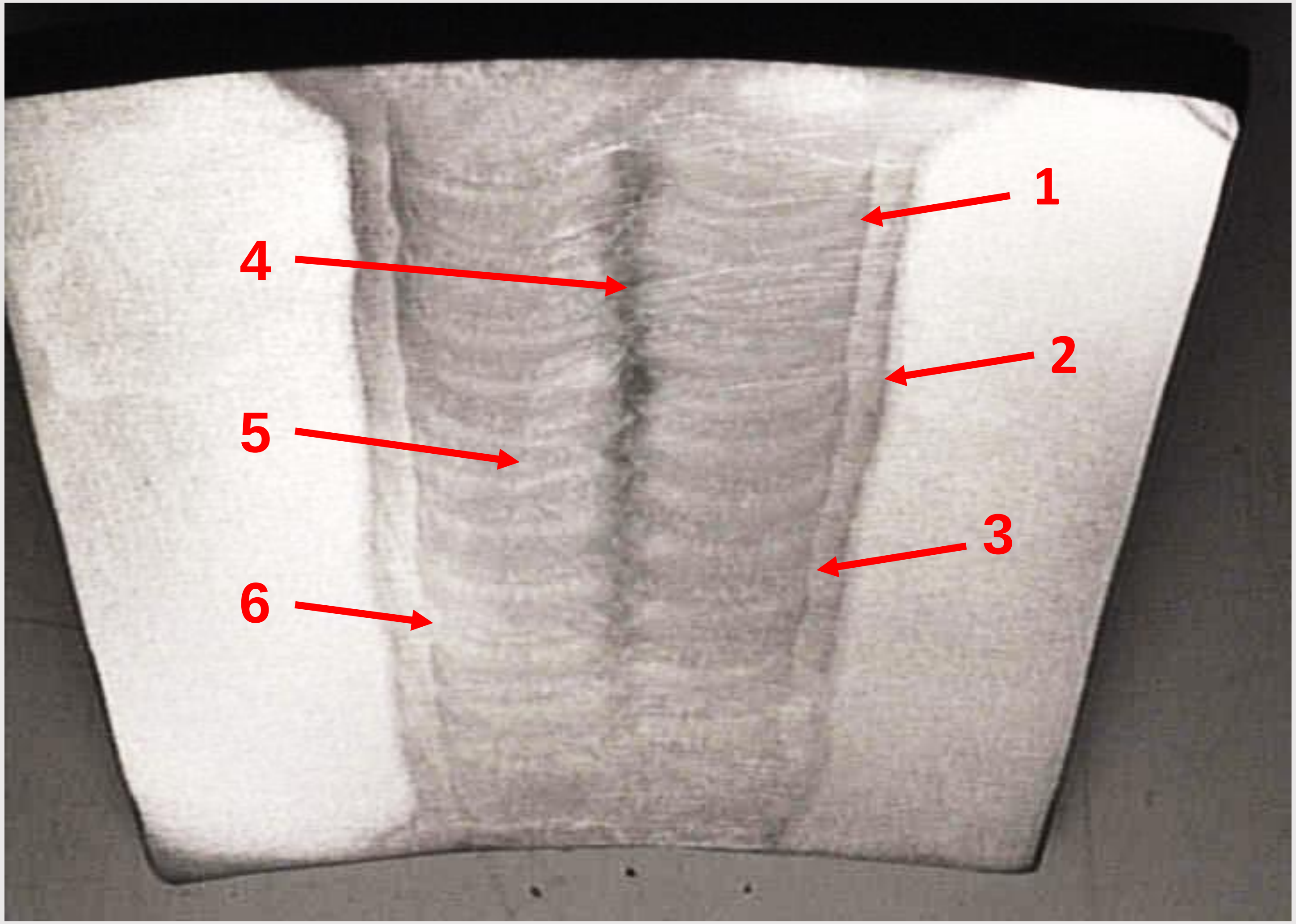

Welds are complex and non-uniform structures – this can be beneficial at lower temperatures but becomes a problem at elevated temperatures

# Experience with Welds in High Temperature Service

4 – Overlapping Intra-Weld HAZ Structure

5 – Weld Bead Centerline

6 – Fusion Boundary

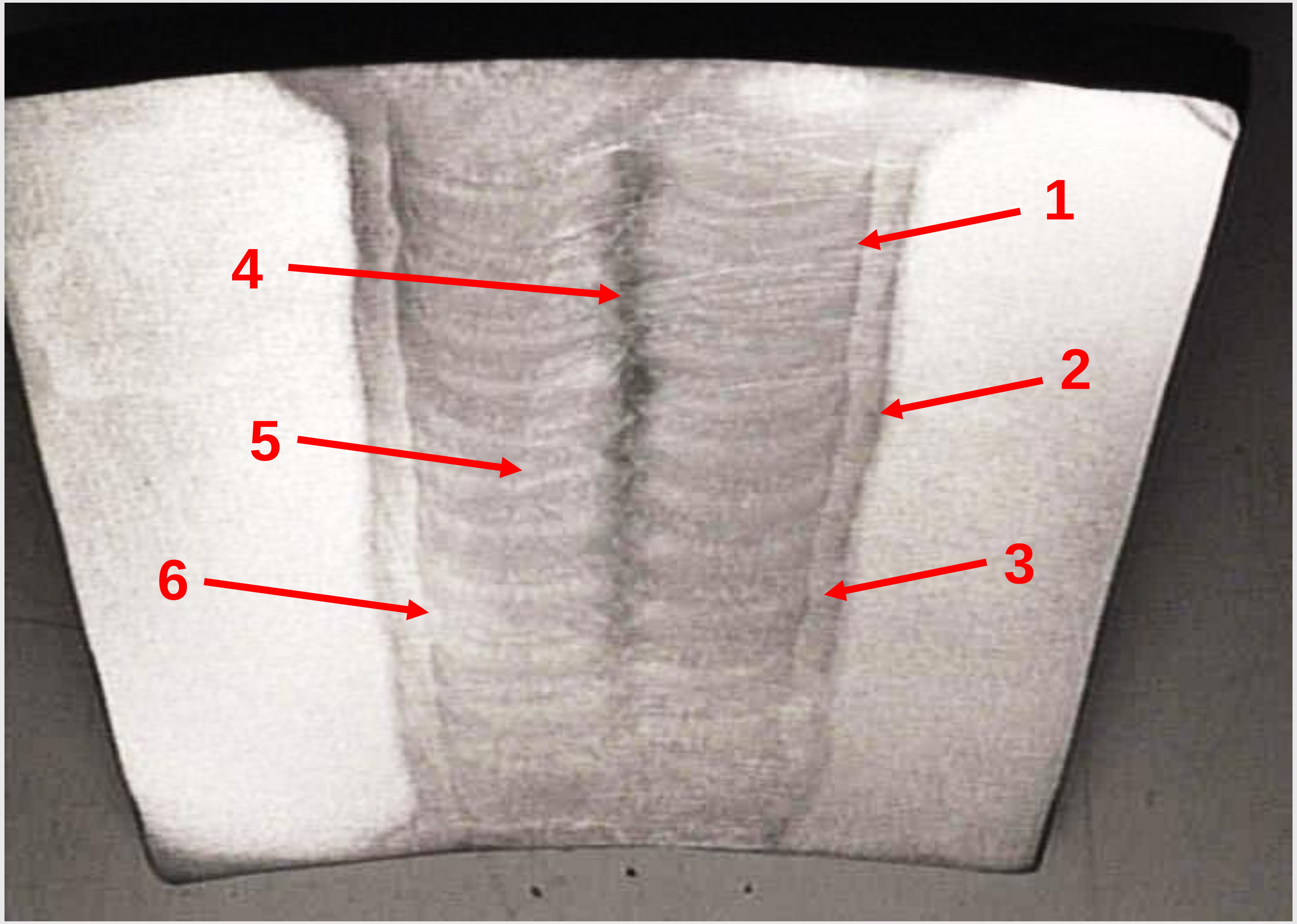



1 – Weld Metal Adjoining Fusion Boundary

2 – Fine-Grained/Intercritical Region of HAZ

3 – HAZ Structure Adjoining Fusion Boundary

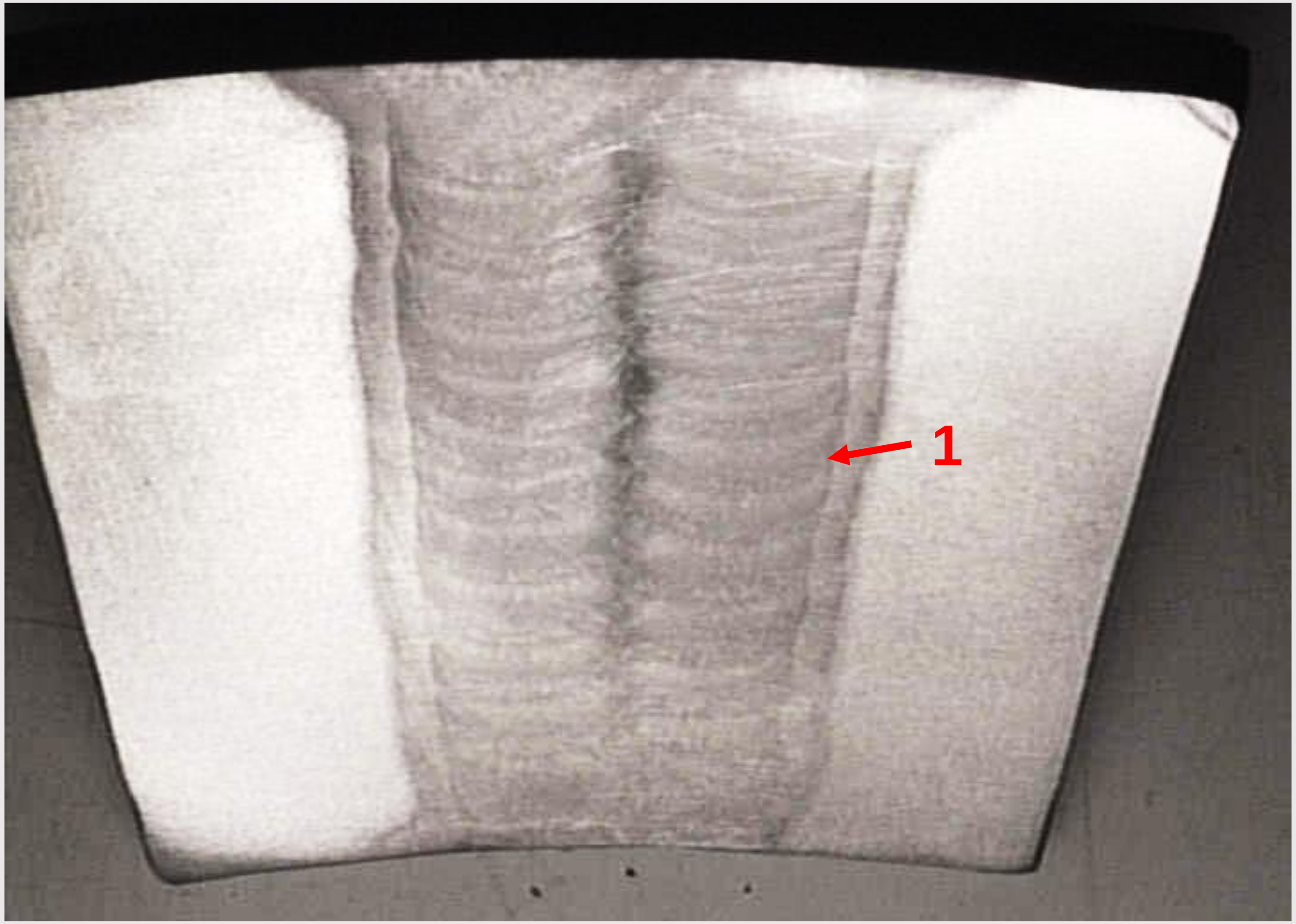
# Welds in High Temperature Service




1 – Compositional effects (inclusions, decarburization), structural effects (inclusion clustering)
2 - Grain size effect; over-tempering effects
3 – Compositional effects (decarburization, reduced rupture ductility); CTE difference in DMWs
4 – Grain size effect; tempering effect; structural effects (inclusion clustering)
5 – Compositional effects
6 – Compositional effects (nickel segregation); structural effects (Type I carbides); tempering effects (suppression of AC1); CTE difference

*In all areas, local stress concentration effects due to strength mismatch*

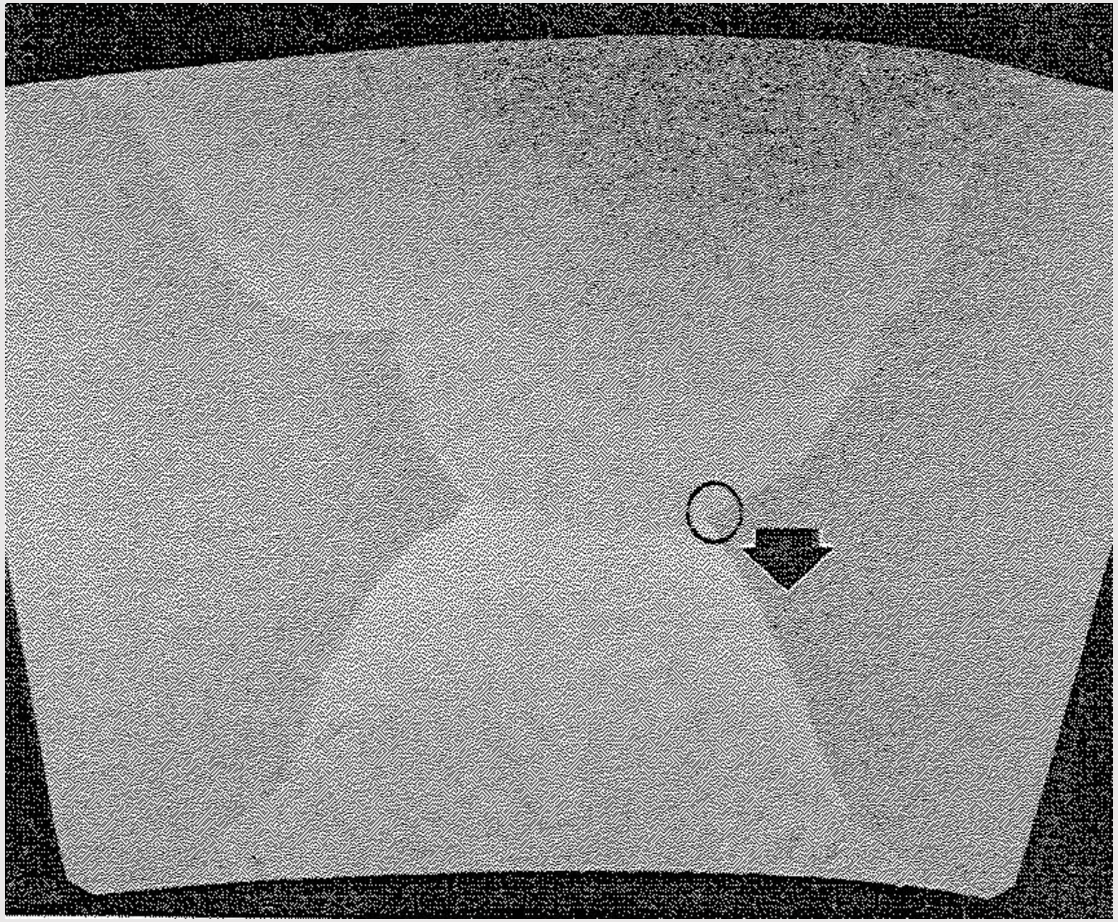
# Welds in High Temperature Service

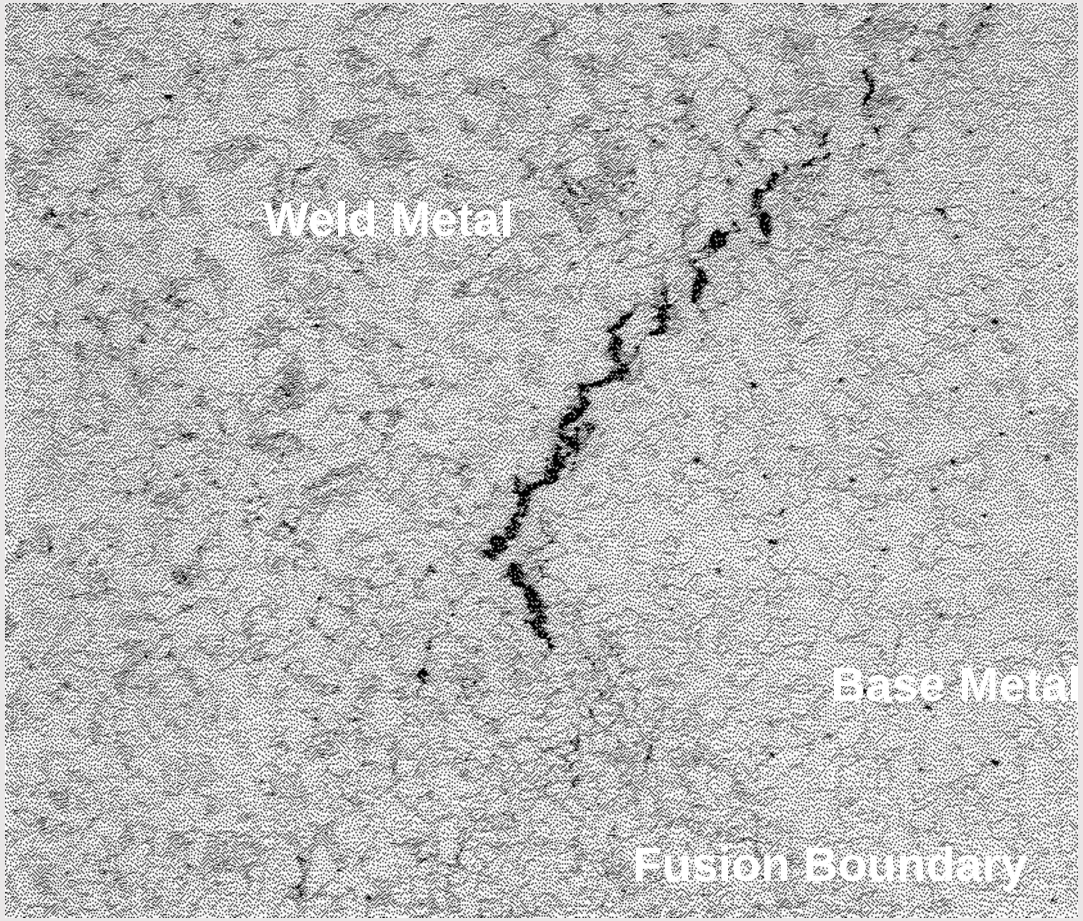



1 – Weld Metal Adjoining Fusion Boundary

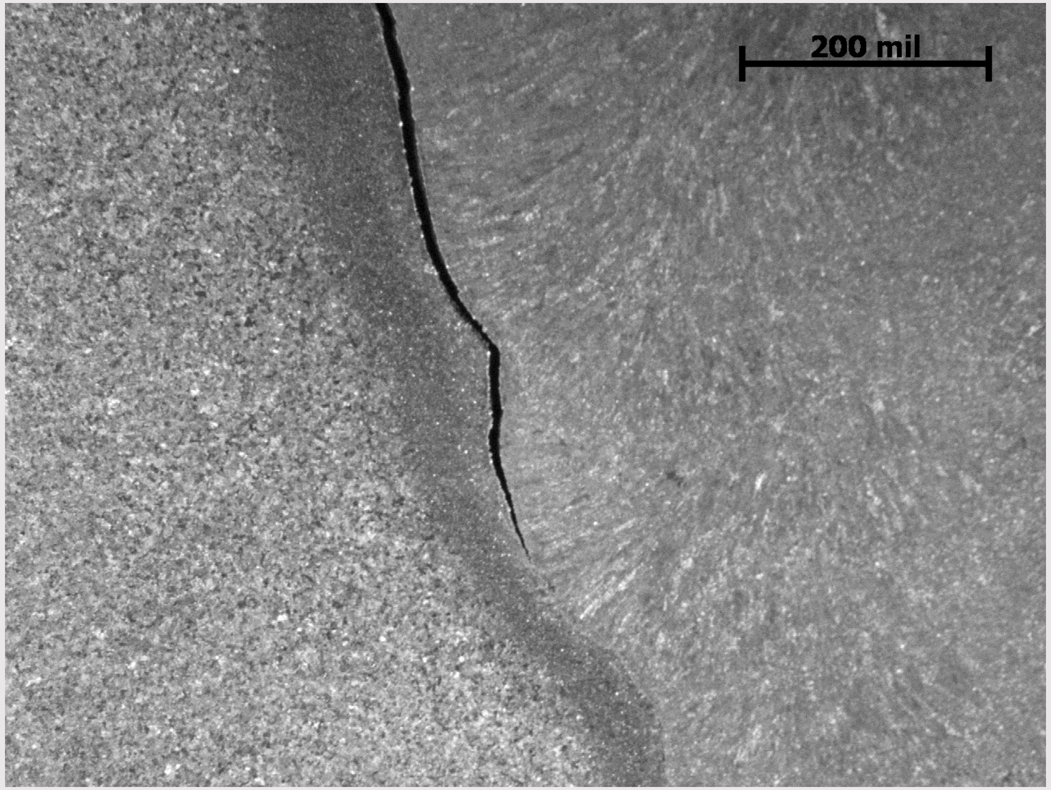
# Failure in Cr-Mo Long Seam Welds

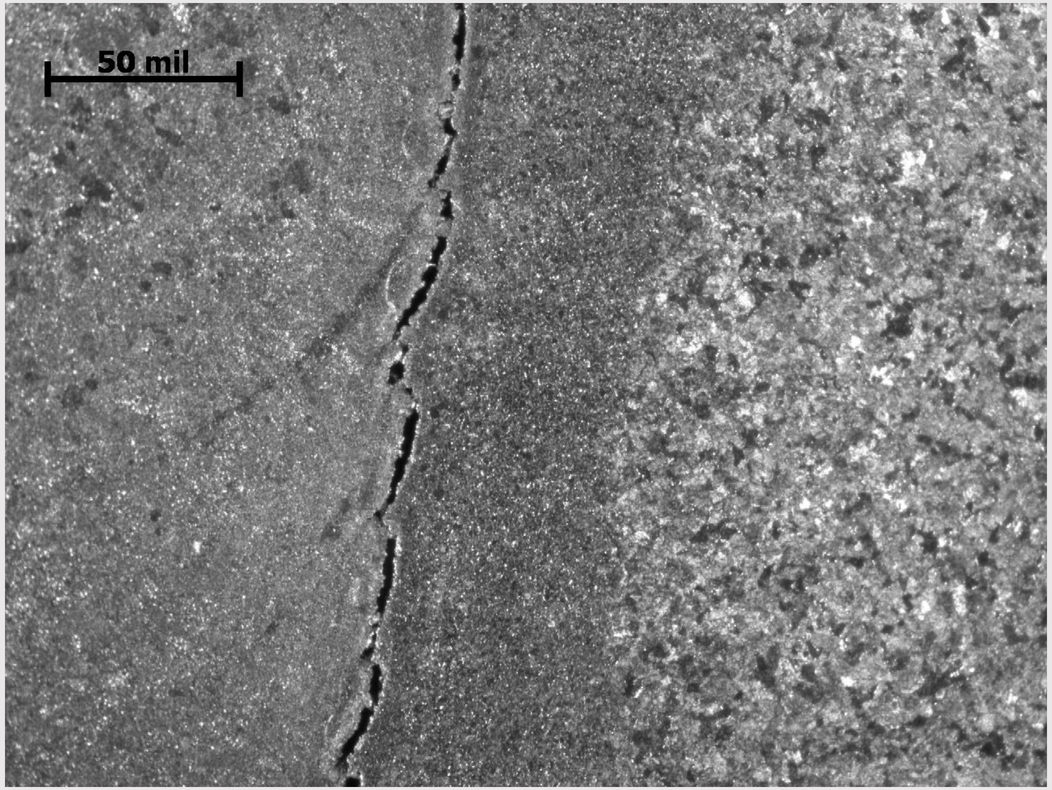
Damage Initiation Site – Region 1 – No HAZ!





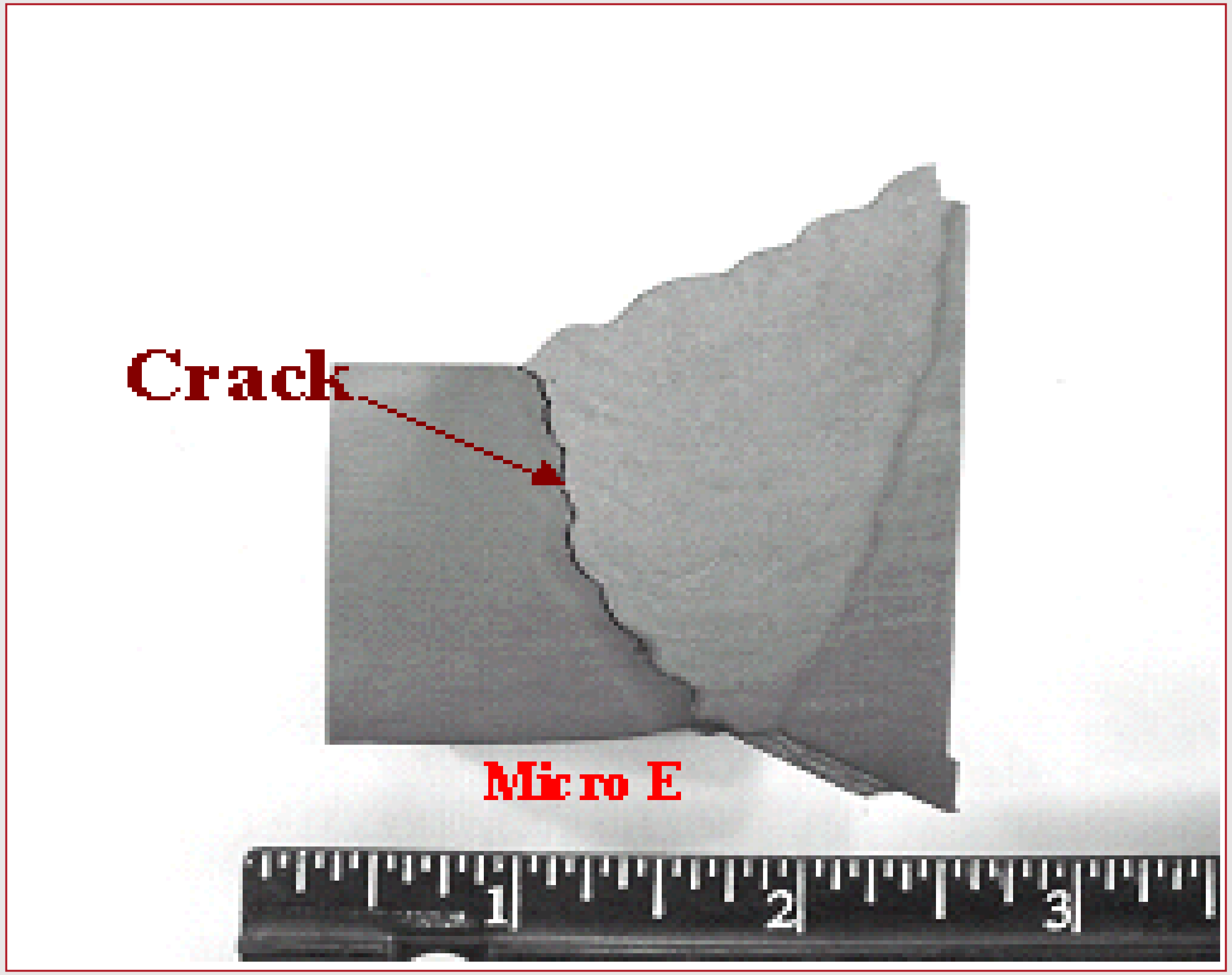
# Failure in Cr-Mo *Girth* Seam Welds – Region 1

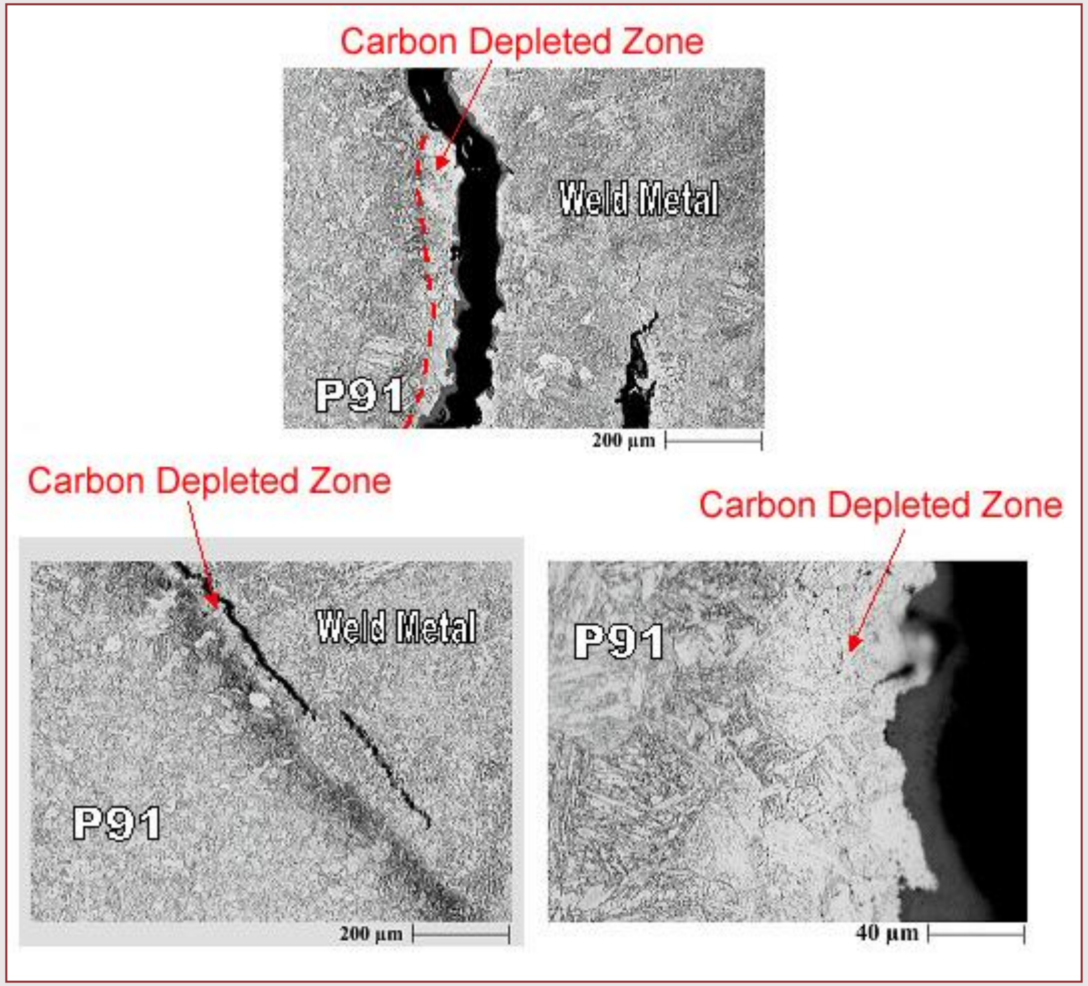


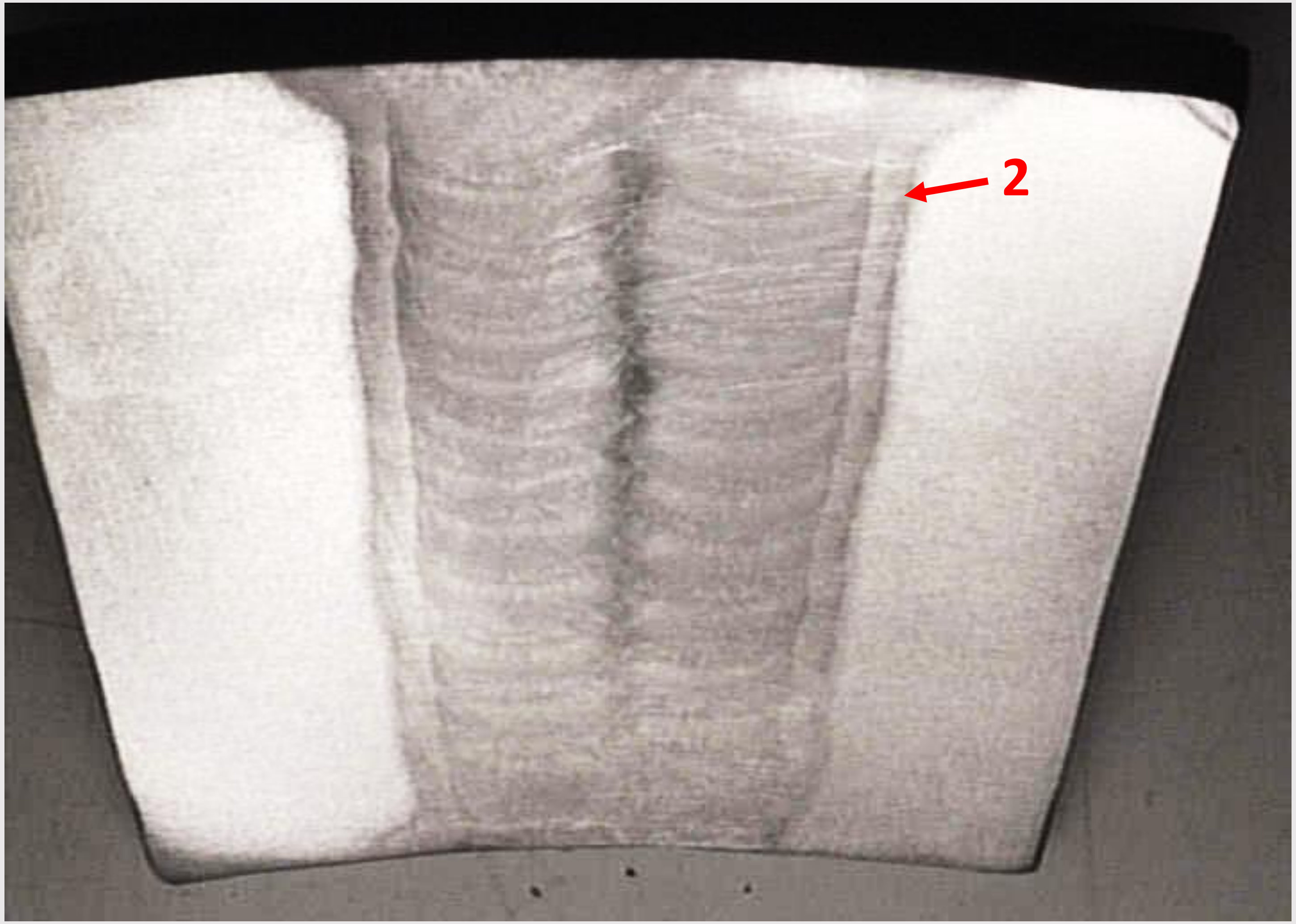
# Failure in DMW (91Pipe to 2-1/4Cr-1Mo Filler Metal)

## Damage Initiation Site – Region 1



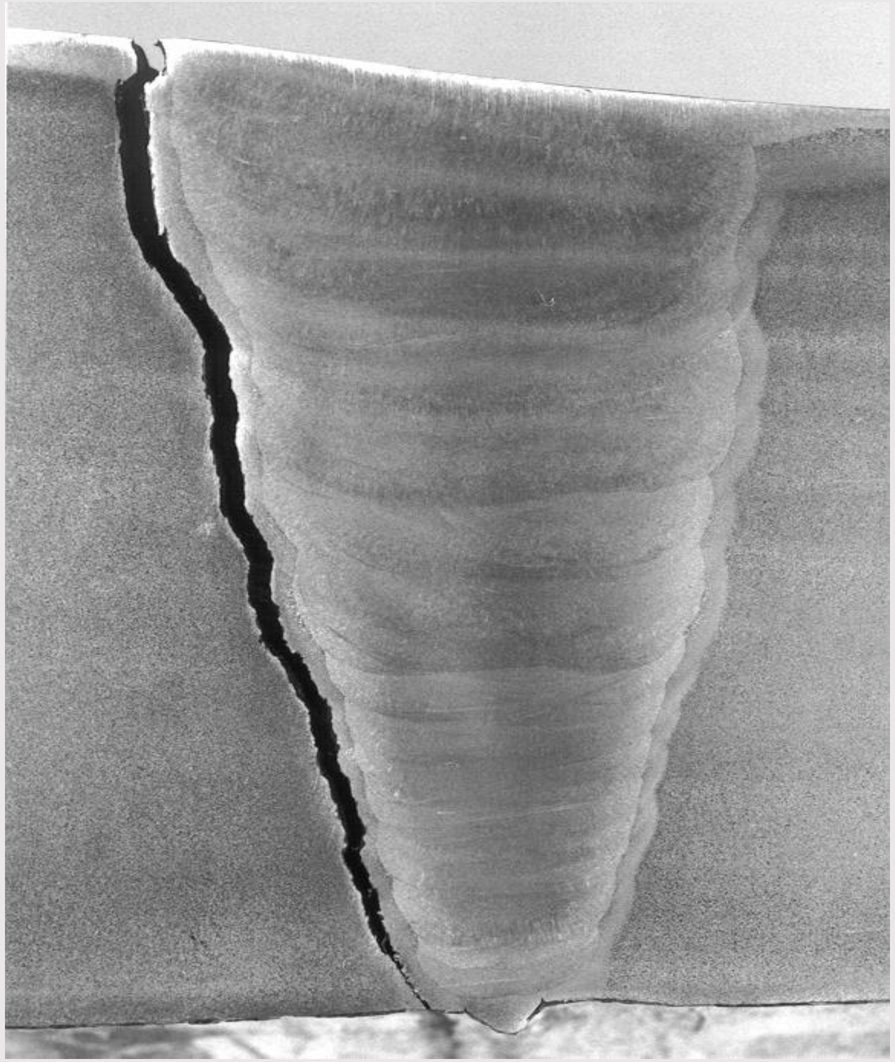



# Welds in High Temperature Service

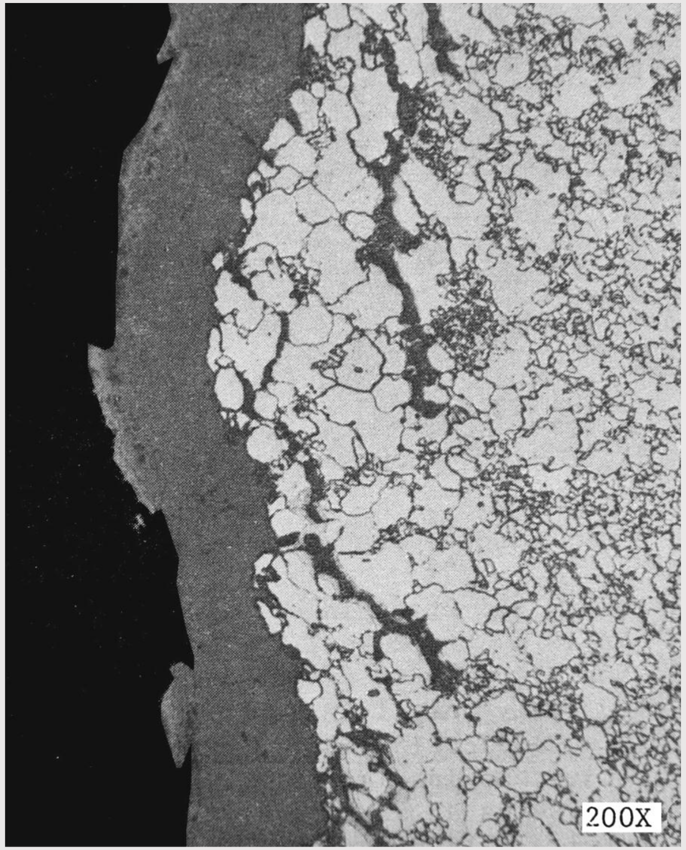



2 – Fine-Grained/Intercritical Region

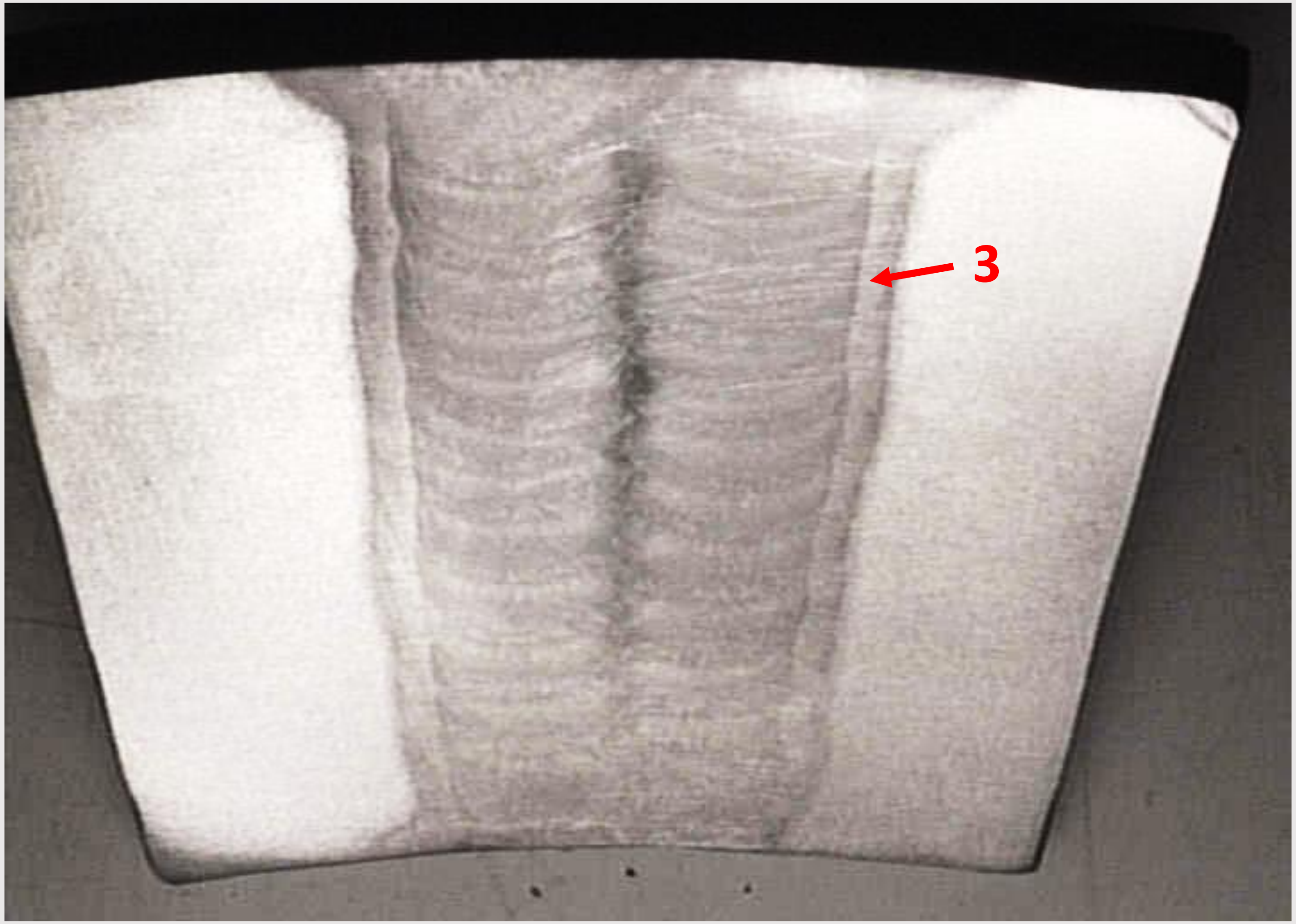
# Cracking in Fine-Grained/Intercritical Structure – Region 2



# Cracking in Fine-Grained/Intercritical Structure – Region 2



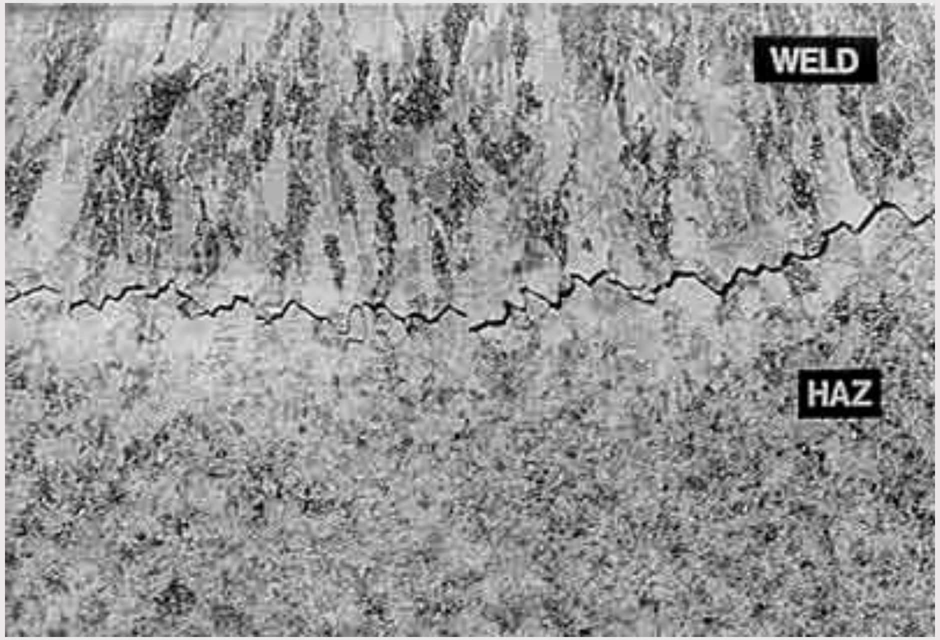
# Welds in High Temperature Service

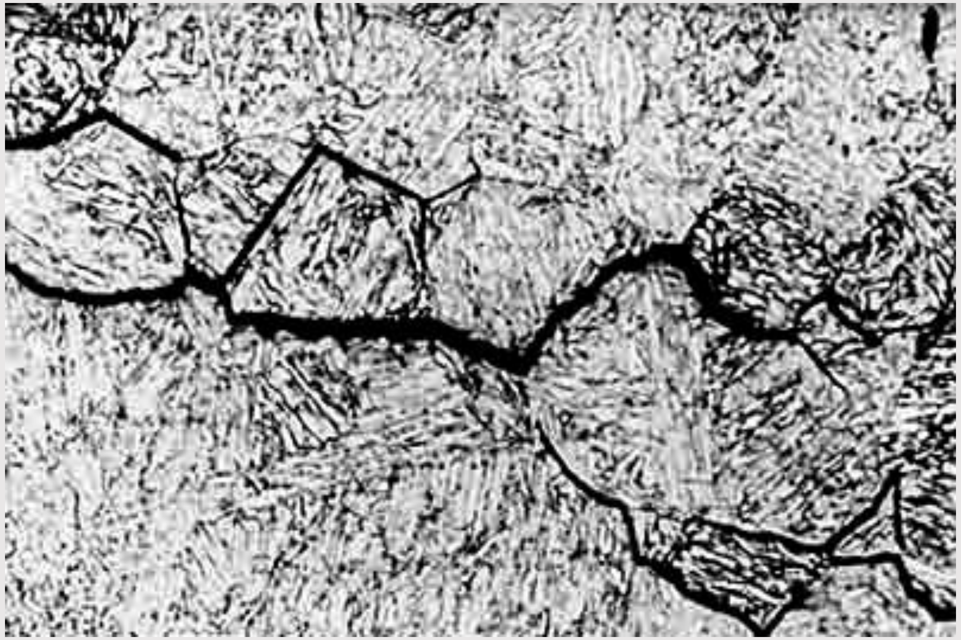



3 – HAZ Structure Adjoining Fusion Boundary

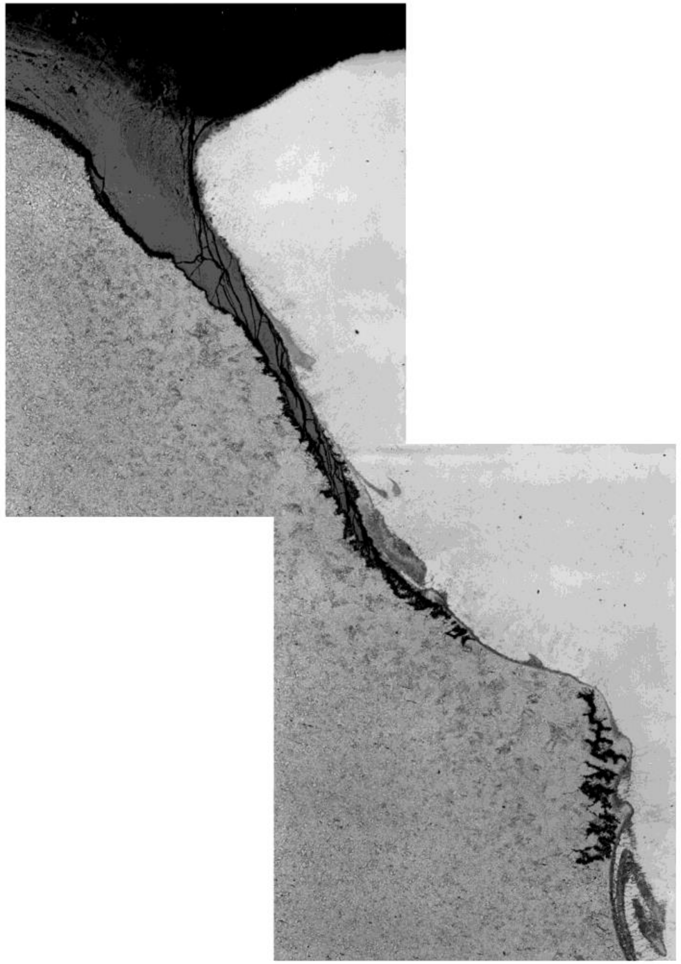
# Cracking in HAZ Structure Adjoining Fusion Boundary – Region 3

# Reheat Cracking in HAZ Structure Adjoining Fusion Boundary – Region 3



# Damage in HAZ Structure Adjoining Fusion Boundary–Region 3



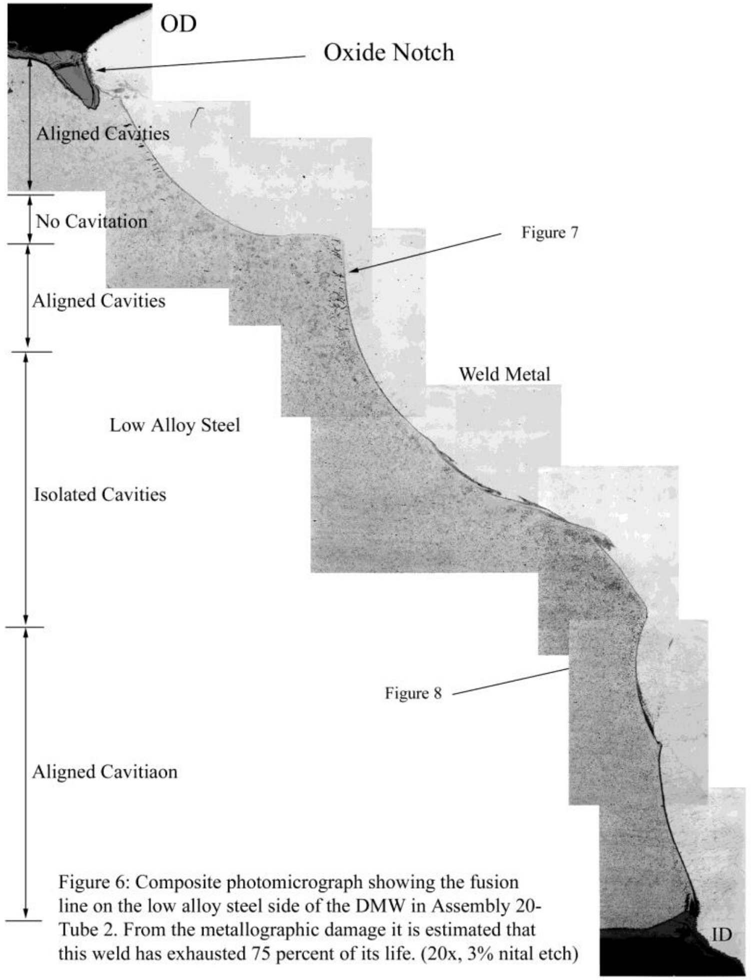
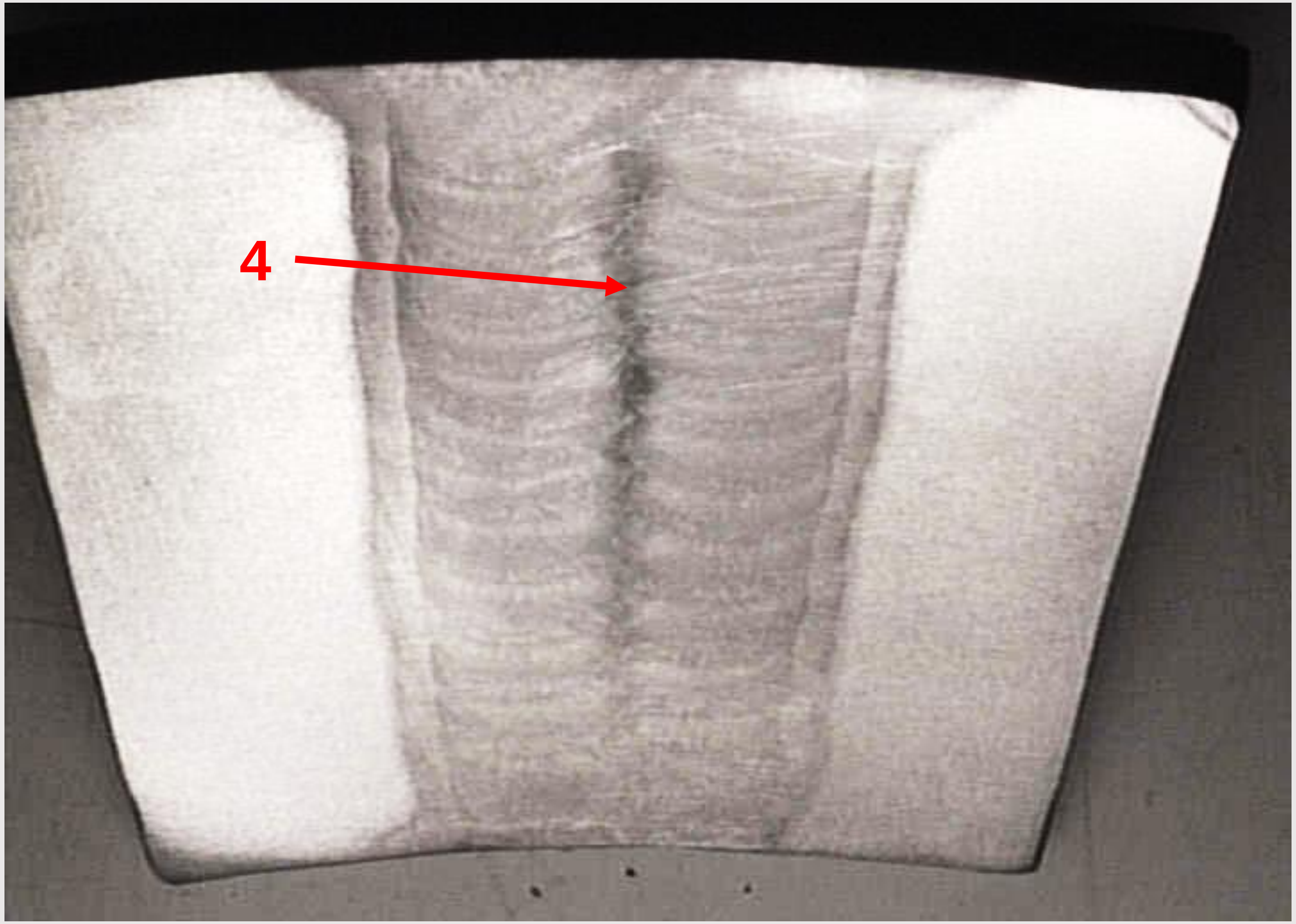


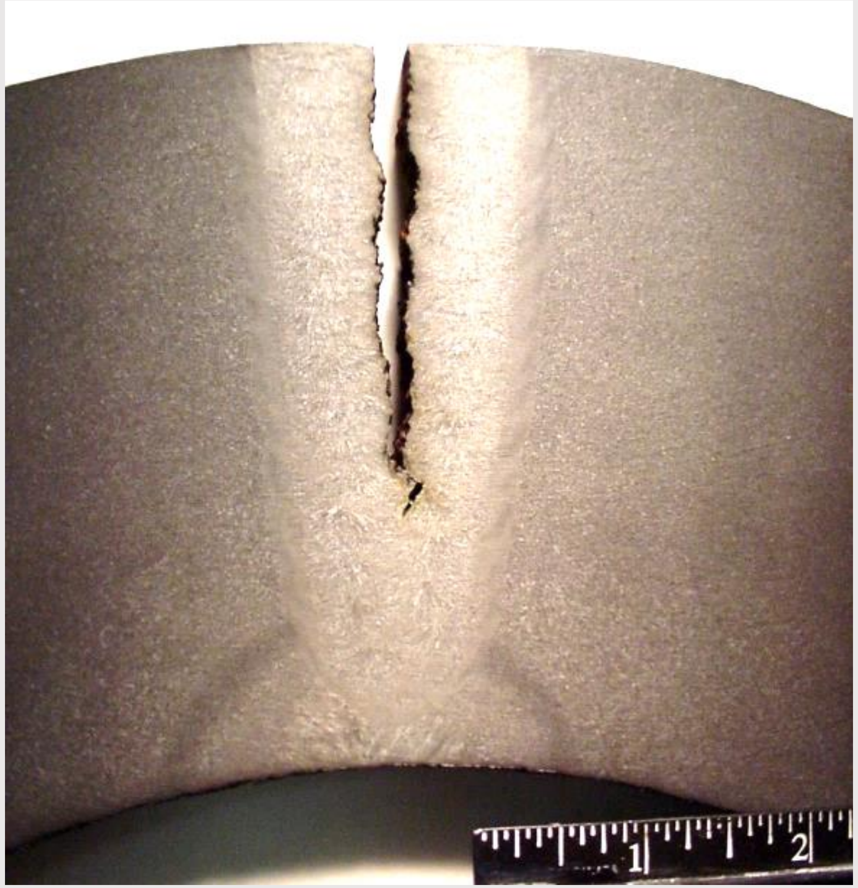

Figure 6: Composite photomicrograph showing the fusion line on the low alloy steel side of the DMW in Assembly 20-Tube 2. From the metallographic damage it is estimated that this weld has exhausted 75 percent of its life. (20x, 3% nital etch)

# Welds in High Temperature Service

4 – Intra-Weld Continuous HAZ Structure

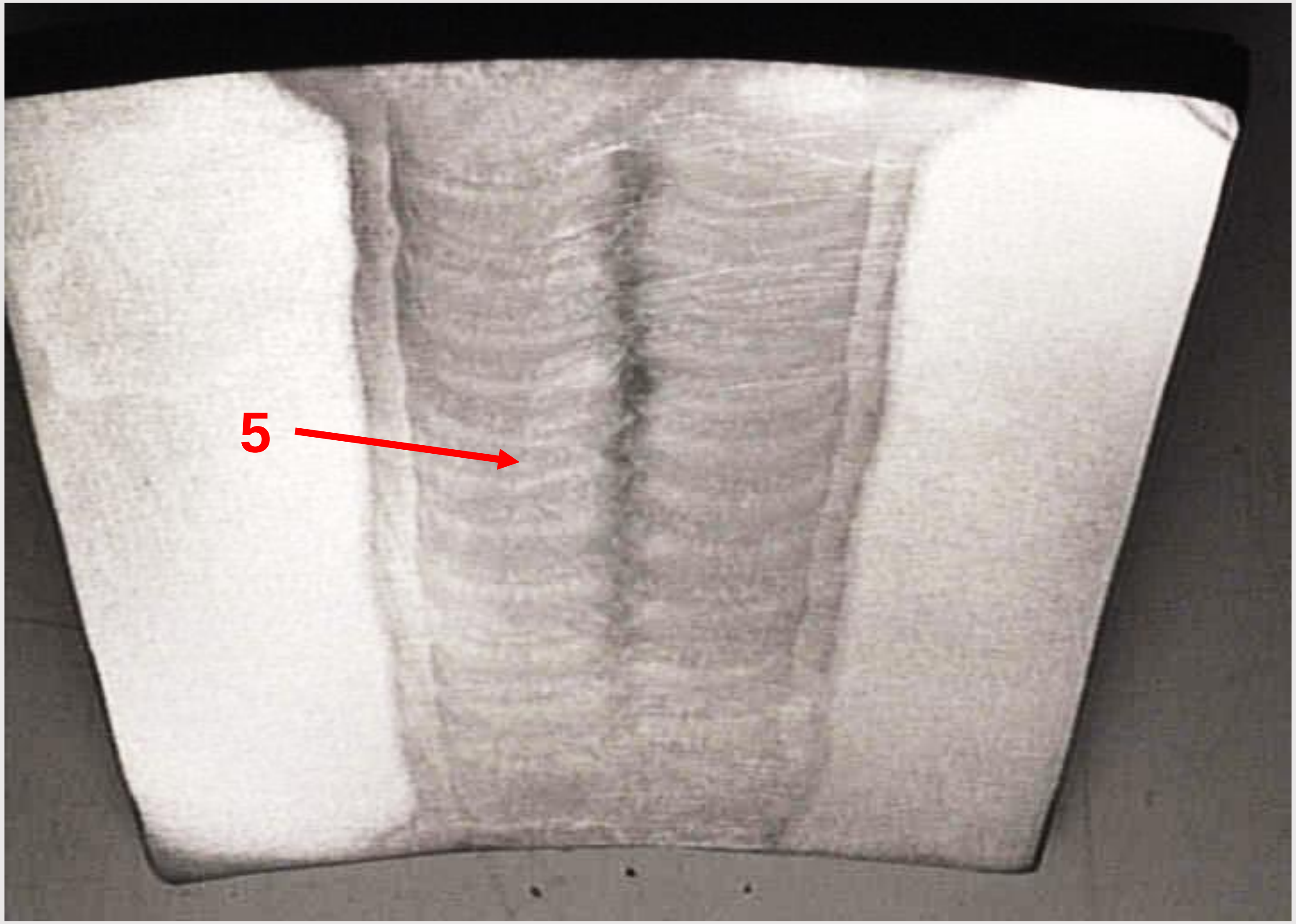


# Cracking in Continuous Fine-Grained/Intercritical Structure Within Weld Metal – Region 4



# Welds in High Temperature Service

5 – Weld Bead Centerline



# Cracking in Center of Weld Beads Within Weld Metal – Region 5

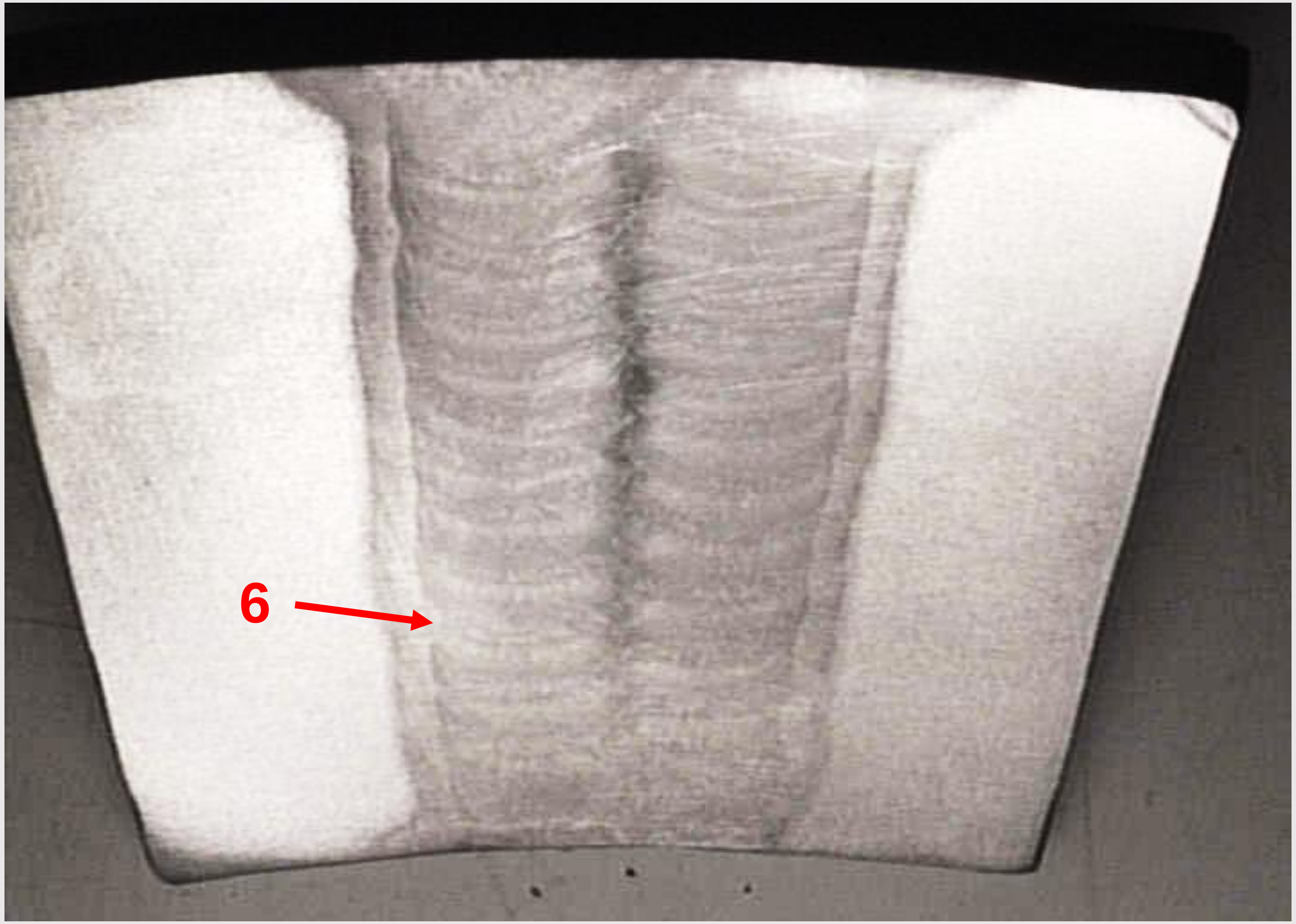
**Stacked bead configuration of weld with sub-surface initiation of cracking – *but cracking is at center of weld beads, not at HAZ in areas of overlap***

# Cracking in Center of Weld Beads Within Weld Metal – Region 5

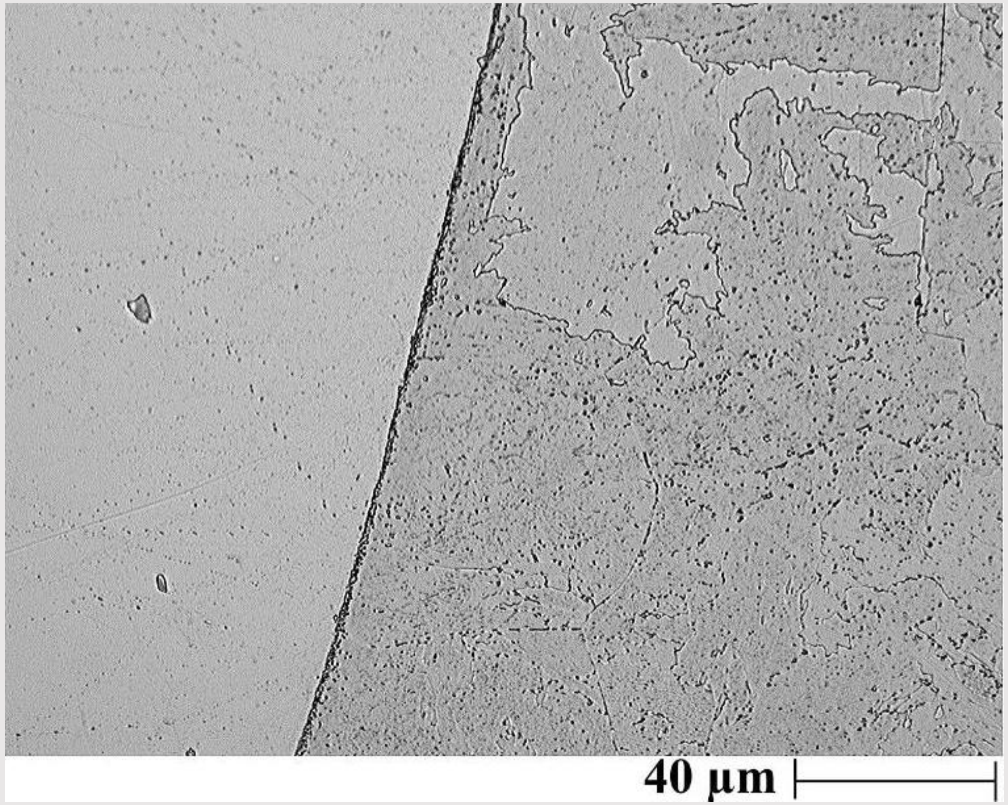
**Creep damage concentrated at centerline of weld beads, with lesser amounts of damage away from centerline**

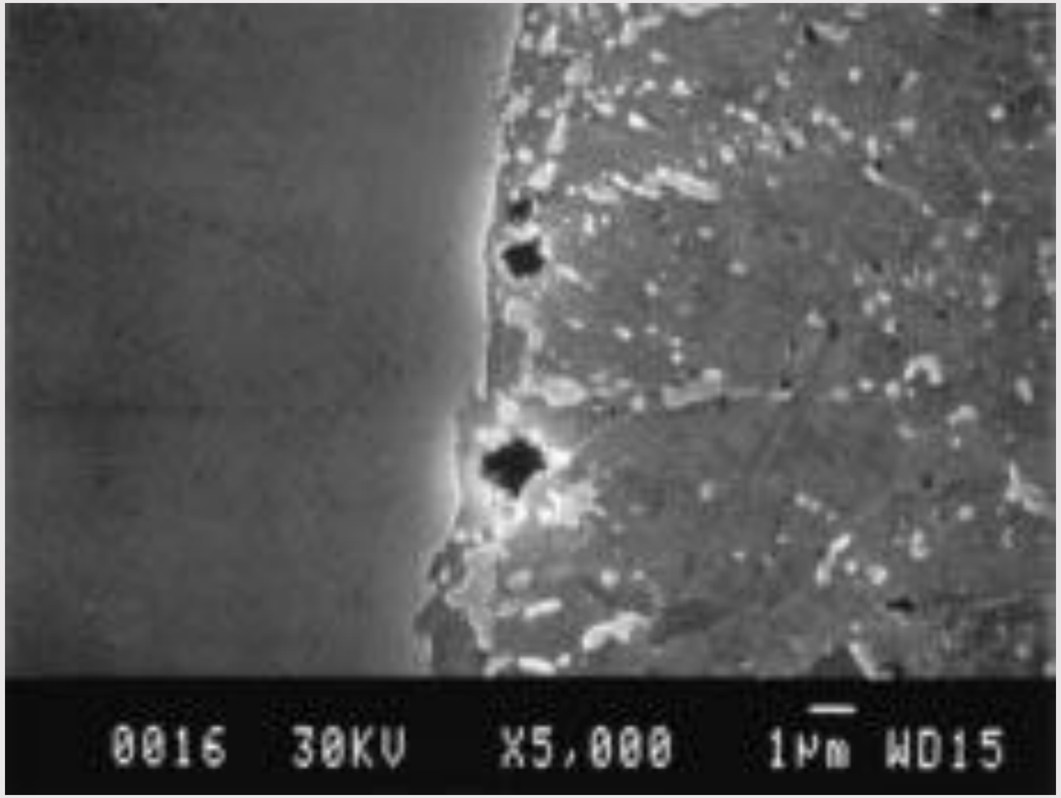
# Welds in High Temperature Service - DMWs

6 – Fusion Boundary



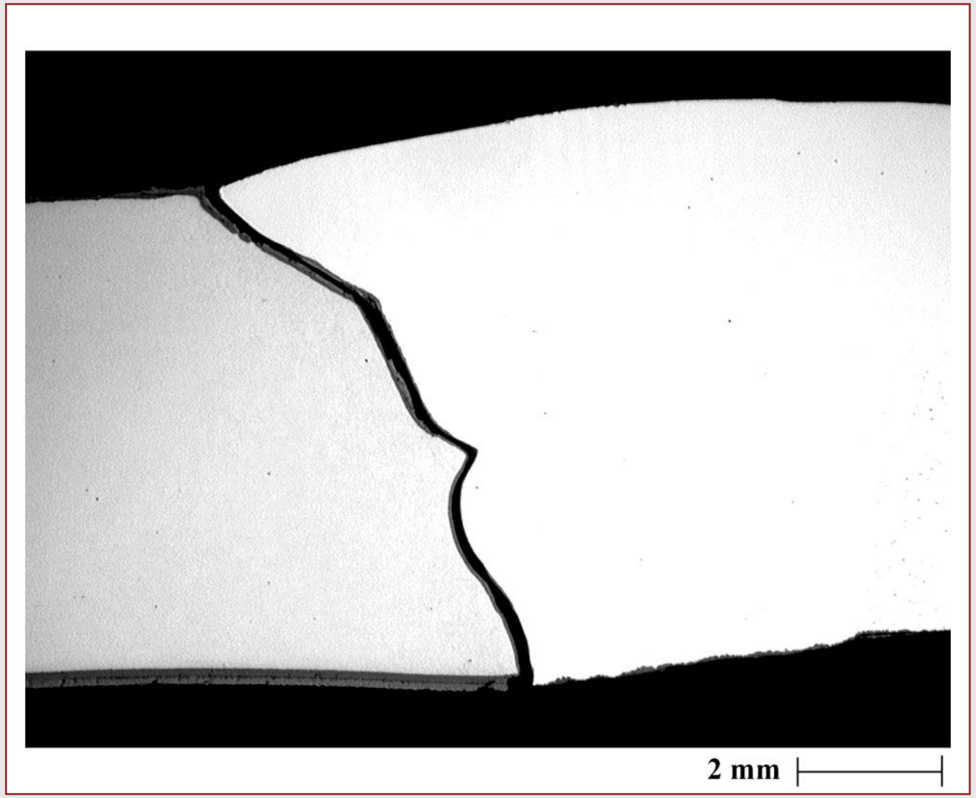
# Damage at Fusion Boundary in DMW – Region 6

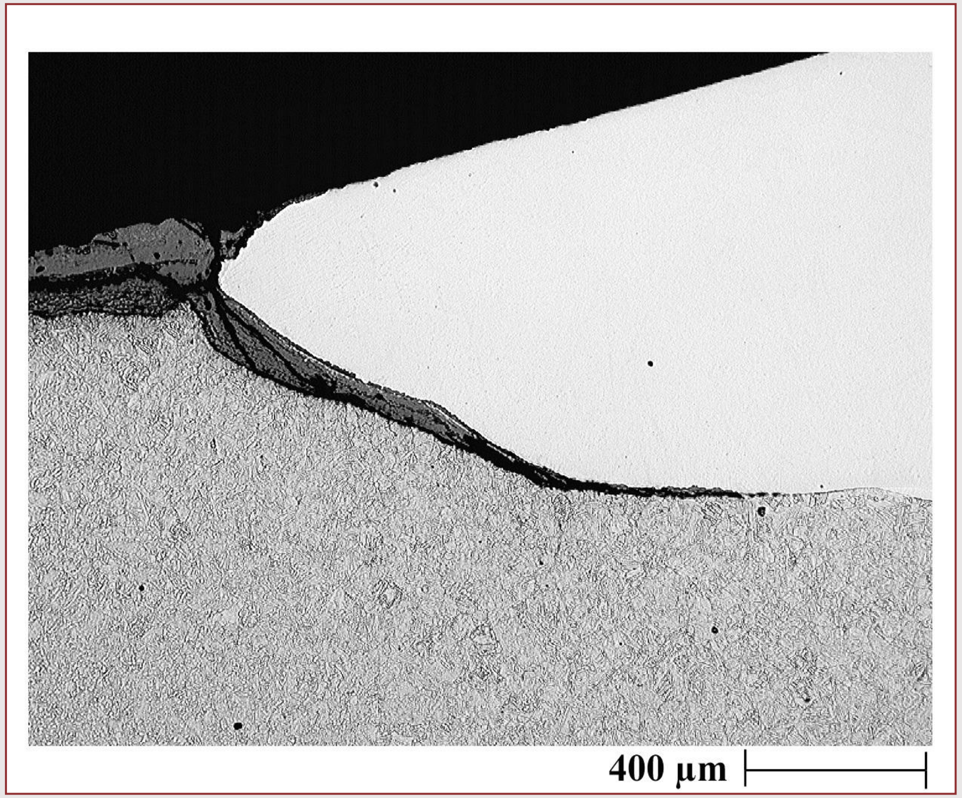



Weld Joining Low Alloy Steel to Stainless Using Nickel-Base Filler Metal – Creep Damage Initiating in Conjunction with Type I Carbides

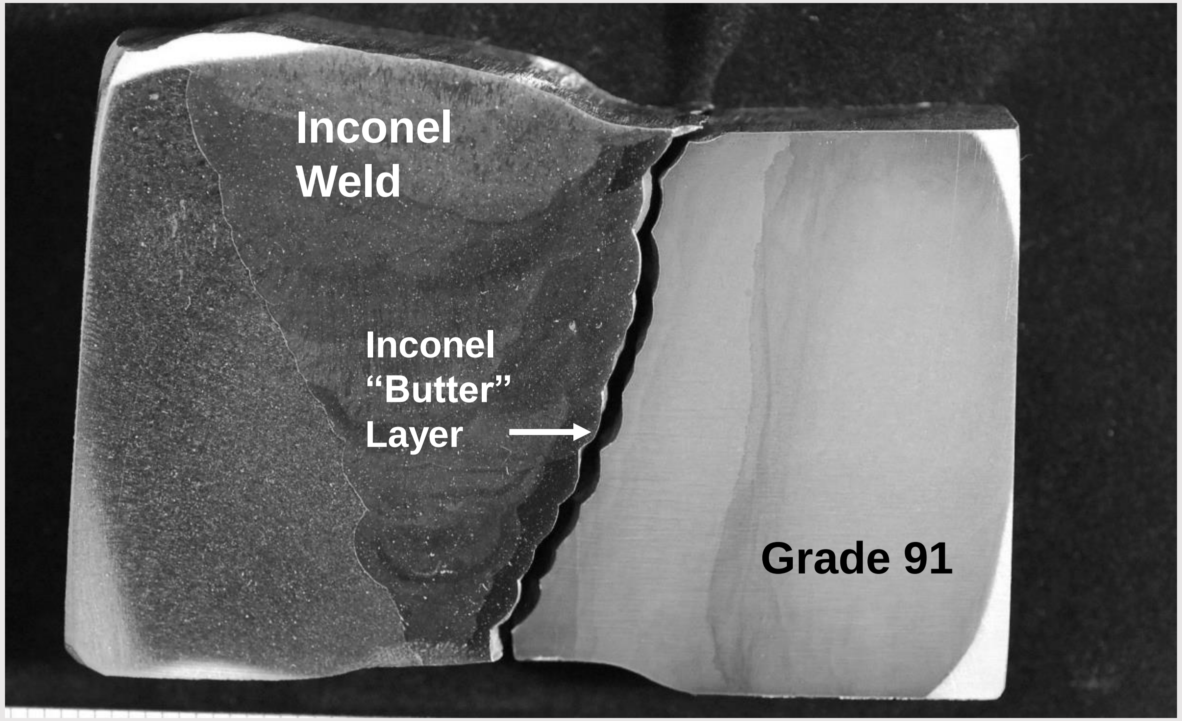
# Damage at Fusion Boundary in DMW – Region 6



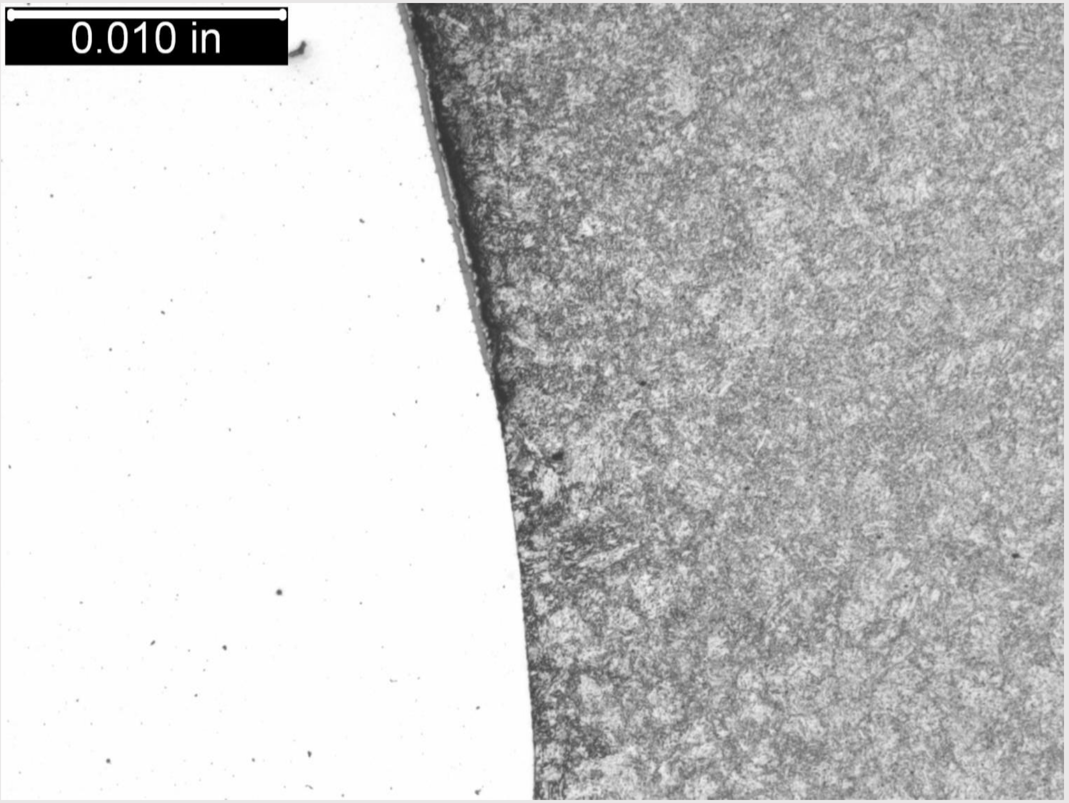

Environmentally-Induced Fracture (Sulfidation) at Interface of Weld Between Grade 91 Tubing and Nickel-Base Filler Metal (Inco 82)

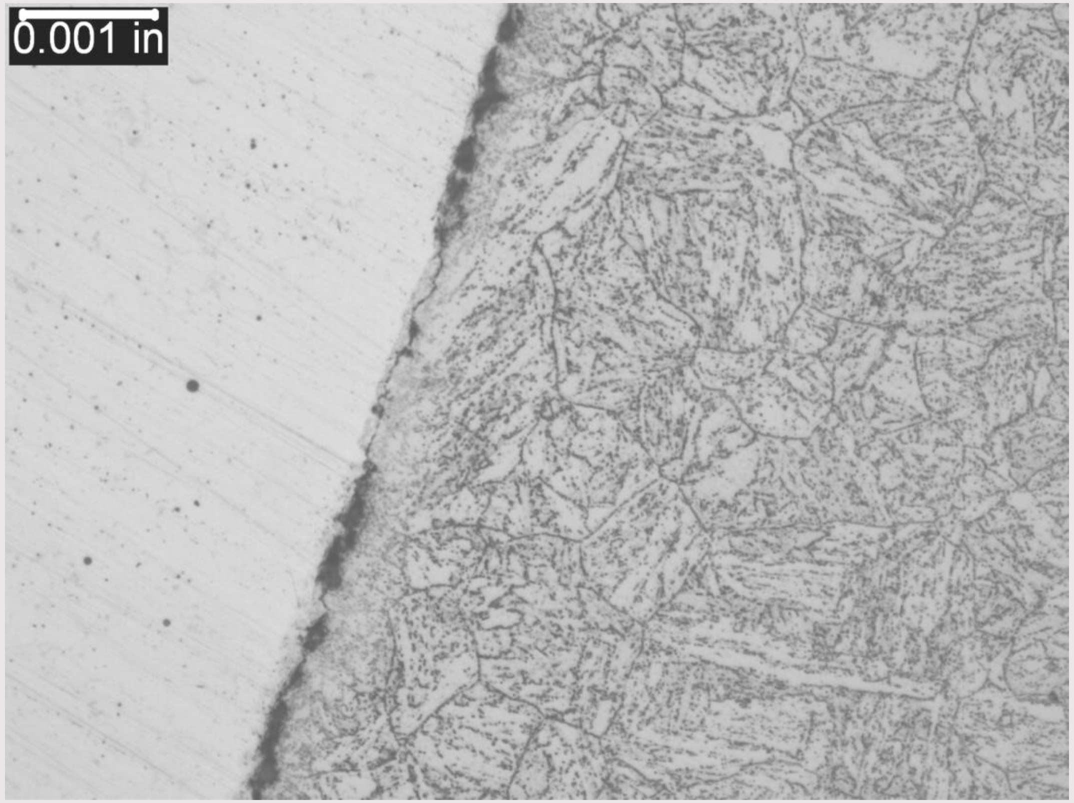
# Damage at Fusion Boundary in DMW – Region 6


DMW Joining Grade 91 Piping to TP316 Piping Using Nickel-Base Filler Metal

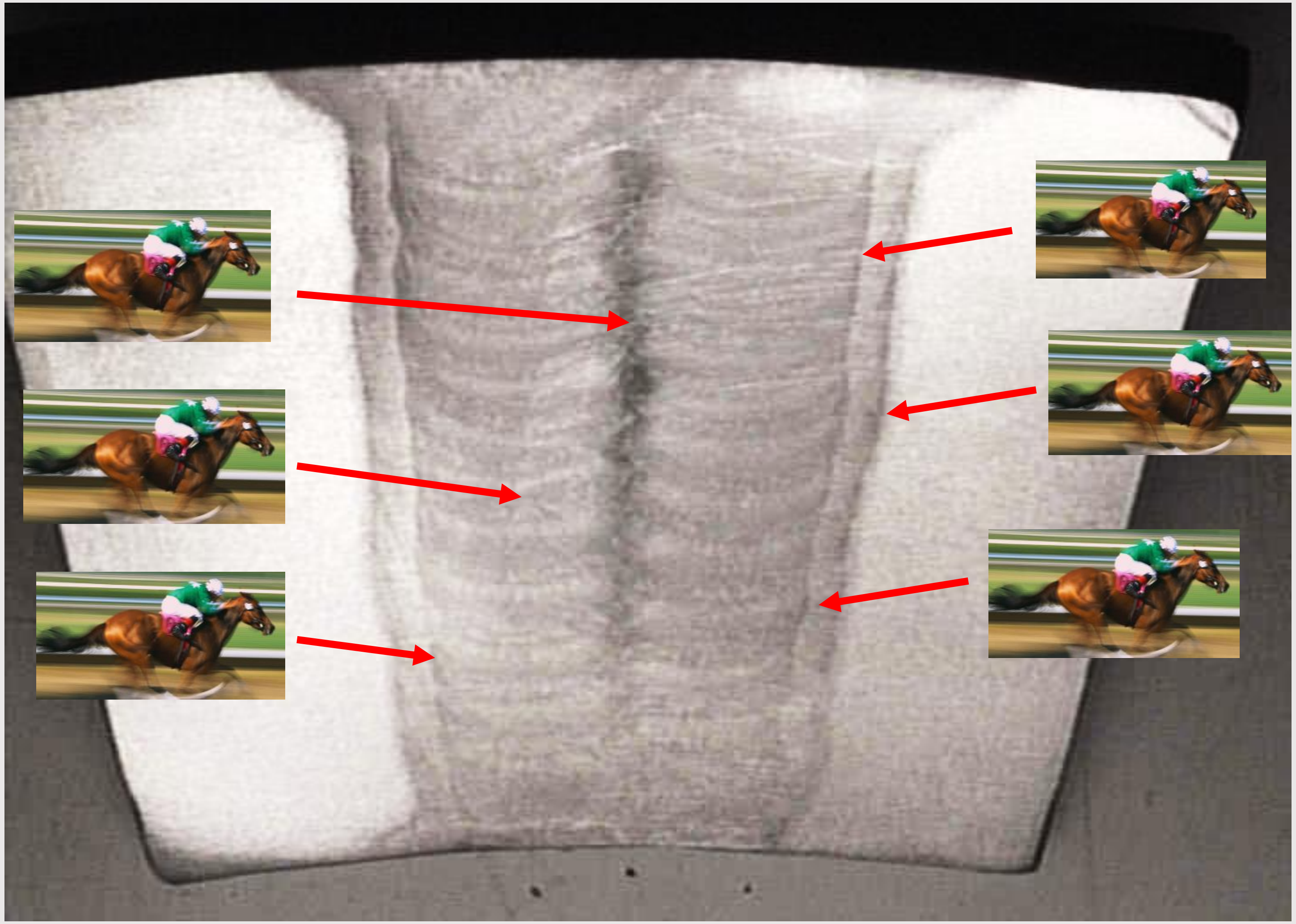
# Damage at Fusion Boundary in DMW – Region 6




Weld Joining Grade 91 to Stainless Using Nickel-Base Filler Metal – Creep Damage Initiating in Conjunction with Type I Carbides

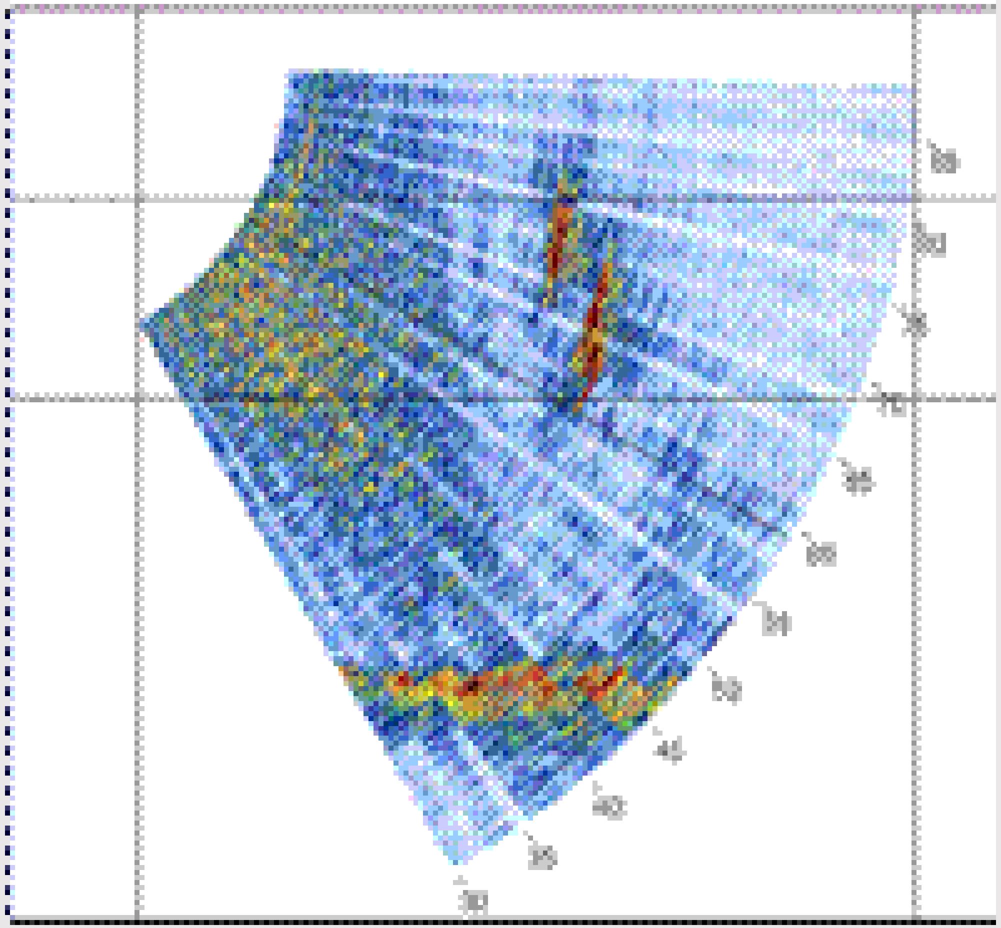
# "…It's a horse race!"



# Finding Damage in High Temperature Components

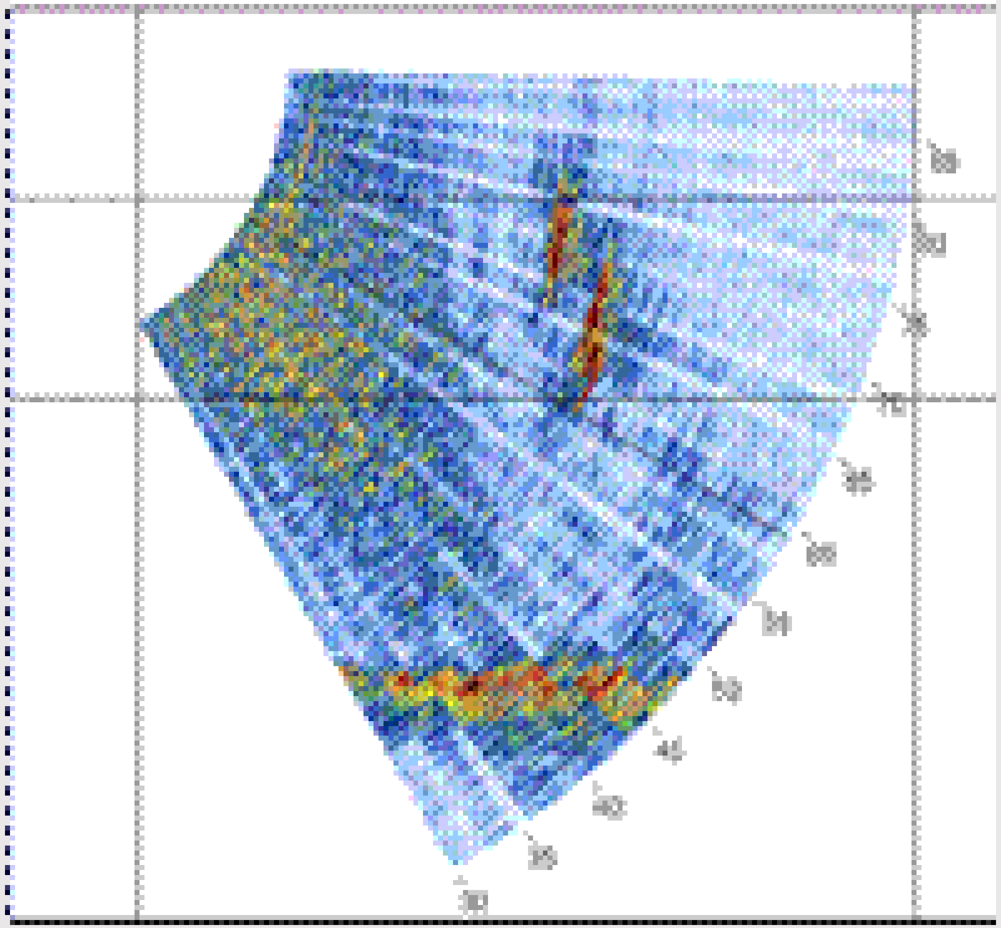
Inspecting welds in high temperature components represents a unique challenge:

- Find damage as early as possible
- Accurately characterize indications detected relative to size, location in weld, orientation, nature of discontinuity, etc.



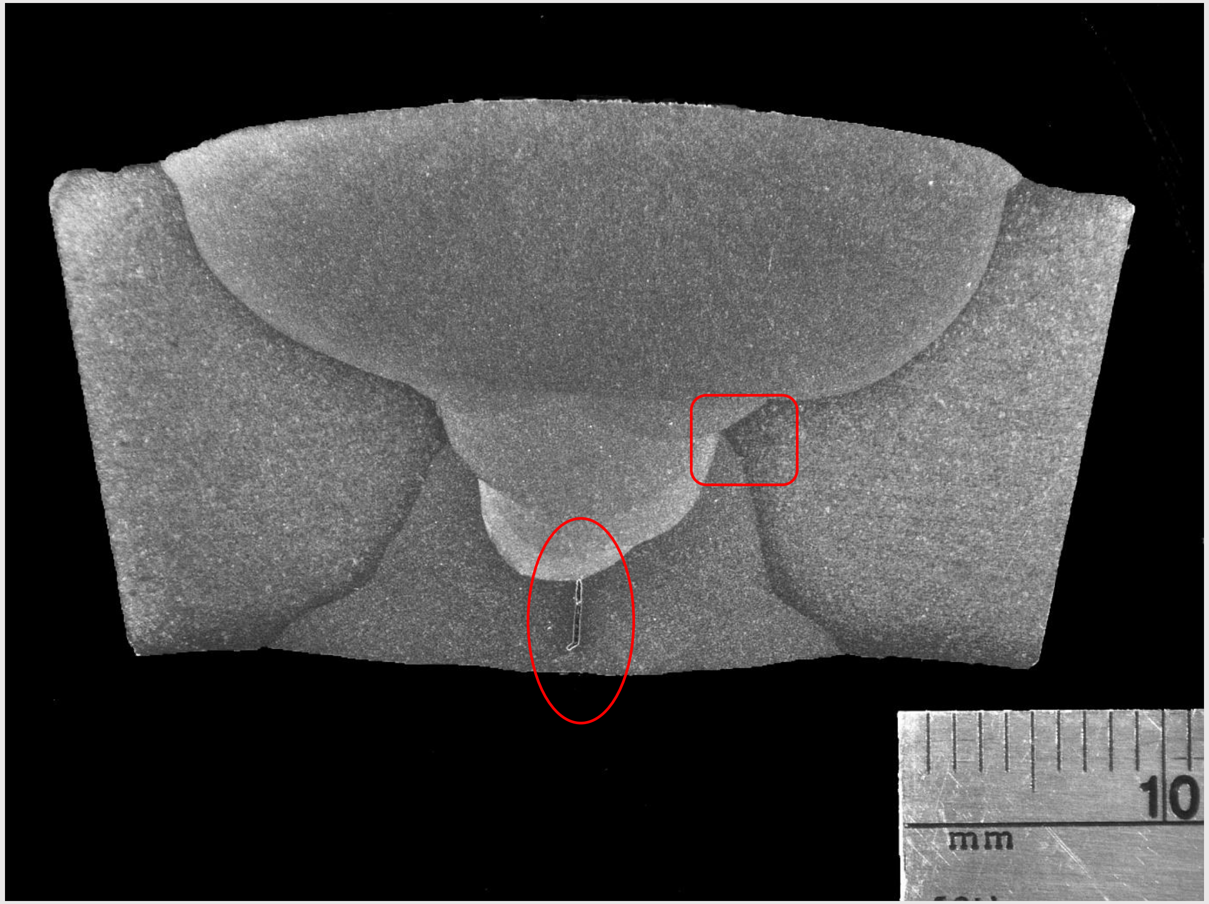
# Finding Damage in High Temperature Components

Must use the proper tools – if damage can initiate sub-surface, then PT, MT or replication will only find damage at late stage of development



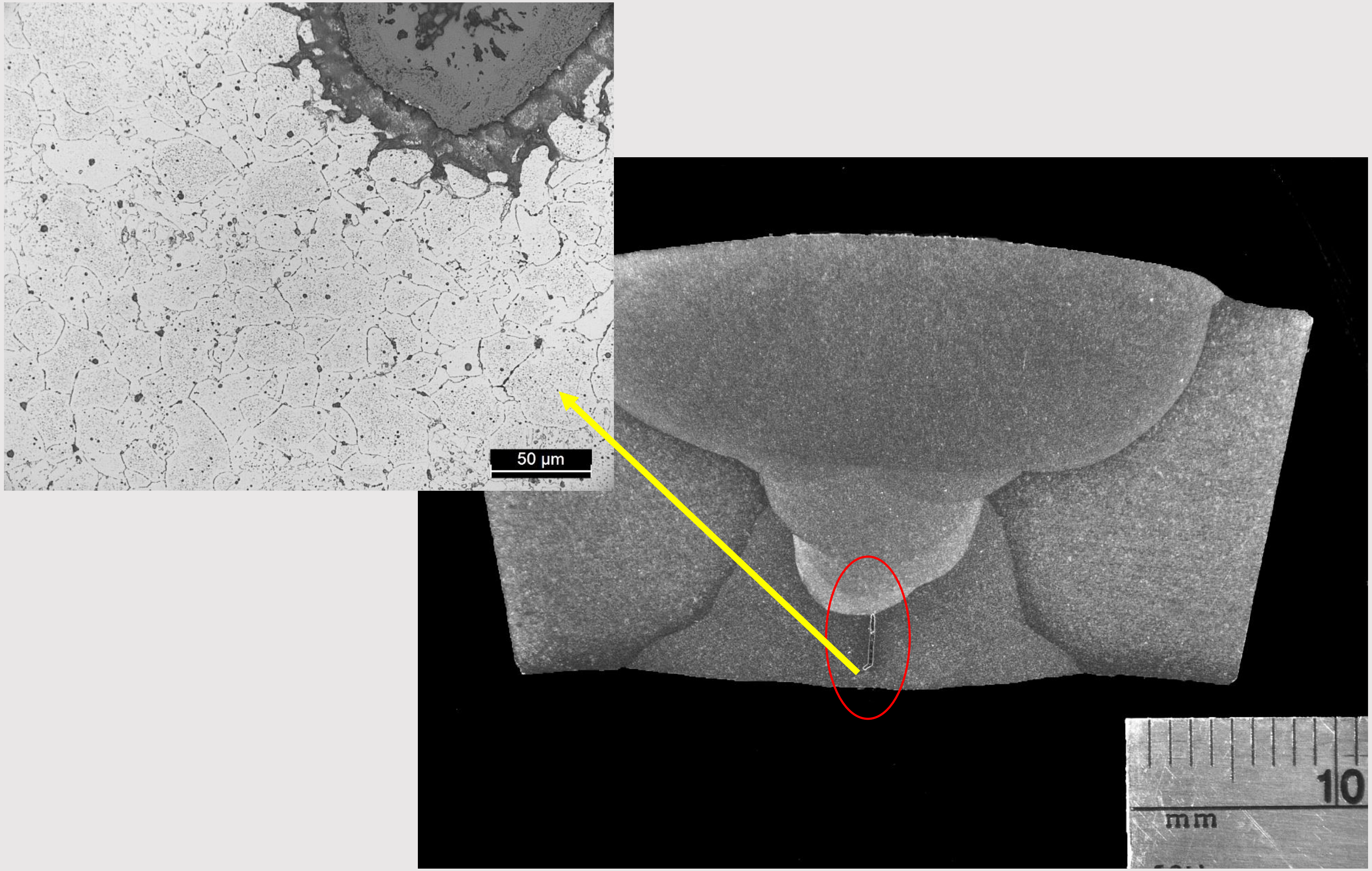
# “Indications” in a Longitudinal Seam Weld

Inspection detected one indication near the root of the weld; early stage creep damage at weld cusp was not detected



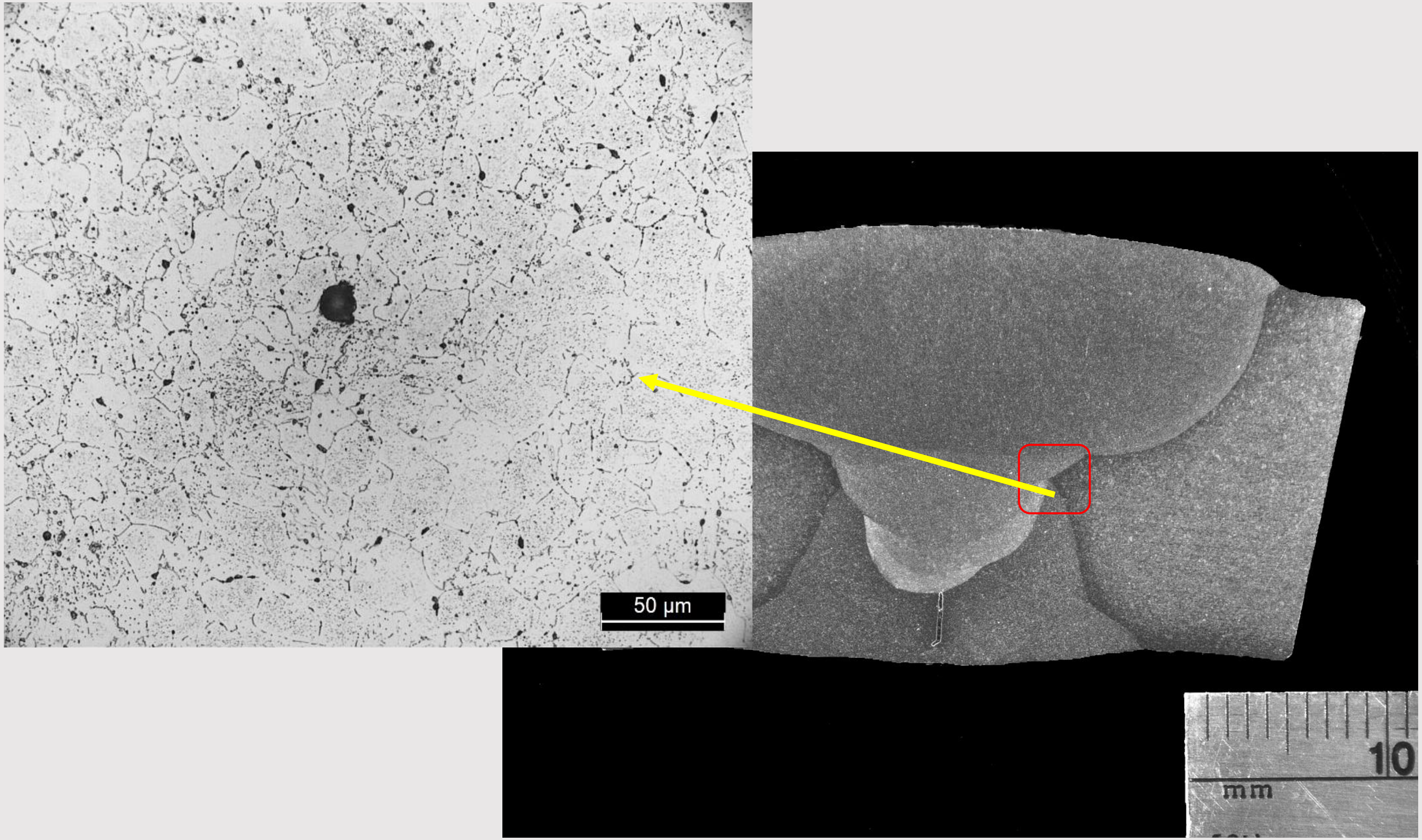
# “Indications” in a Longitudinal Seam Weld

An original weld defect with early stage damage propagation at the tip of the defect



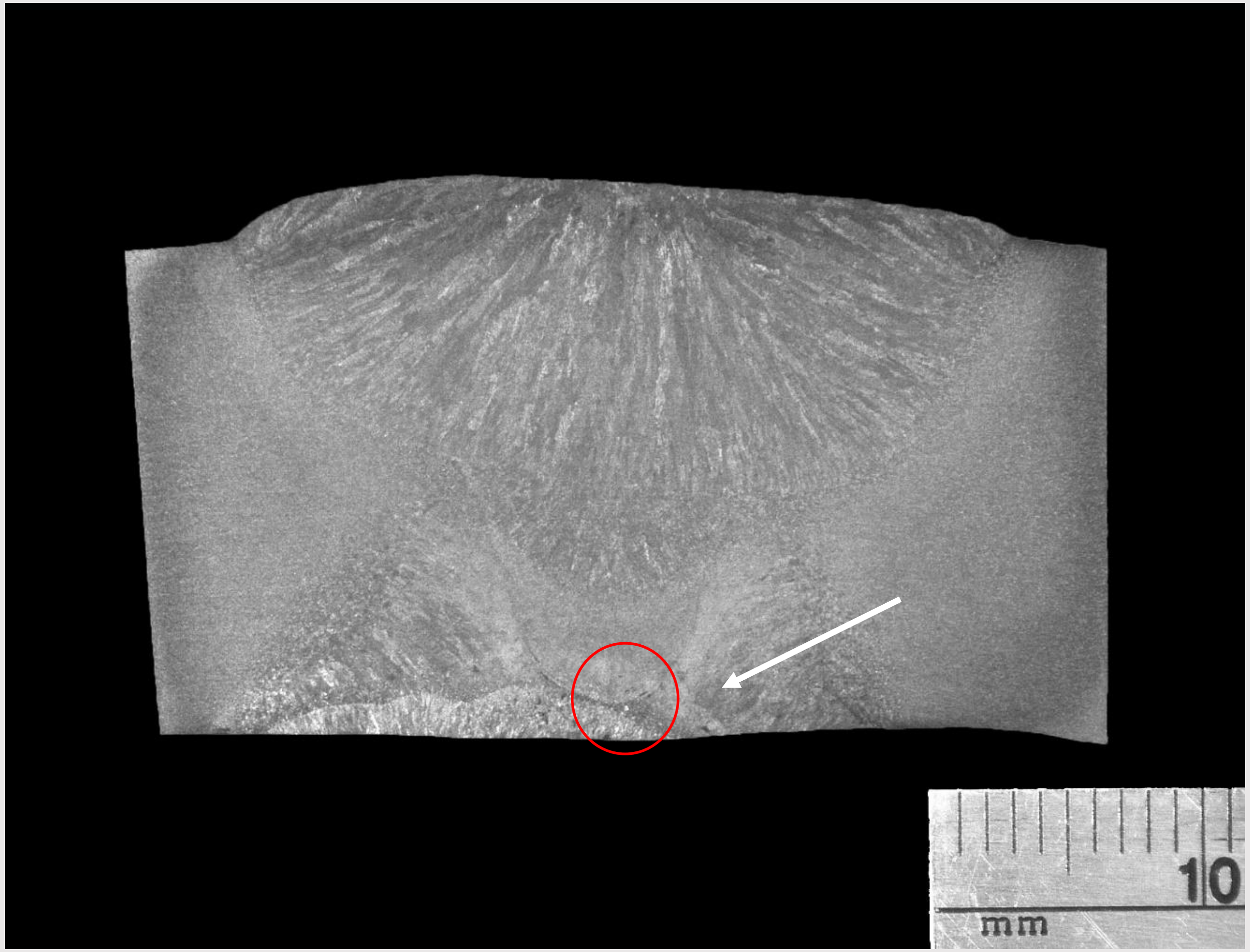
# Damage in a Longitudinal Seam Weld

Early stage creep damage at higher stress location



# "Indications" in a Longitudinal Seam Weld

Inspection detected one indication near the root of the weld; early stage creep damage at other locations in the weld was not detected



# “Indications” in a Longitudinal Seam Weld

detected
on near the
weld; early
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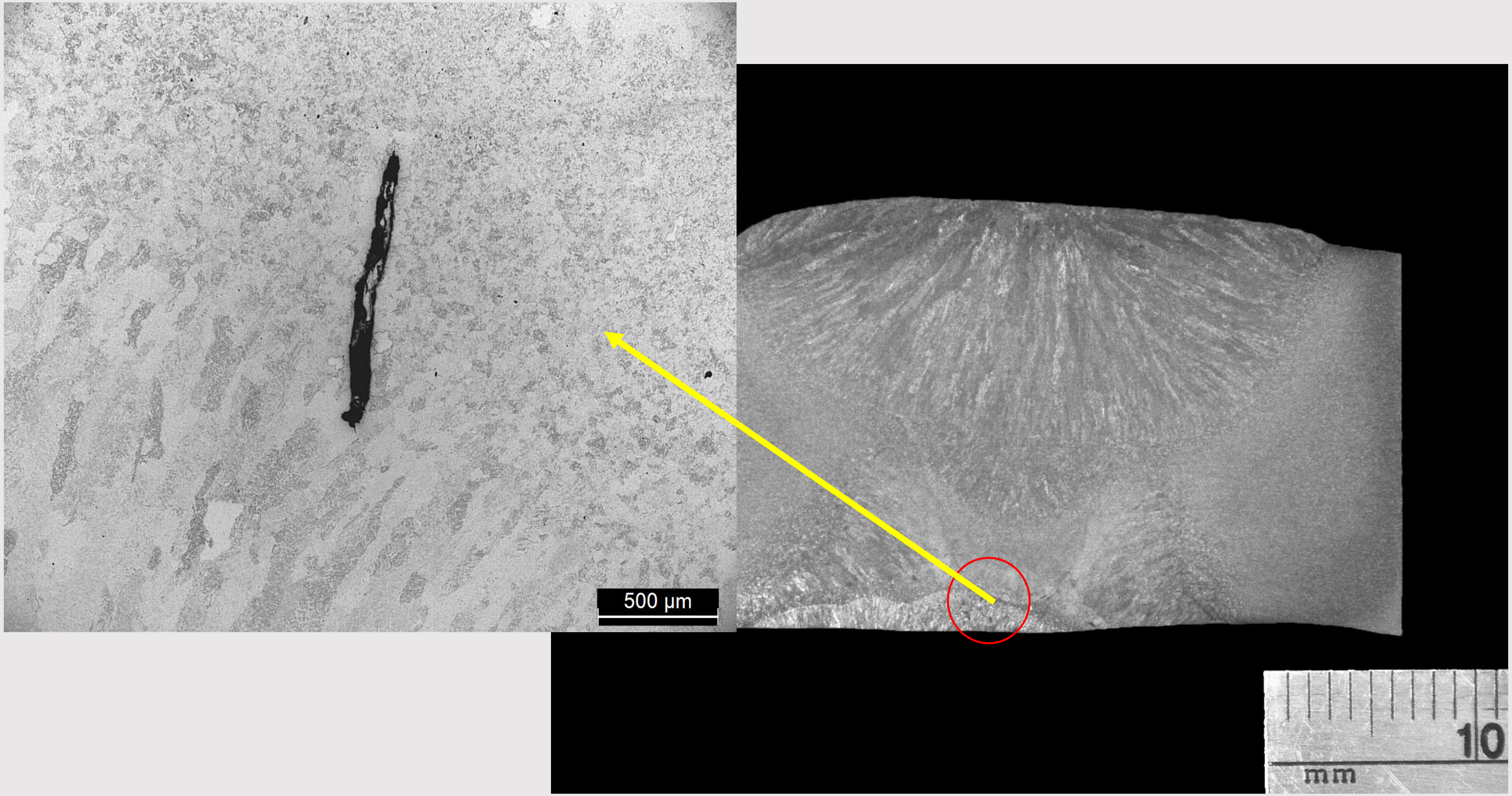
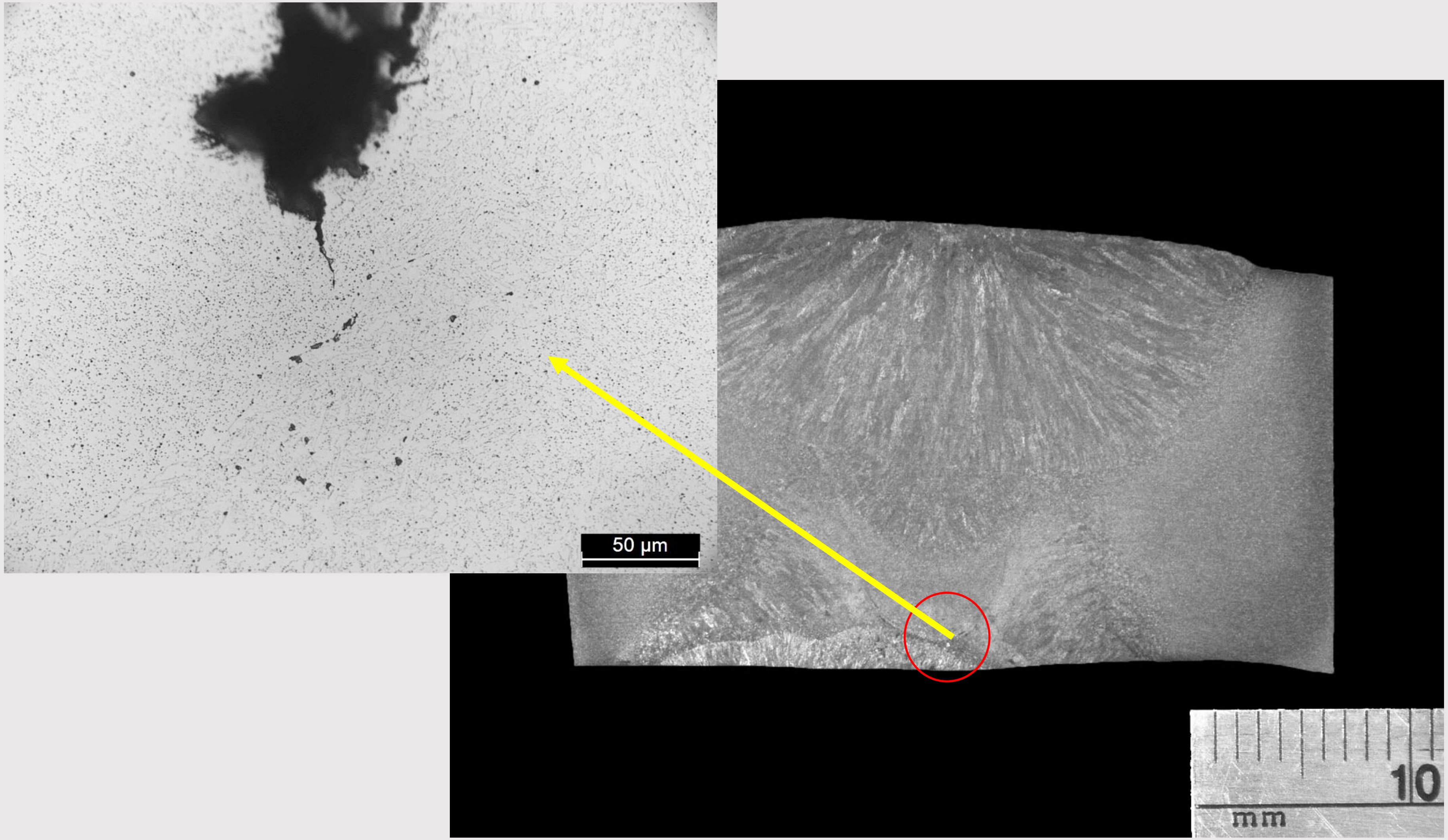


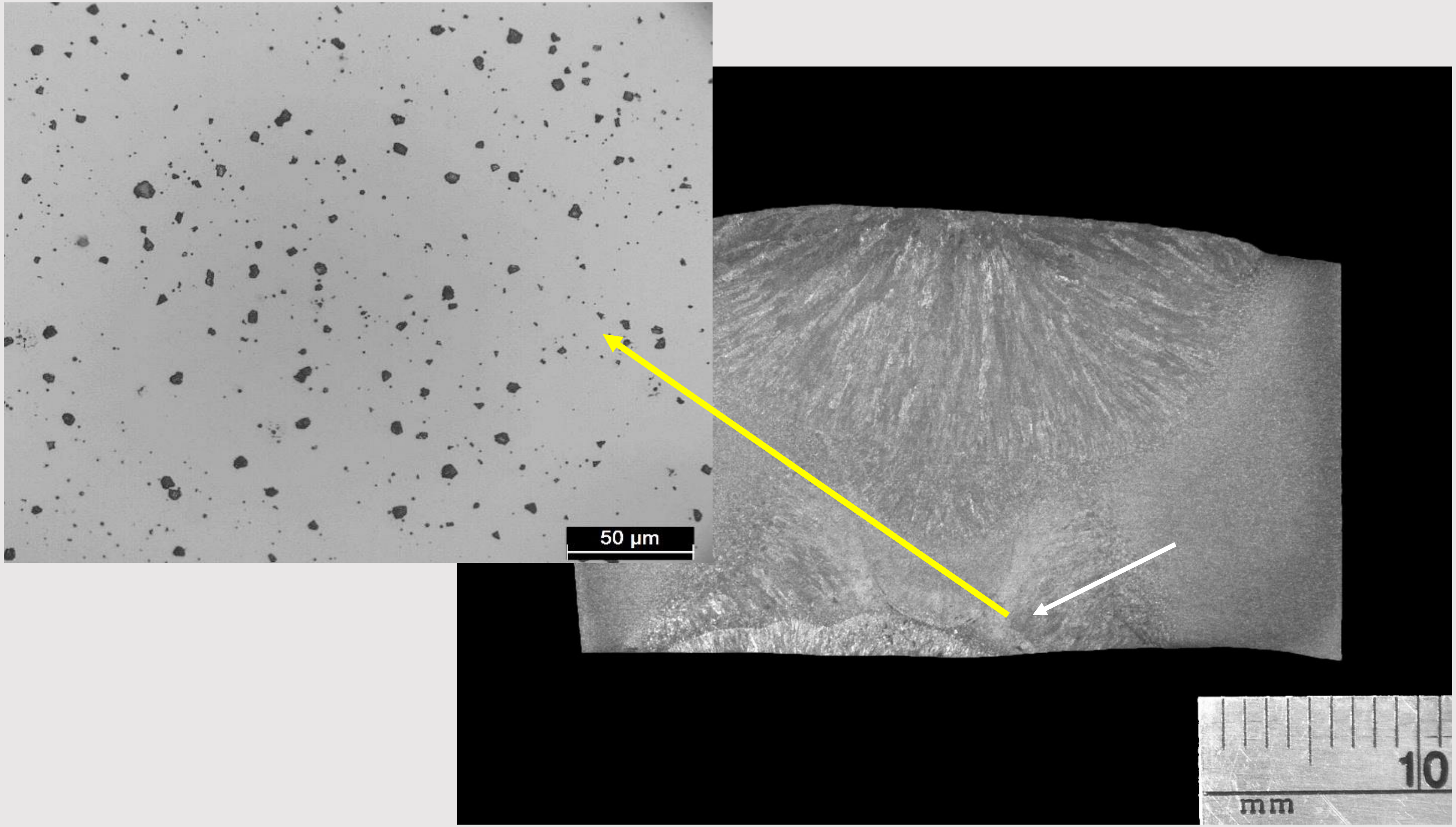
# “Indications” in a Longitudinal Seam Weld

Early stage propagation of creep damage from the tip of the defect



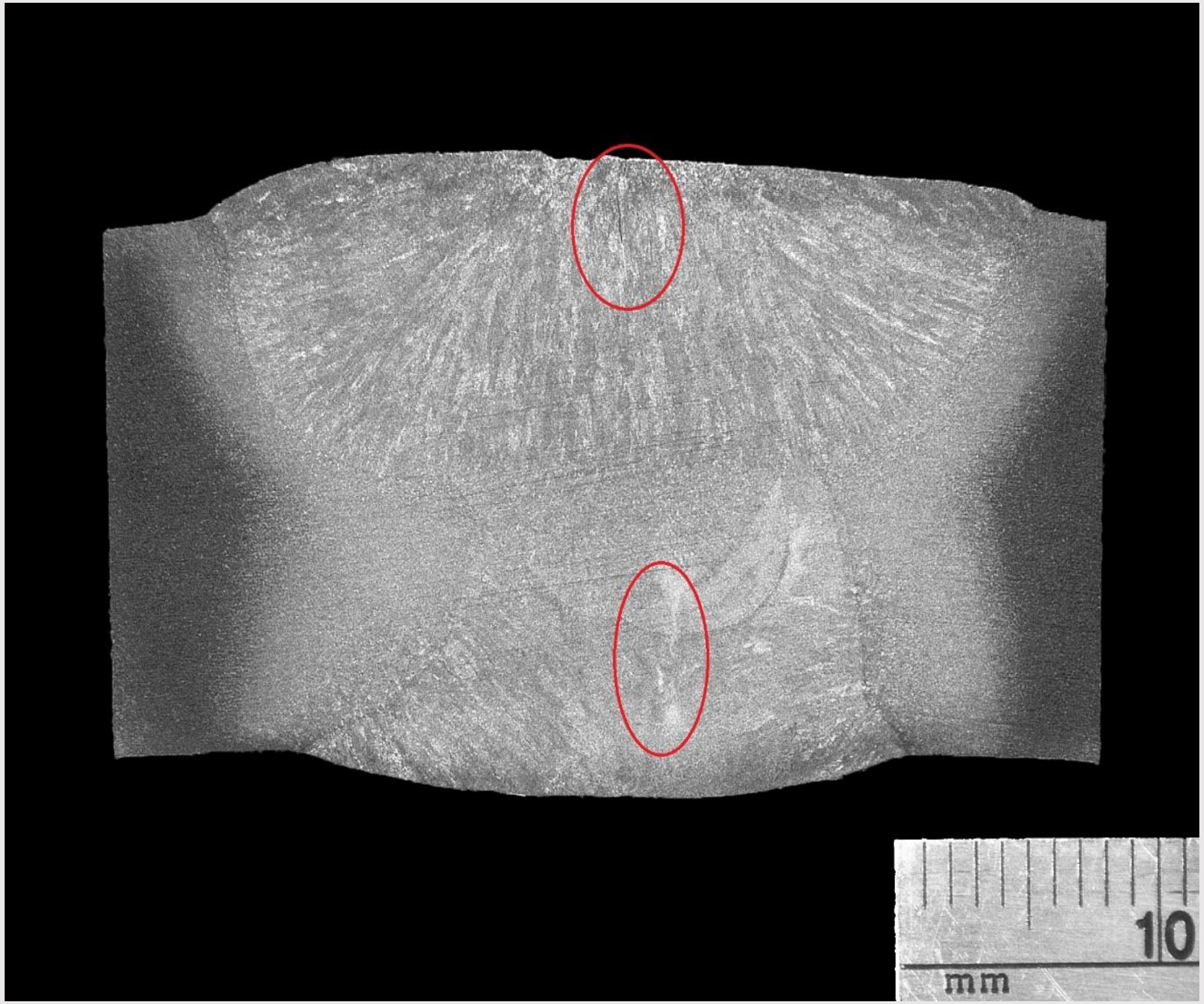
# Undetected damage in a Longitudinal Seam Weld

Inspection did not detect early stage creep damage at other locations in the weld away from the defect



# “Indications” in a Longitudinal Seam Weld

Inspection detected indications at two different locations in the weld; indications described as “anomalous”, but creep damage detected at both locations



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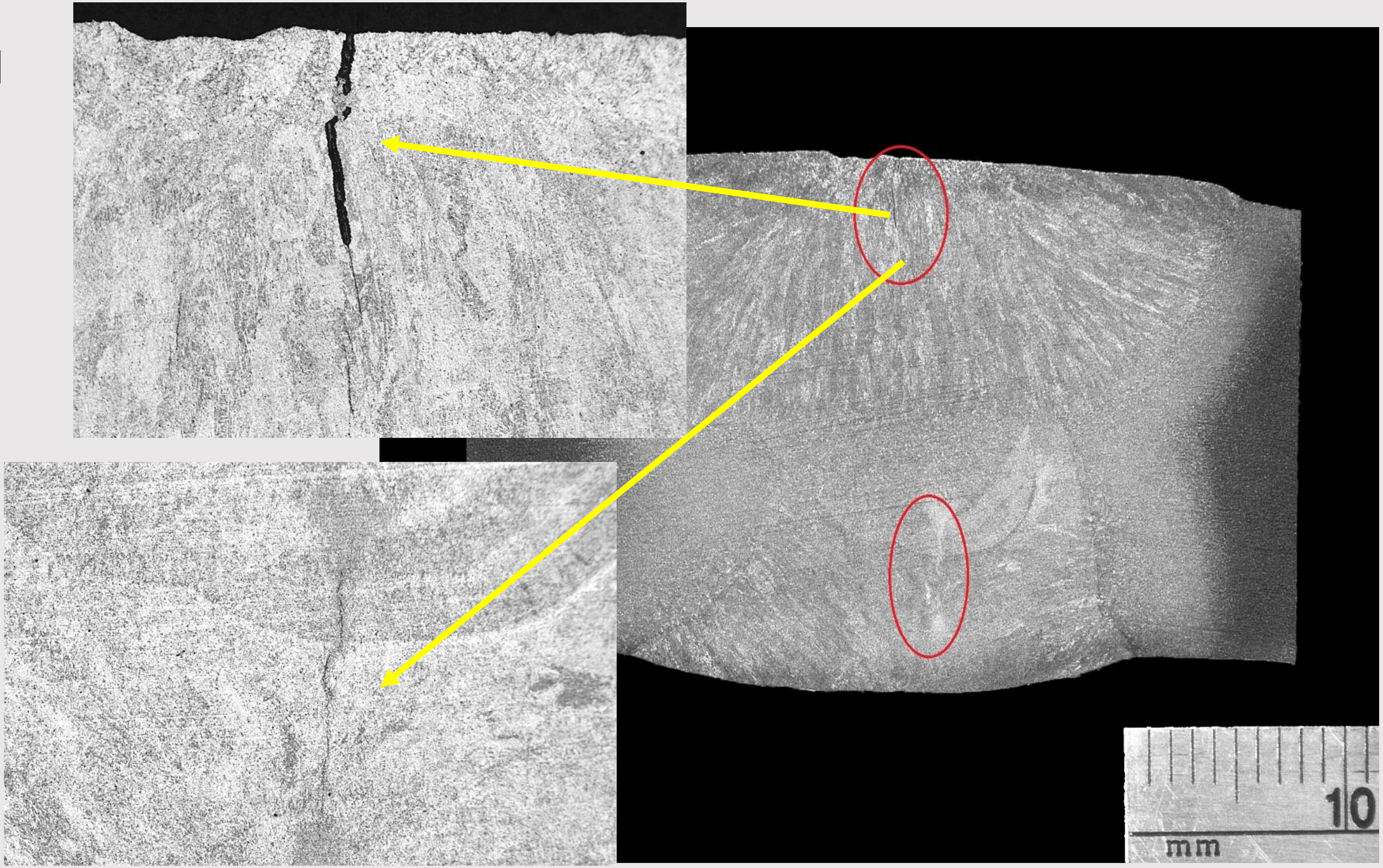

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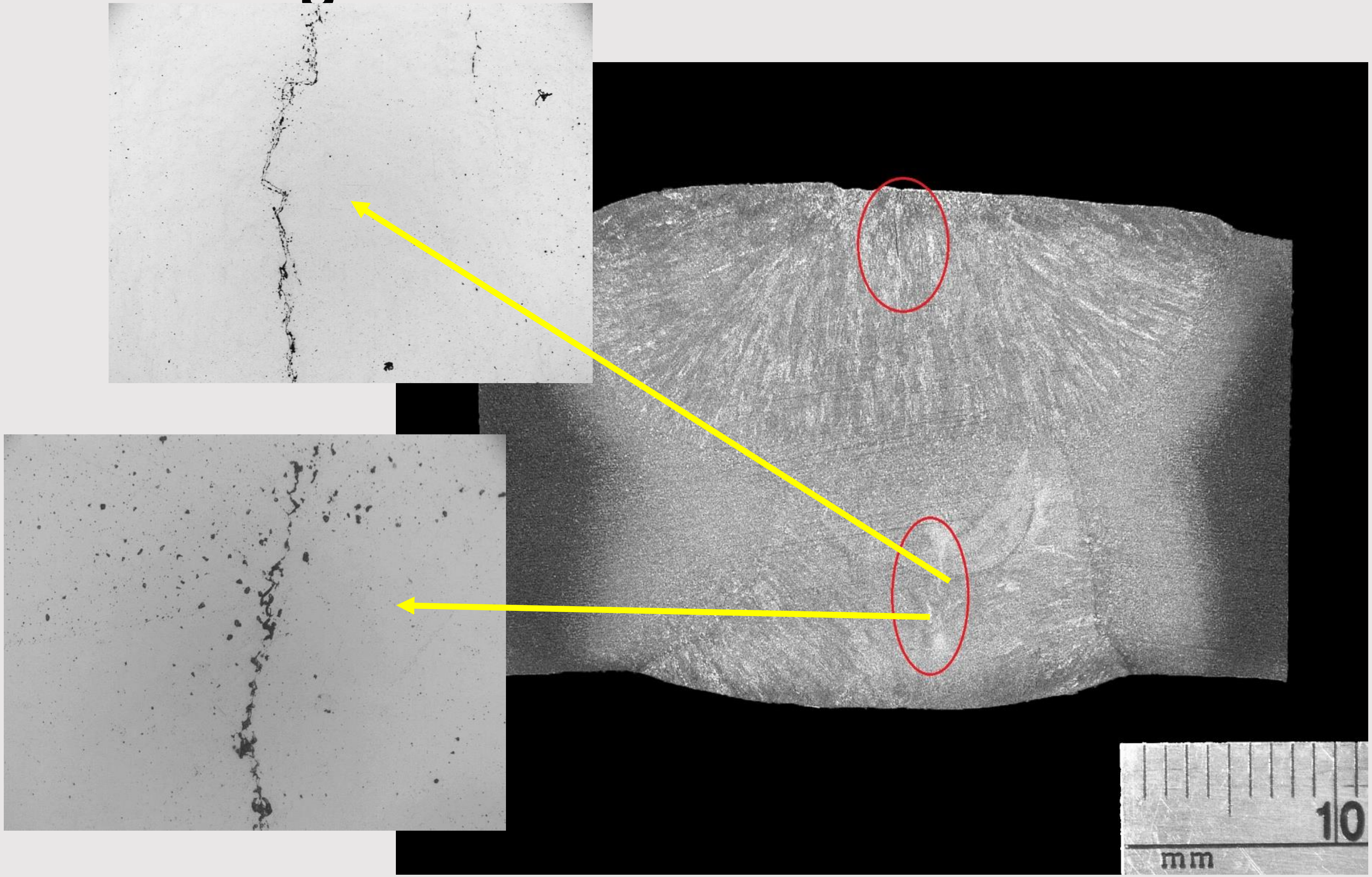


# The Inspection of High Temperature Seam Welds

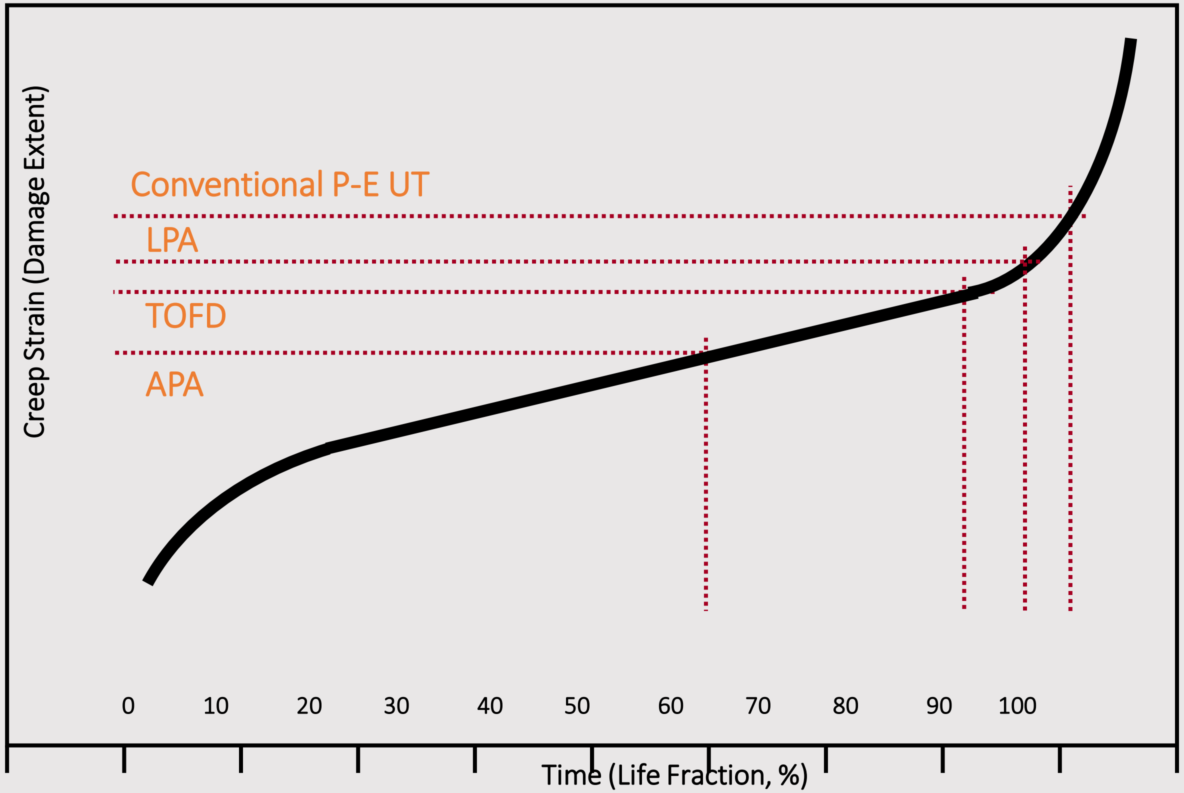
Weld damage can initiate at the ID, at the OD or at mid-wall. Applied inspection techniques must address the expected damage modes.

| Inspection Method | Coverage | Damage Level Sensitivity | |
|---|---|---|---|
| | | Micro | Macro |
| Replication | Surface | Yes | Yes |
| Sampling | Surface/Subsurface | Yes | Yes |
| Magnetic Particle | Surface | No | Yes |
| Radiography | Volumetric | No | Yes |
| Linear Phased Array (shear wave UT) | Volumetric | No | Yes |
| Time of Flight Diffraction | Volumetric | Yes* | Yes |
| Focused Shear Wave UT Imaging | Volumetric | Yes | Yes |

*TOFD is capable of detecting heavy microdamage levels, e.g. aligned creep cavitation and microcracking.

# Creep Detection Sensitivities

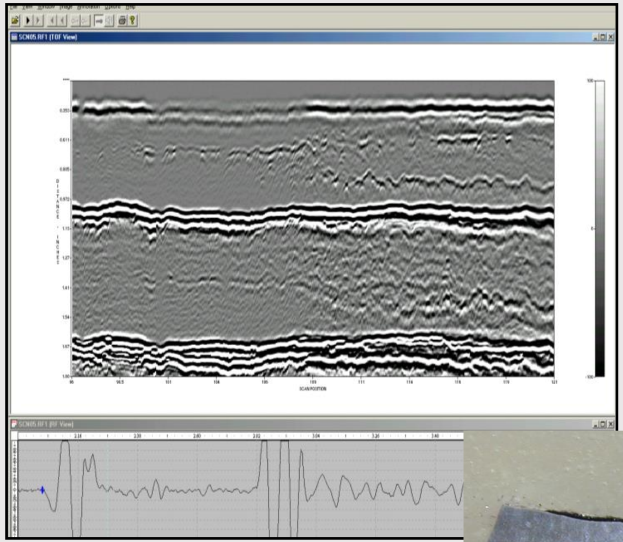
**Theoretic Creep Detection Sensitivity for UT Techniques – *Highly Dependent on the Skill and Experience of the UT Specialist***




Early detection provides time for proper planning and reduced risk.

# Ultrasonic Inspection

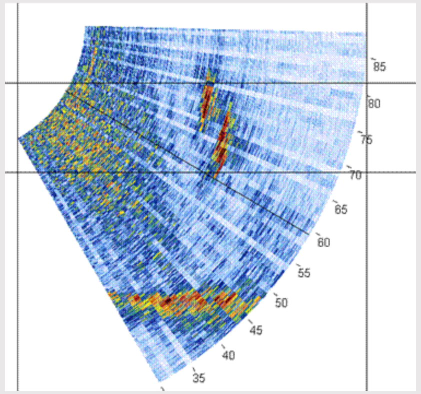
1

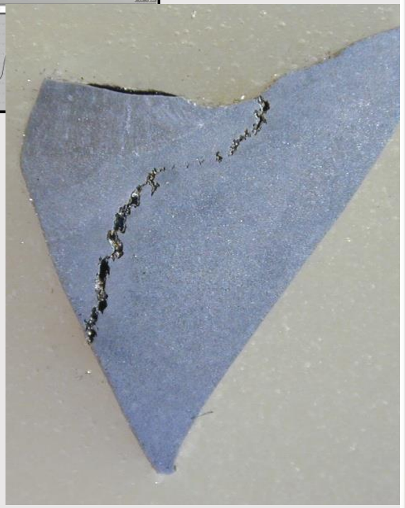


## Macro- and Micro-Cracking

1. Time-of-Flight Diffraction (TOFD)
2. Linear Phased Array (LPA)
3. Focused Annular Phased Array (APA)

2



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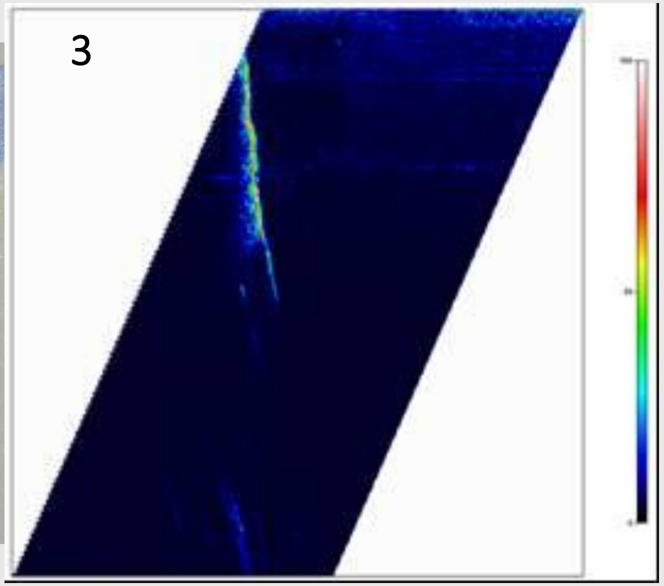
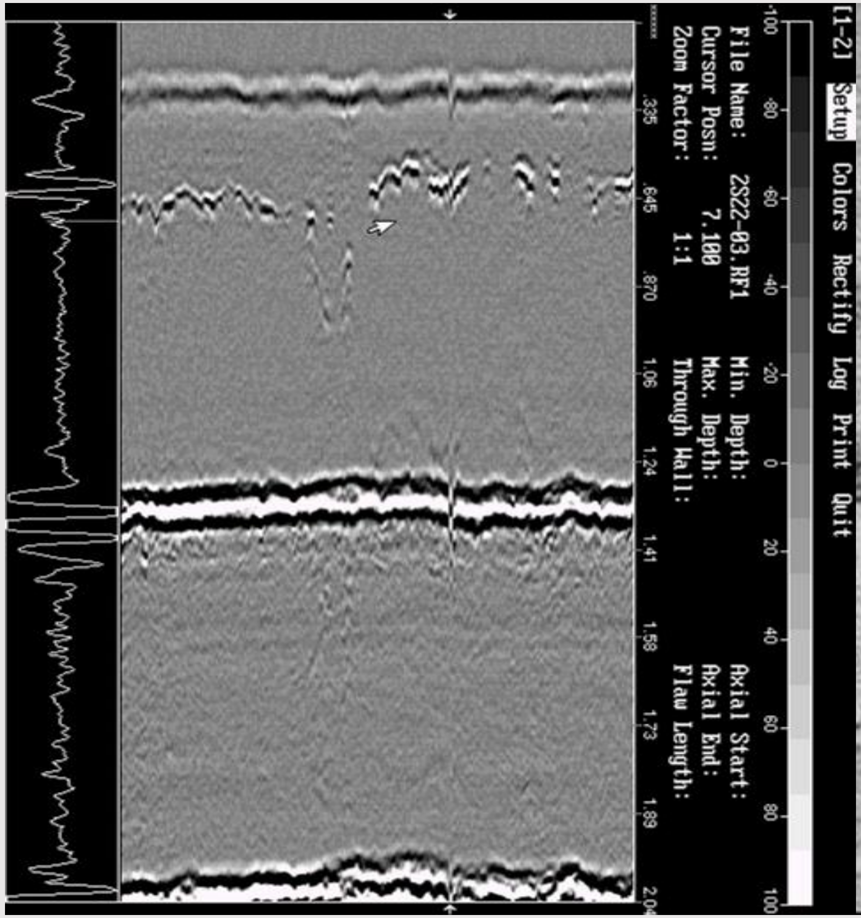
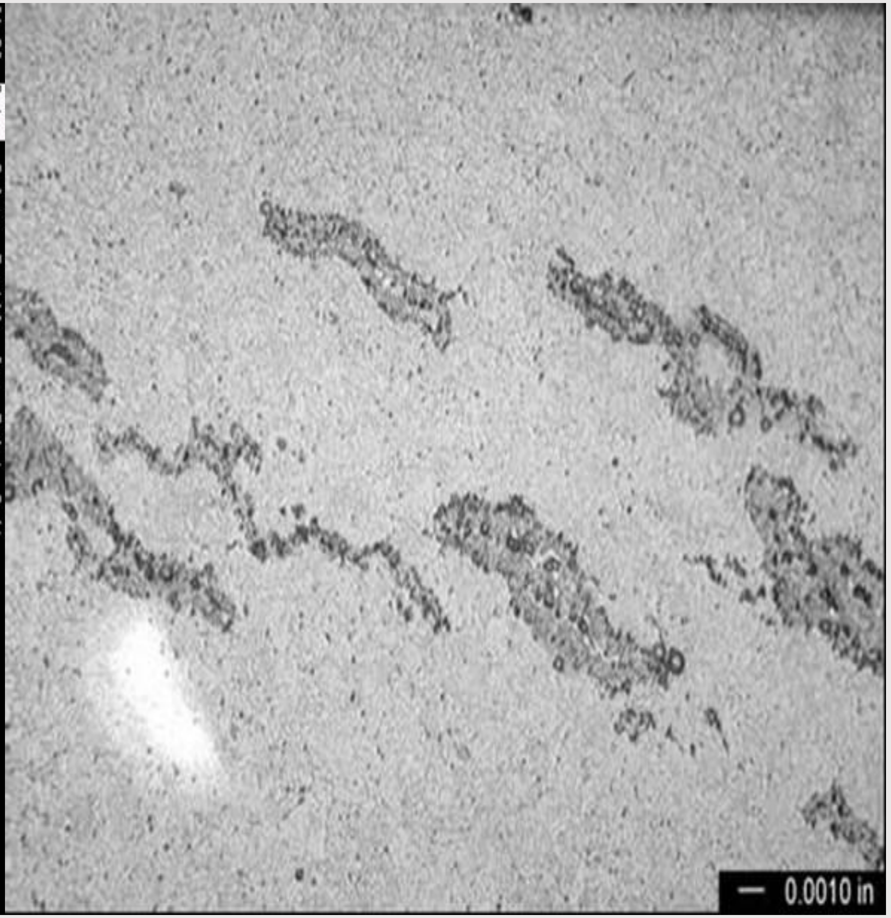
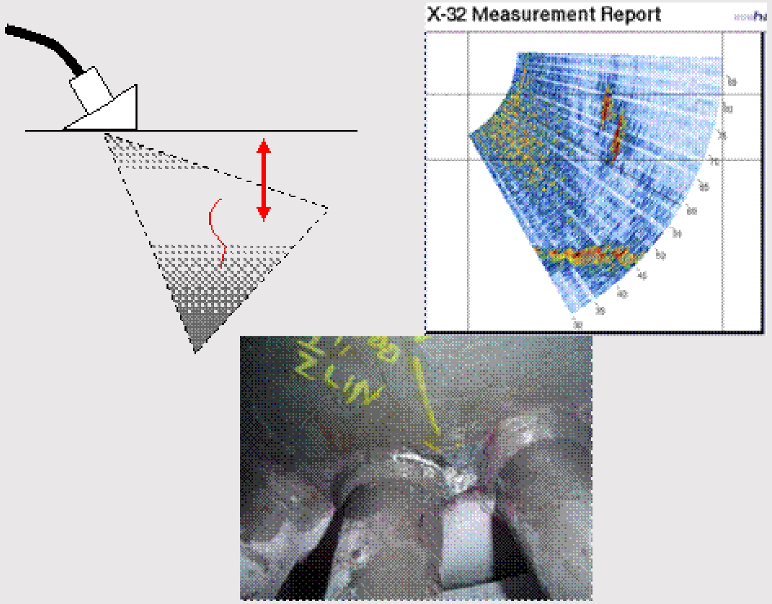


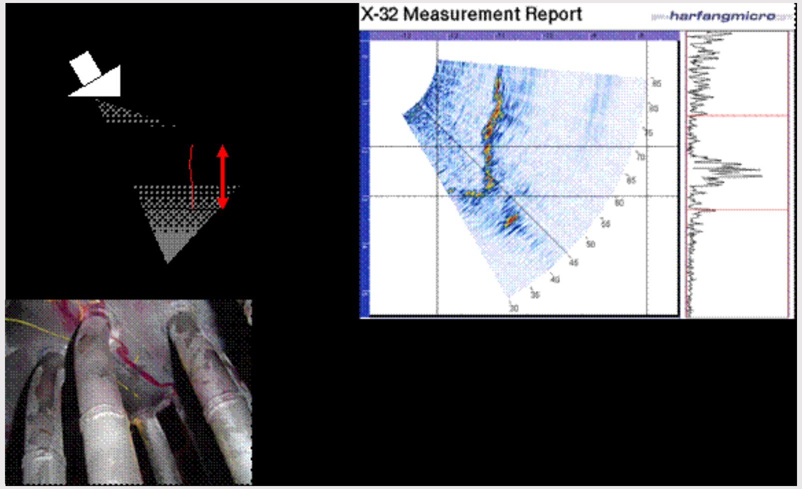
# TOFD of Weld With Micro-Cracks



# Linear Phased Array (LPA)



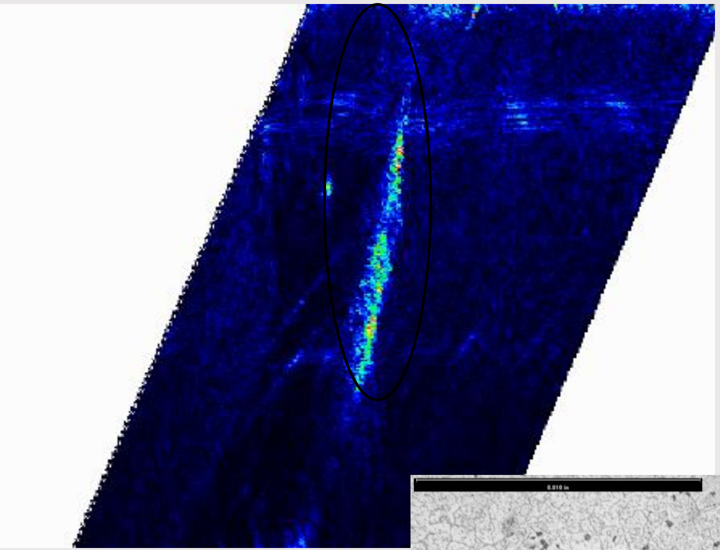



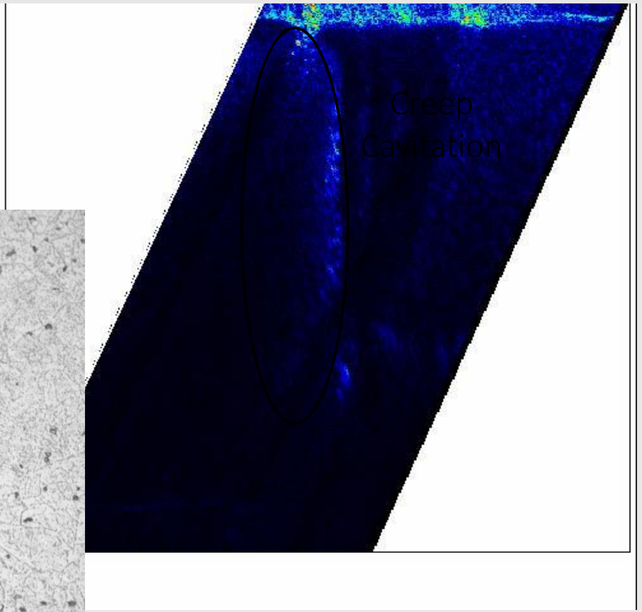

- Macro-Cracking
- Late Stage Creep Cavitation
- Complex Geometries
- Digital Imaging
- Precise Flaw Measurement
- Accurate Flaw Characterization

# Focused Annular Phased Array (APA)

- Macro and Micro Cracking
- Incipient Creep Cavitation***
- Very High Resolution
- Volumetric Imaging
- Precise Flaw Measurement
- Accurate Flaw Characterization

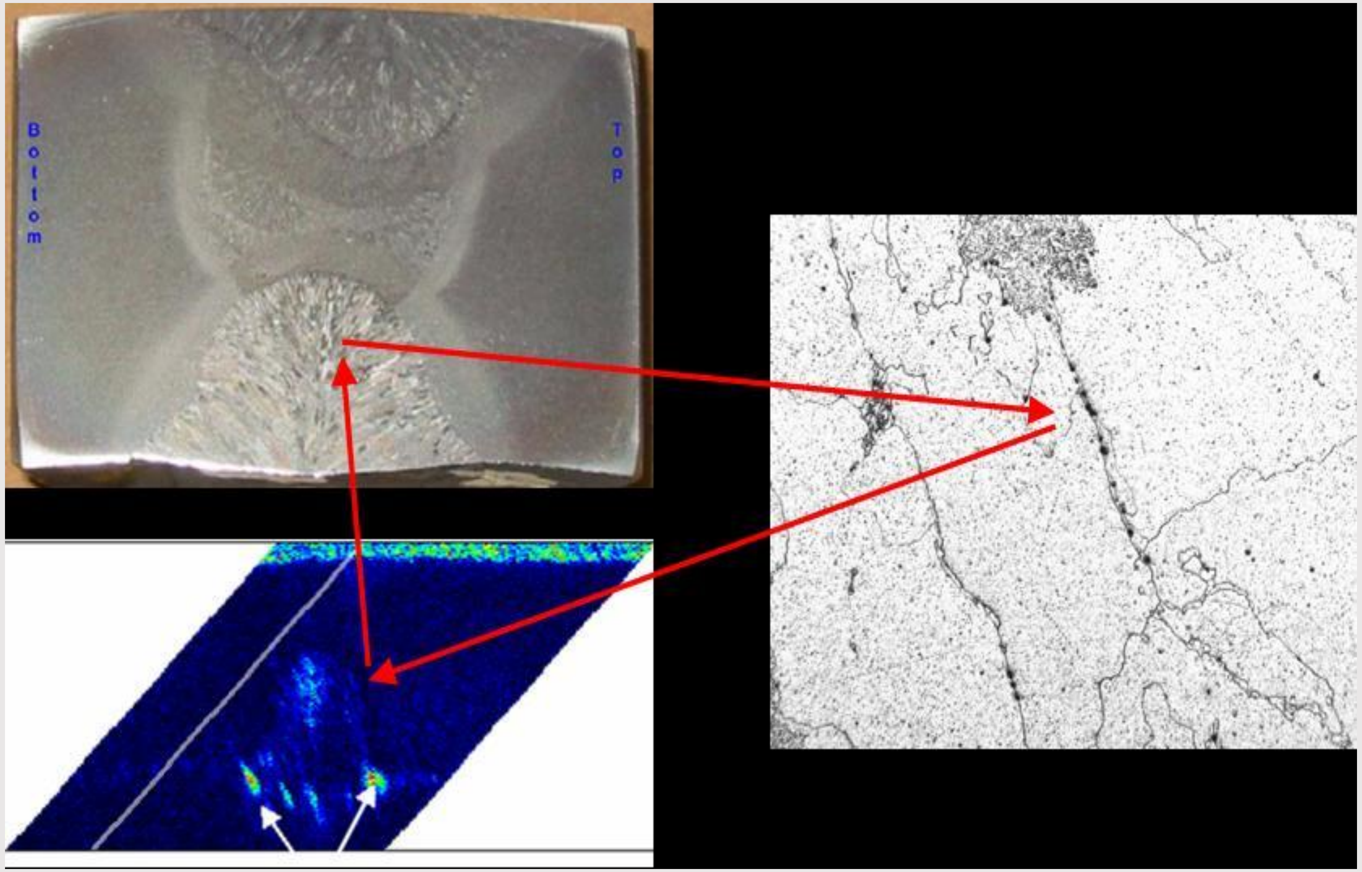
Creep Cracking



# Focused Annular Phased Array (APA)

Higher resolution for detection of early stage creep damage



# Dealing With Damage:
# Executing An Effective Repair

*Do It once - Do it Right*

## Requirements for an Effective Repair

1. *Understand the Root Cause of the Failure*
   - You cannot execute an effective repair unless you know what caused the failure
   - Not all damage in high temperature components is creep-dominated
   - NDE may not detect all damage that has developed at a weld; destructive examination may be required to fully characterize the extent of damage

# Dealing With Damage:
# Executing An Effective Repair

***Do It once - Do it Right***

Requirements for an Effective Repair

1. Understand the Root Cause of the Failure
   - You cannot execute an effective repair unless you know what caused the failure
2. *Factor in Plant Operation*

# Dealing With Damage:
# Executing An Effective Repair

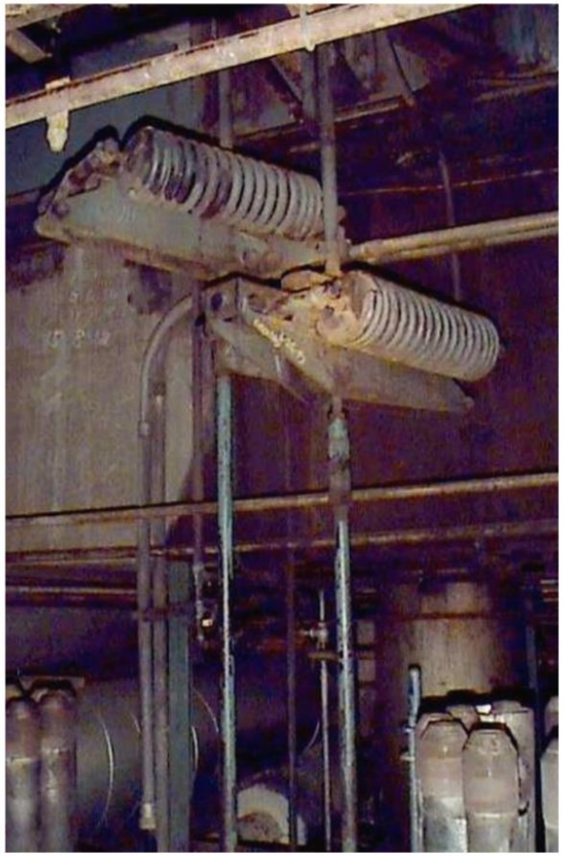
***Do It once - Do it Right***

## Requirements for an Effective Repair

1. Understand the Root Cause of the Failure
   - ➢ You cannot execute an effective repair unless you know what caused the failure
2. Factor in Plant Operation
3. *Consider System Stresses*

# Dealing With Damage:
# Executing An Effective Repair

*Do It once - Do it Right*



# Dealing With Damage:
# Executing An Effective Repair

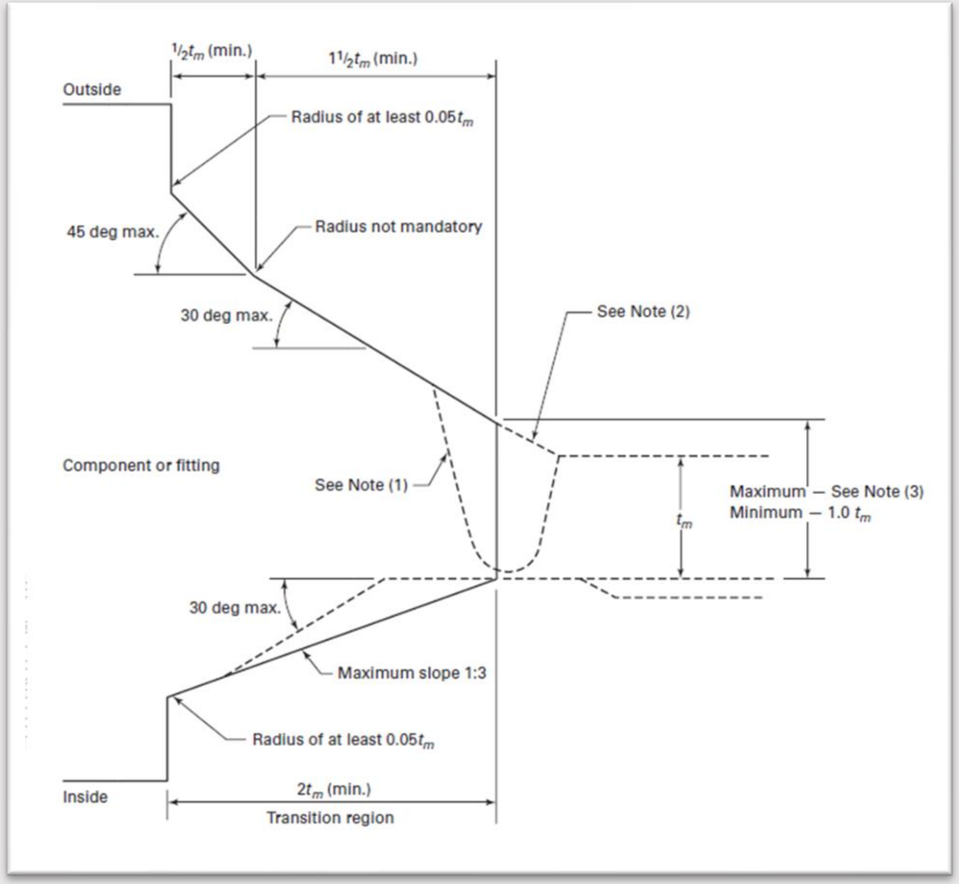
***Do It once - Do it Right***

Requirements for an Effective Repair

1. Understand the Root Cause of the Failure
   - You cannot execute an effective repair unless you know what caused the failure
2. Factor in Plant Operation
3. Consider System Stresses
4. *Consider Original Design and Fabrication*

# Dealing With Damage:
# Executing An Effective Repair

*Do It once - Do it Right*



# Dealing With Damage: Executing An Effective Repair

***Do It once - Do it Right***

Requirements for an Effective Repair

1. Understand the Root Cause of the Failure
   - You cannot execute an effective repair unless you know what caused the failure
2. Factor in Plant Operation
3. Consider System Stresses
4. Consider Original Design and Fabrication
5. Evaluate for Previous Repairs
6. *Sample, Sample, Sample*
   - *If you are going to make a welded repair anyway take a boat sample*
   - *In-situ Replication as a minimum*

# Dealing With Damage:
# Executing An Effective Repair

***Do It once - Do it Right***

Requirements for an Effective Repair

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   - You cannot execute an effective repair unless you know what caused the failure
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4. Consider Original Design and Fabrication
5. Evaluate for Previous Repairs
6. Sample, Sample, Sample
   - If are going to make a welded repair anyway take a boat sample
   - In-situ Replication as a minimum
7. *Recognize that temporary repairs tend to become permanent*

# Dealing With Damage:
# Executing An Effective Repair

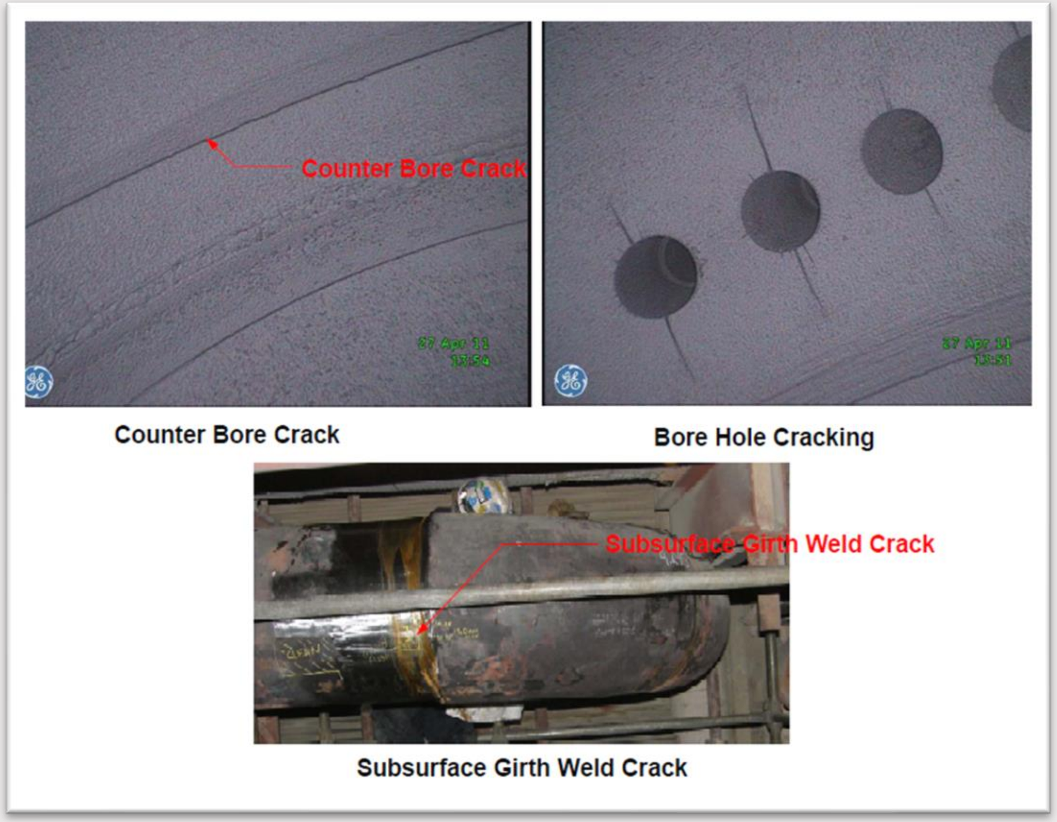
***Do It once - Do it Right***

Determine Proper Repair Method

1. *The best repairs are performed in a calm and controlled manner*

# The Best Repairs are Performed in a Calm and Controlled Manner

***DO I NEED TO DO THE REPAIR RIGHT NOW - FFS?***



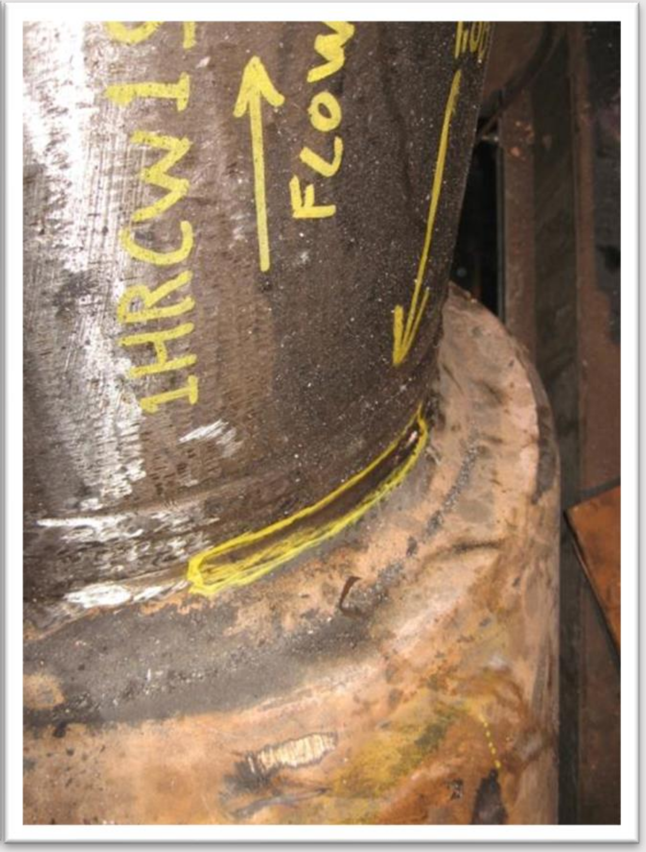
# Dealing With Damage: Executing An Effective Repair

***Do It once - Do it Right***

Determine Proper Repair Method

1. The best repairs are performed in a calm and controlled manner
2. *Failure Mechanism Drives the Repair Method*

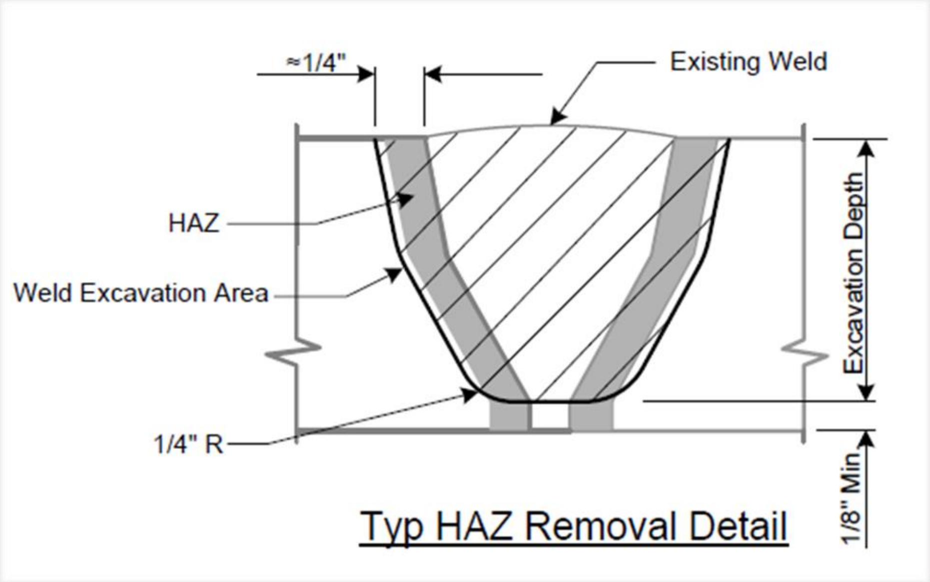
# Dealing With Damage:
## Executing An Effective Repair
*Do It once - Do it Right*



# Dealing With Damage:
# Executing An Effective Repair

***Do It once - Do it Right***

- Creep Related Failure Requires Full Excavation of Damaged Material to Restore Full Serviceability




# Dealing With Damage:
# Executing An Effective Repair

***Do It once - Do it Right***

## Be Cognizant of Material Characteristics

- Stainless Steels
  - Stress Corrosion Cracking
  - Sigma Phase Embrittlement
- High Strength Steels
  - Hydrogen Cracking
  - Ductility Issues
- CSEF
  - Thermal Processing Controls
  - Maintenance of Microstructure

# Thank You For Your Attention – Questions?