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Webinar:

Metallurgical Failure Analysis: Root Cause Investigations

Cole Rademacher, Sr. Failure Analysis Engineer at Covalent

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About Covalent



Your Trusted Partner

Convenient access to the world of metrology with analytical services reimagined



Putting Customers First

Built to deliver faster, more impactful materials analysis and R&D support

ISO Accredited

Accredited to ISO/IEC 17025 for 60+ standardized and self-developed methods

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Covalent is the High-Growth, Innovation Leader in Outsourced Analytical Services

Revenue & Growth

$25M revenue
@ 20% growth in 2025

Expert Staff

105 employees; 30+ with advanced technical degrees

High-Tech Customers

~550 customers/yr from 30+ industries (largest segments are Semi, Battery, Biotech/MedTech)

Industry Partners

Partnerships with 12 manufacturers of analytical instruments

Extended Offerings

Vetted network of 500+ additional labs globally



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Analytical Service Categories

Electron Microscopy



SEM | TEM | STEM | EDS | EELS | HAADF | EBSD | Nano-Diffraction

X-ray Characterization



Micro-CT | X-ray Radiography | XRD | XRR | XRF | XPS / UPS / ISS

Optical Imaging & Analysis



Laser Confocal | Optical Microscopy | Interferometry | 3D Patterned Light | Raman Spectroscopic Ellipsometry | UV-Vis-IR |

Analytical Chemistry



GCMS | ICPOES | ICPMS / LA-ICPMS | GDOES | Solid/Liquid NMR | FTIR

Material Property Testing



AFM / MFM / KPFM | Acoustic Microscopy Nano-scratch / Nano-indent | nano-DMA / DMA | DSC | TGA

Particle Analysis



Laser Diffraction | DLS | ELS | Zeta Potential

In addition to our in-house capabilities, Covalent has a network of 500 partner labs specializing in niche techniques to provide our customers an effective One-Stop-Shop



Cole Rademacher

Senior Failure Analysis Engineer, Covalent

- Failure Analysis Engineer at Covalent (since 2024)
- Specializes in metallurgical and fractographic failure analysis
- Extensive experience conducting root cause investigations across biomedical, aerospace, and infrastructure applications
- Focused on advancing Covalent's metallurgical failure analysis capabilities through innovative methodologies and analysis techniques
- Expertise in the characterization and evaluation of diverse alloy systems
- Dedicated to delivering accurate results, actionable insights, and innovative solutions for clients
- Driven by a commitment to improving consumer safety and product reliability

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Metallurgical Failure Analysis

Metallurgical Failure Analysis: What is it?

- **Metallurgical Failure Analysis**: the process of determining the mechanisms behind metal component failures
  - Provide insight into the root cause of a failure
  - Determine preventative actions to prevent similar failures in the future



Metallurgical Failure Analysis: Standard Industry Applications

- **Fracture characterization** and determination of failure origins
  - Fatigue-related damage and progressive crack propagation mechanisms
  - Brittle fracture and ductile overload failure analysis
- **Corrosion** and oxidation-related degradation
  - Stress corrosion cracking and hydrogen-assisted cracking failures
- **Material and process** related failures:
  - Heat treatment–related defects and failures
  - Casting defects
- **Wear** and tribological failure mechanisms
- **Design deficiencies** and stress-induced failures
- **Plating and surface coating** failures







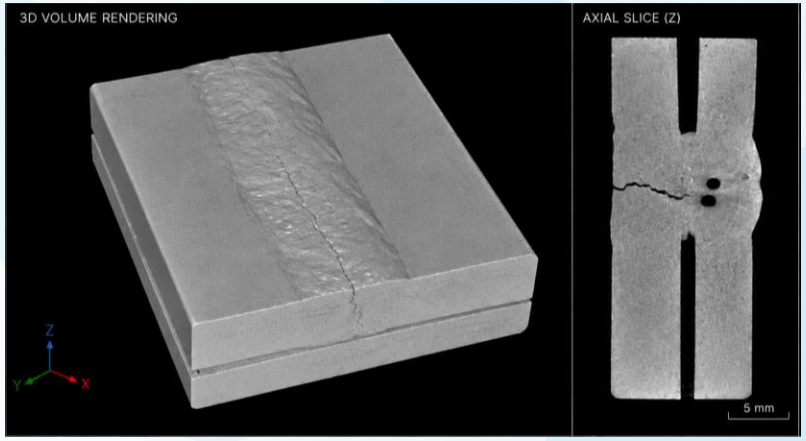


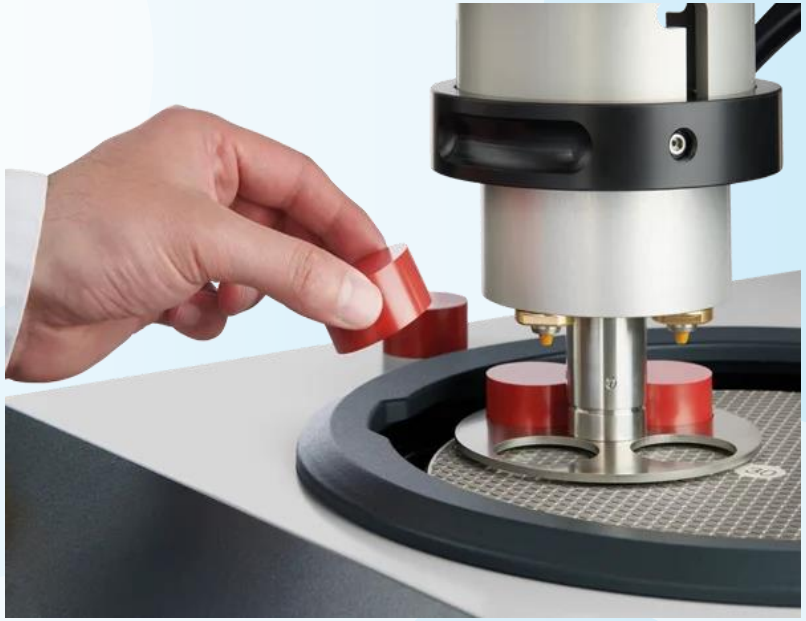
Metallurgical Failure Analysis: Generalized Workflow

Background Information			
Component Material	Service Conditions	Failure History	Maintenance Records

Non-destructive Examination			
Photo Documentation	Visual/Optical Inspection	X-ray Radiography	Penetrant Testing

Destructive Analysis			
Cross-sectioning	Mechanical Testing	Electron Microscopy	Chemical Analysis





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Weld Examination

What is a Weld?

Definition

Weld — localized coalescence of metals produced by heating above the melting point, with or without filler metal and pressure

Metallurgical bond — atoms bridge the joint — not a mechanical fastener or adhesive

A miniature casting — the molten pool solidifies rapidly; properties set by chemistry and cooling rate

Key Elements of Fusion Welding

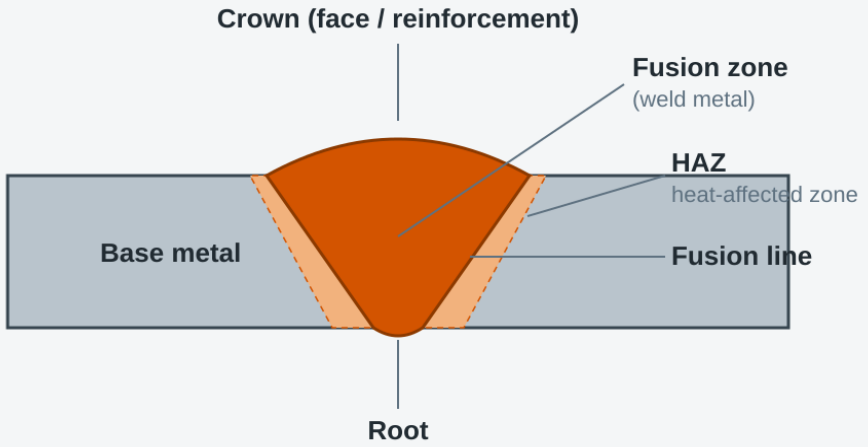
Heat source — electric arc, flame, laser, resistance, or friction

Filler metal — consumable wire or rod that fills the joint

Shielding — gas or flux protects the molten pool from atmospheric oxygen and nitrogen

Common processes — SMAW (stick), GMAW (MIG), GTAW (TIG), FCAW, SAW

Anatomy of a Weld (Cross-Section)



Heat melts the base metal (and filler) into a pool; on cooling it solidifies into the fusion zone. The surrounding HAZ never melts, but its microstructure — and properties — are changed by the heat.

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Common Weld Terminology

Joint & Weld Types

Butt joint — pieces joined edge-to-edge in the same plane

Fillet weld — triangular weld joining surfaces at ~90°

Groove weld — weld in a prepared groove (V, U, J, bevel)

Lap joint — overlapping members joined at the overlap

Weld Zones & Structure

Base / filler metal — parent material / metal added to joint

Fusion zone — melted and resolidified weld metal

HAZ — unmelted base metal altered by welding heat

Root / toe — deepest penetration / weld-to-base junction

Crown & reinforcement — weld face; metal above flush

Process Terms

Pass / bead — one progression along the joint (root, fill, cap)

Heat input — energy per unit length; drives HAZ size

Preheat / interpass — temperature control to avoid cracking

PWHT — post-weld heat treatment for stress relief

Penetration — depth of fusion into the base metal

Defects & Discontinuities

Porosity — gas pockets trapped in weld metal

Lack of fusion / penetration — incomplete bonding or depth

Undercut — unfilled groove melted at the weld toe

Slag inclusion — nonmetallic material trapped in weld

Hot / cold cracking — solidification / delayed hydrogen cracks

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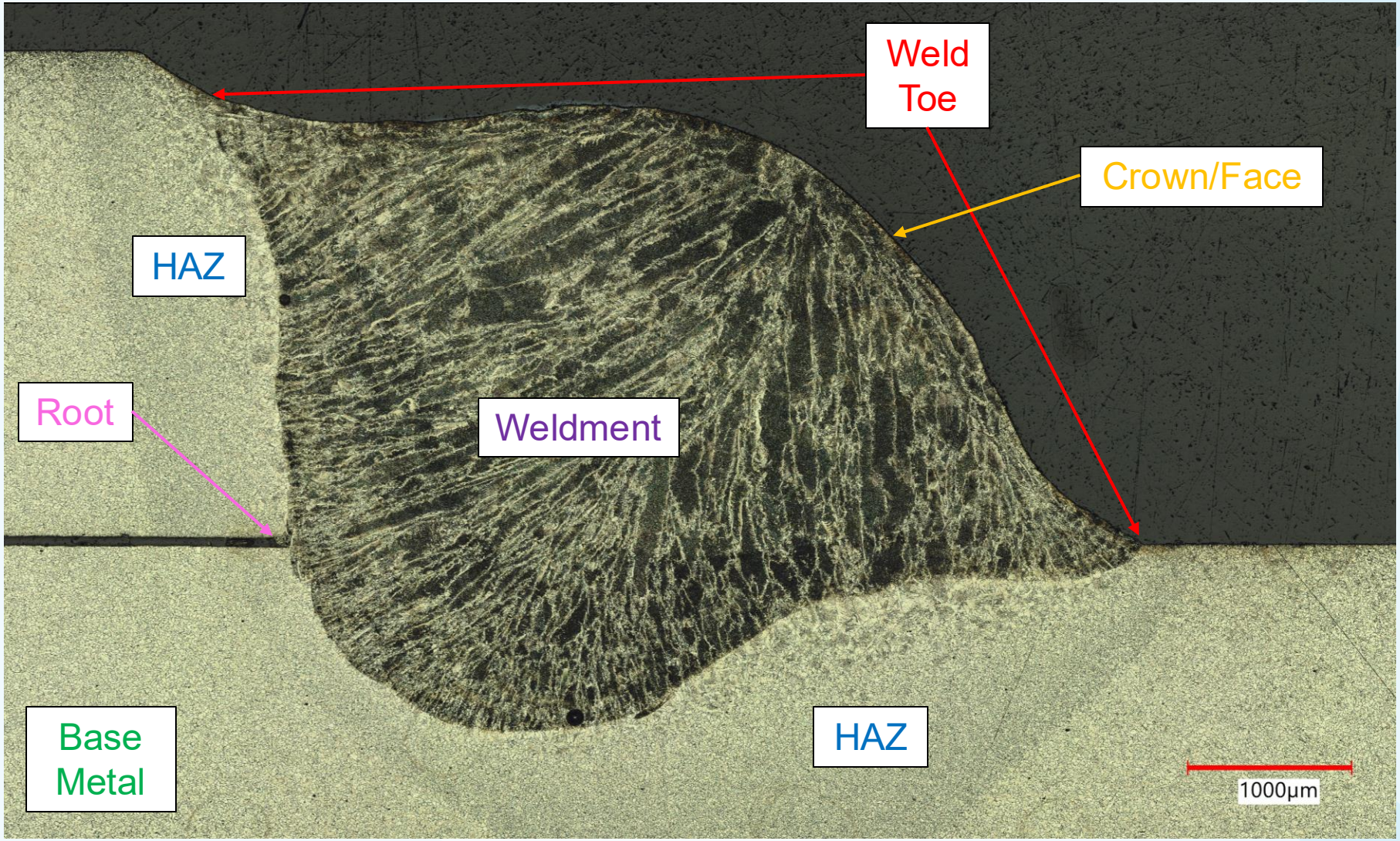
Weld Example



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Common Defects and Failures in Welds

Visual / Non-Destructive Examination

Surface cracks — toe, crater, longitudinal, transverse

Undercut — unfilled groove melted into base metal at the toe

Surface porosity — gas pores open to the weld surface

Overlap (cold lap) — weld metal rolled over base metal without fusion

Excess / insufficient reinforcement — improper weld profile

Misalignment & distortion — hi-lo fit-up, warping, shrinkage

Spatter & arc strikes — adherent droplets; stray-arc damage

Internal flaws (RT / UT) — subsurface porosity, slag, lack of fusion, incomplete penetration

Destructive Examination

Hydrogen (cold) cracking — delayed HAZ / weld-metal cracks seen in cross-sections

Hot cracking — solidification or liquation cracks along grain boundaries

Lack of fusion / penetration — confirmed in macro-etched sections

Inclusions & segregation — revealed by metallography

Lamellar tearing — stepped through-thickness cracks in base plate

Fracture features — fatigue beach marks; cleavage vs. dimple rupture (fractography)

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Case Study: Weld Examination of Children's Bike



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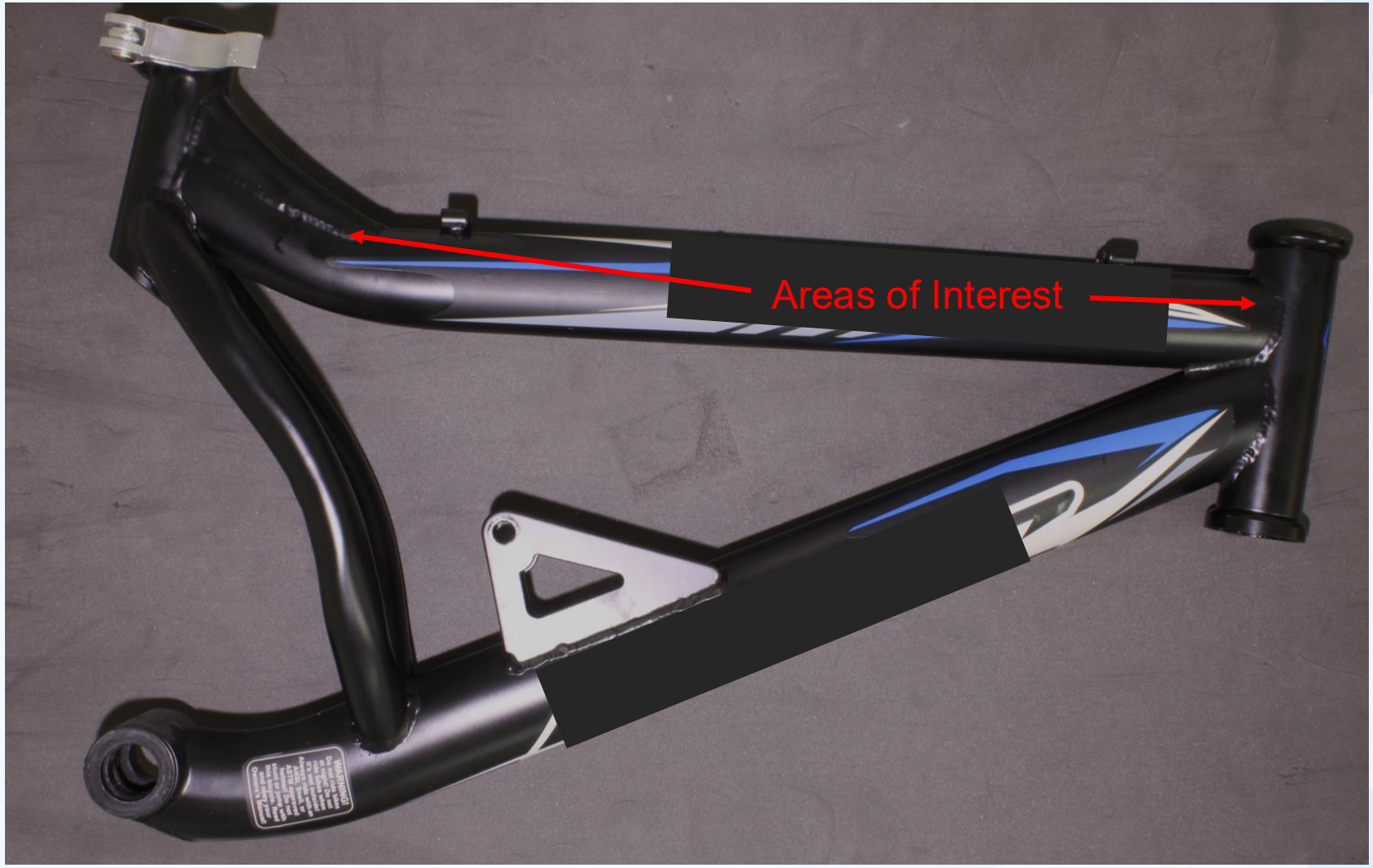
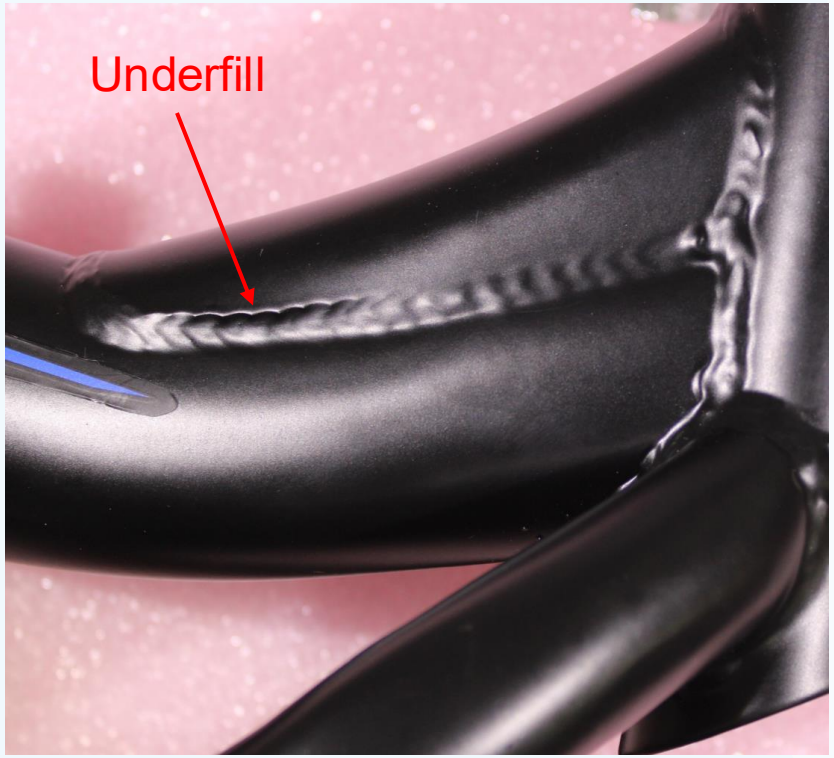
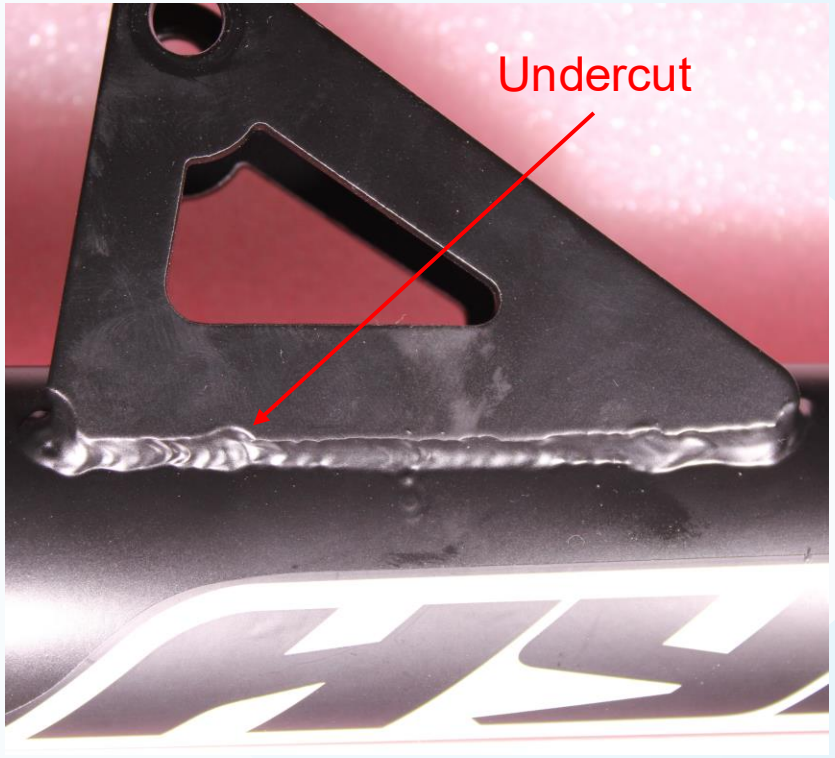
Case Study: Weld Examination of Children's Bike



Case Study: Weld Examination of Children's Bike







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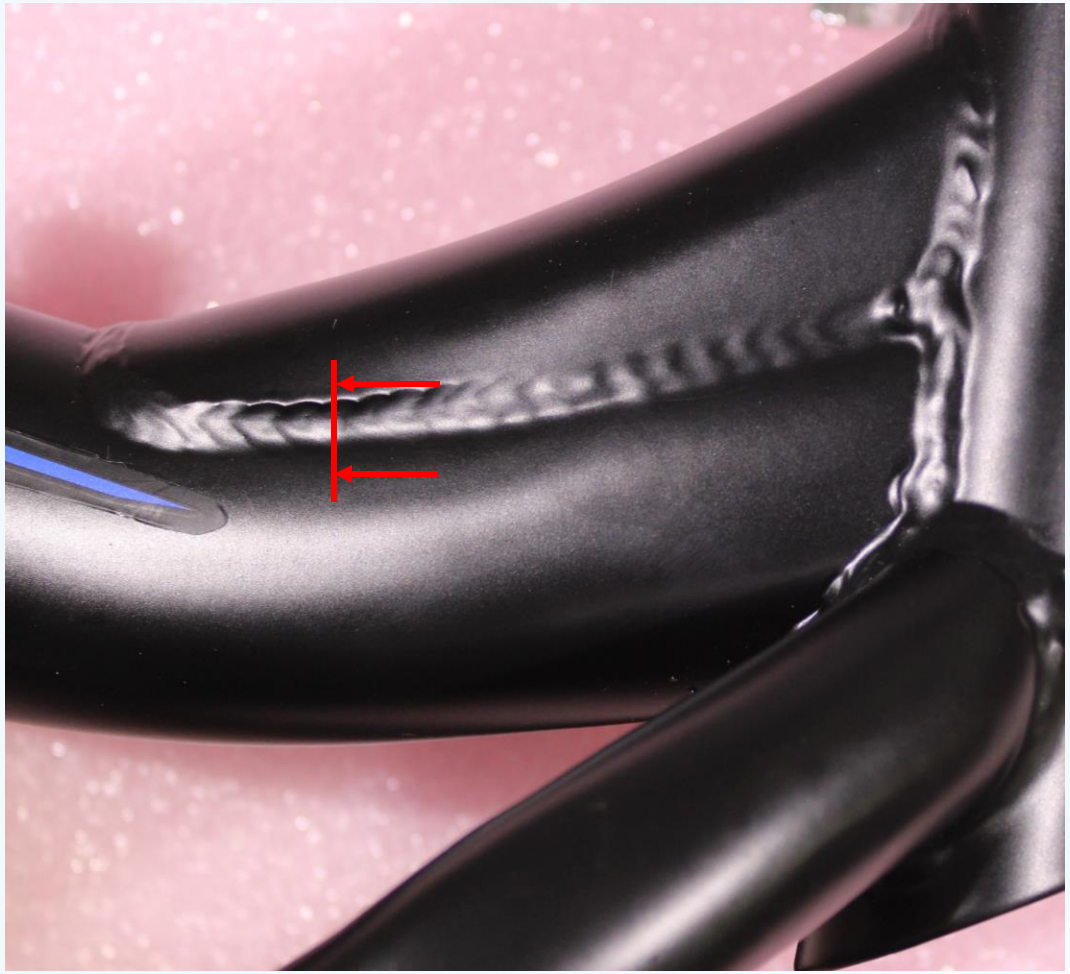
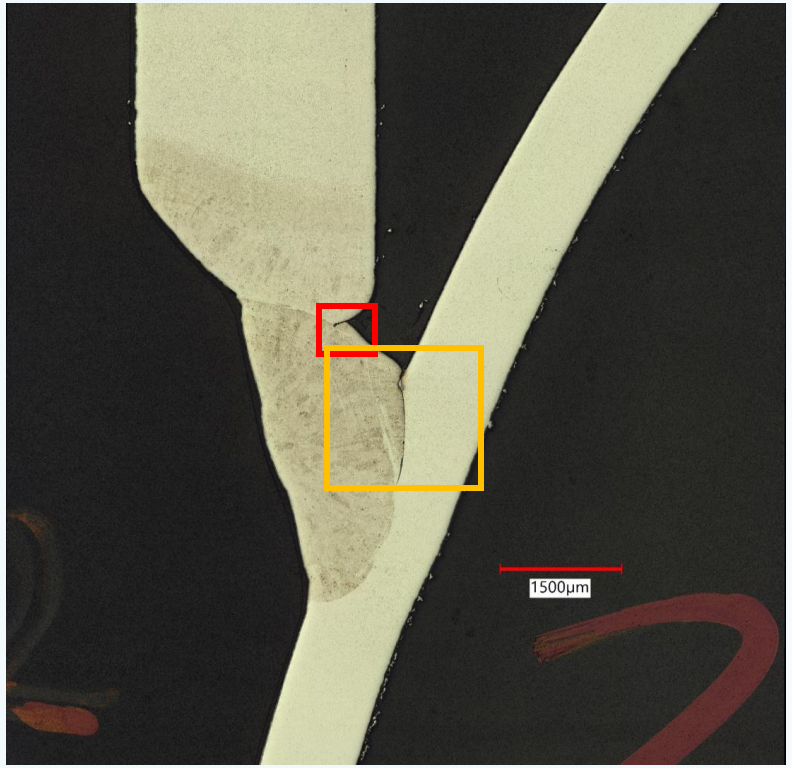
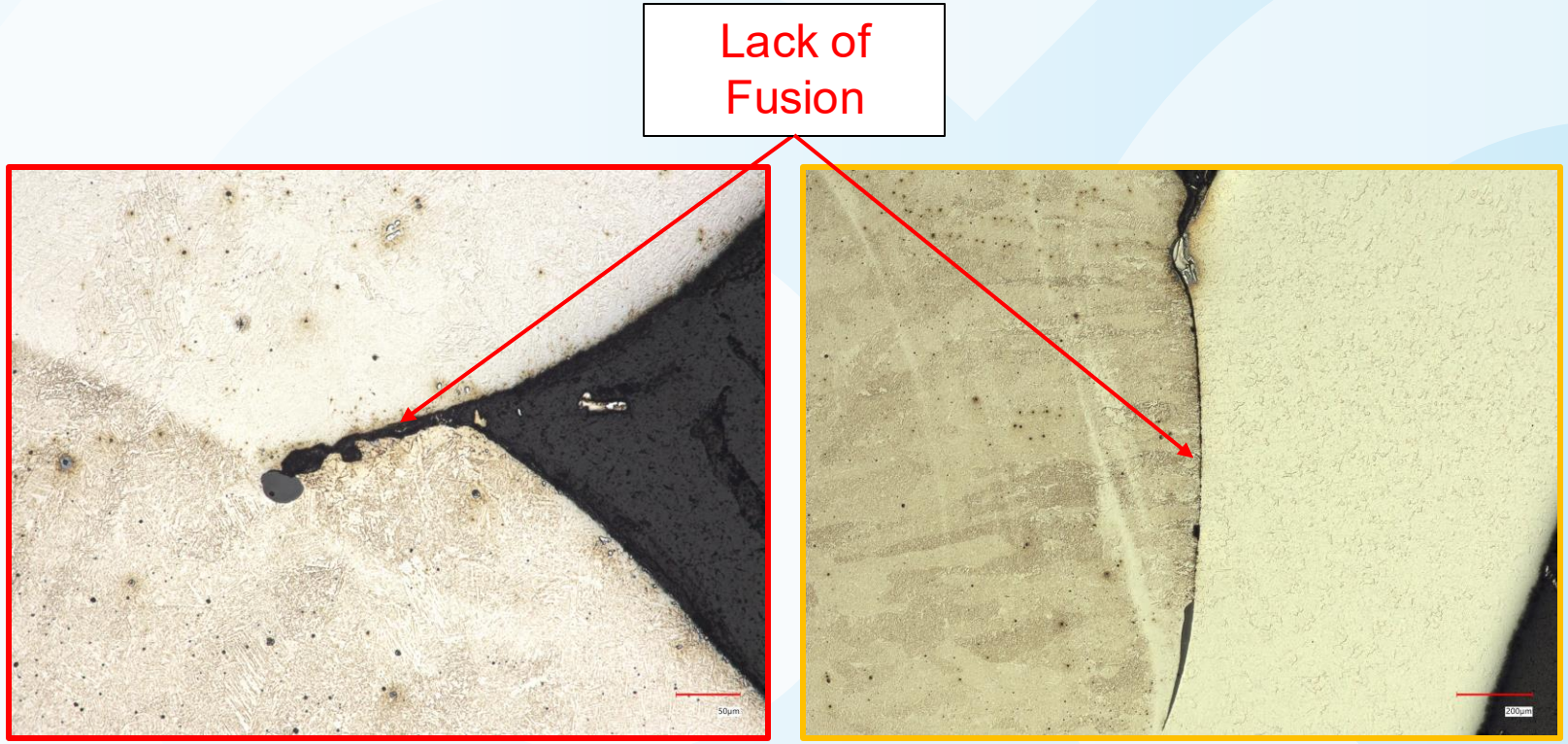


Cross-section location and direction indicated



Case Study: Weld Examination of Children's Bike





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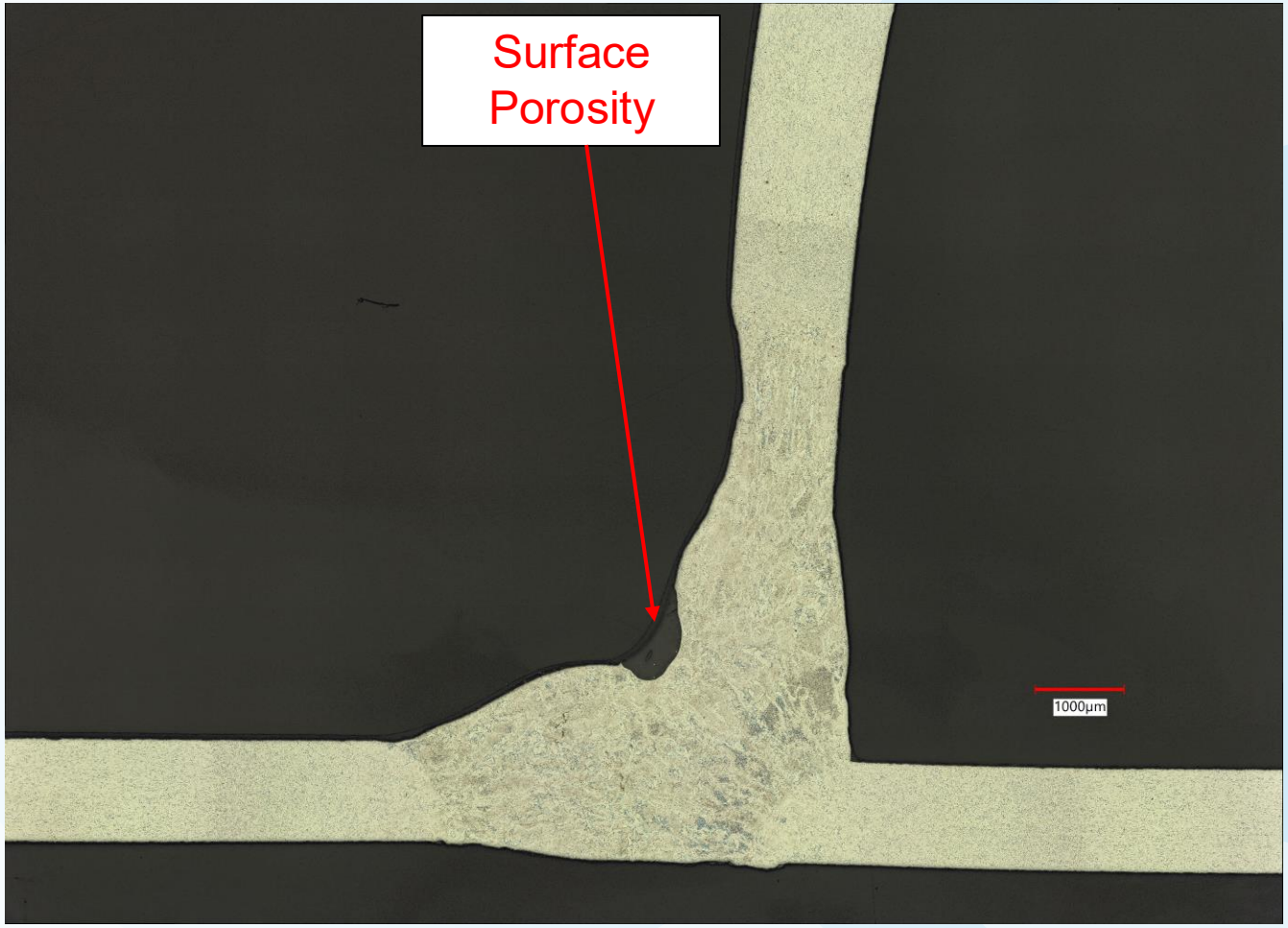

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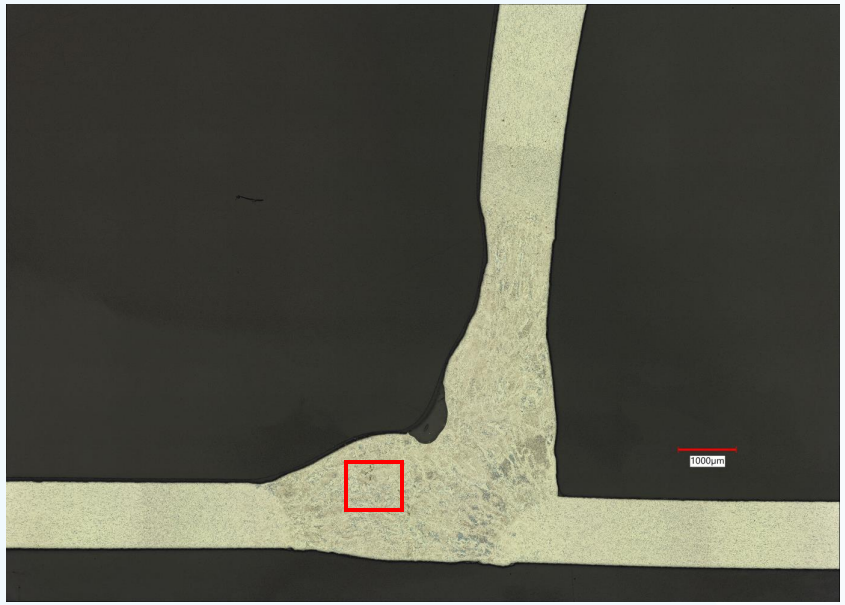
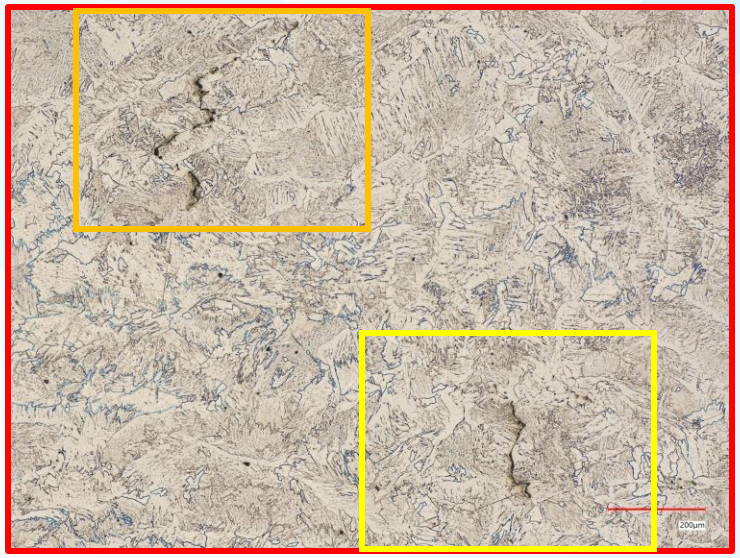








Cracking

Weld Examination at Covalent

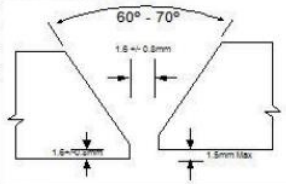
Welding Procedure Specification

Client:	Mobil	Project:	221010Goatee	REF No.	WPS 6 R1
Procedure Description:	12" Heavy Wall Offshore Tie-in				0290/1/WPS5
Material:	AS3679.1 Grade 250API 5L X65	Diameter:	168.3	Thickness:	18.3
Position:	6G	Clamp Type:	Internal		
Preheat °C (Min):	100	Interpass °C (Max):	300		

	ROOT	HOT PASS	FILL & CAP
Welding Process	SMAW	SMAW	SMAW
Welding Direction	Vertical Down	Vertical Down	Vertical Down
Filler	Lincoln SA70+	Lincoln SA70+	Bohler BVD90M
Polarity	DC +ve	DC +ve	DC +ve
Shielding Gas	N/A	N/A	N/A
Purge Gas	N/A	N/A	N/A

Pass No	Filler Size (mm)	Amps	Volts	Speed (mm/sec)	Heat Input (kJ/mm)
1	3.2mm	70-130	18-33	3.3-6.6	0.4-0.8
2	4.0mm	110-210	18-35	2.9-6.8	0.6-1.3
FILL	4.0mm	145-260	16-27	1.6-7.0	0.6-2.2
CAP	4.0mm	130-230	16-26	1.8-5.3	0.6-1.7

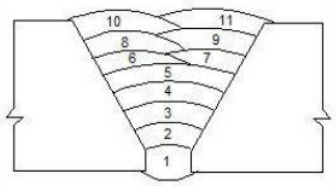
Weld Preparation



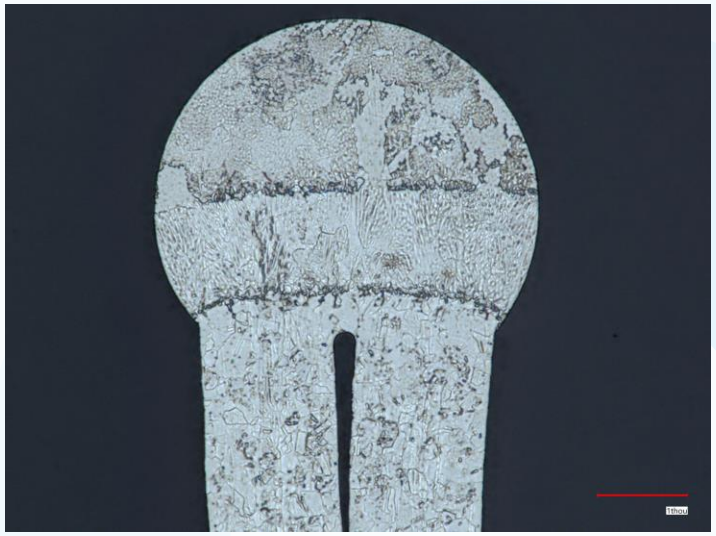
NOTES

1. API Std 1104BP3094-SP-PL-3010R1
2. Clamp removal stage : **100% completion of root (external clamp may be used in the event of a breakdown – removed after 50% minimum completion of the root.)**
3. Time lapse between root and second pass : **16 Minutes**
4. Time lapse between second pass and 1st fill : **12 Minutes**
5. Minimum number of passes before pipe movement : **2 passes**
6. Minimum number of passes before break in welding : **3 passes**
7. Minimum Number of welders- **Root & second pass: 2 , Fill & Cap : 1**
8. Method of cleaning : **Grinder / Wire brush**
9. Method of Preheat : **Gas Torch**
10. Qualification reference number : **48280/PP/WP6 R1**

Pass Location



Company Welding Engineer Approved ..... **Approved for Client** .....







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Metallurgical Coating Analysis

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Metallurgical Coatings

Definition

Coating — engineered surface layer applied for corrosion, wear, or thermal protection

Adhesion — the bond to the substrate — mechanical, chemical, or metallurgical

A coating is a system — substrate + surface prep + layer stack; the weakest interface controls life

Common Coating Families

Electroplated — Cr, Ni, Zn, Cd deposited from solution

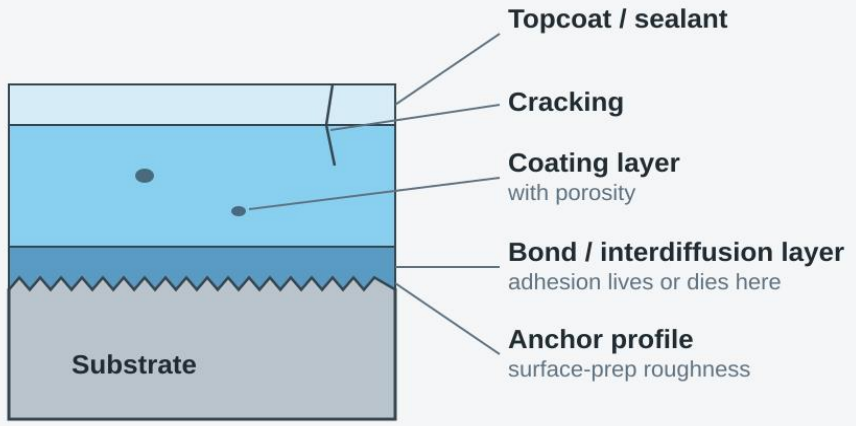
Hot-dip & thermal spray — galvanizing; HVOF, plasma spray

Conversion — anodize, phosphate, chromate — grown from the substrate

PVD / CVD — thin hard films (TiN, DLC) from vapor

Organic — paint and powder coat over metal prep

Anatomy of a Coating (Cross-Section)



Performance depends on the whole stack: substrate condition, anchor profile from surface prep, the bond layer, coating density, and total thickness.

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Metallurgical Coatings: Terminology

Coating Properties

Thickness — first thing measured; drives most performance

Adhesion — resistance to separation from the substrate

Porosity — voids that let environment reach the substrate

Hardness — wear resistance; microhardness on cross-sections

Residual stress — tensile stress promotes cracking and peeling

Structure & Interfaces

Substrate — the base metal being protected

Anchor profile — surface-prep roughness that keys the coating

Bond coat / interlayer — intermediate layer improving adhesion

Intermetallic layer — brittle phases from interdiffusion (e.g., Fe-Zn, Fe-Al)

Topcoat / sealant — outermost barrier layer

Measurement & Testing

Cross-section metallography — thickness, layers, porosity, defects

XRF / eddy current / magnetic — non-destructive thickness gauges

Pull-off adhesion — quantitative bond strength (ASTM D4541)

Bend, scratch & tape tests — quick adhesion screening

Salt spray — accelerated corrosion exposure (ASTM B117)

Analytical Techniques

SEM / EDS — morphology plus elemental composition of layers

XRD — phase identification — plating, intermetallics, corrosion products

GDOES — composition depth profiling through the stack

FIB cross-sections — site-specific sections of thin films

FTIR — organic binder chemistry and degradation

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Metallurgical Coatings: Defects and Failures

As-Applied (Processing) Defects

Pinholes / porosity — through-thickness paths to the substrate

Thin or uneven thickness — edges, corners, and recesses run thin

Poor adhesion — contamination or inadequate surface prep

Inclusions — dirt, overspray, or entrapped particles

Mud cracking — shrinkage cracking of thick or fast-dried layers

Holidays — skipped or uncoated areas

Hydrogen embrittlement — plating charges high-strength steel with hydrogen; bake-out required

In-Service Failures

Blistering — local adhesion loss; osmotic or corrosion-driven

Delamination / spalling — sheet-like or chip-like detachment

Underfilm / filiform corrosion — attack creeping beneath the coating from a defect

Galvanic attack — exposed substrate corrodes at coating damage

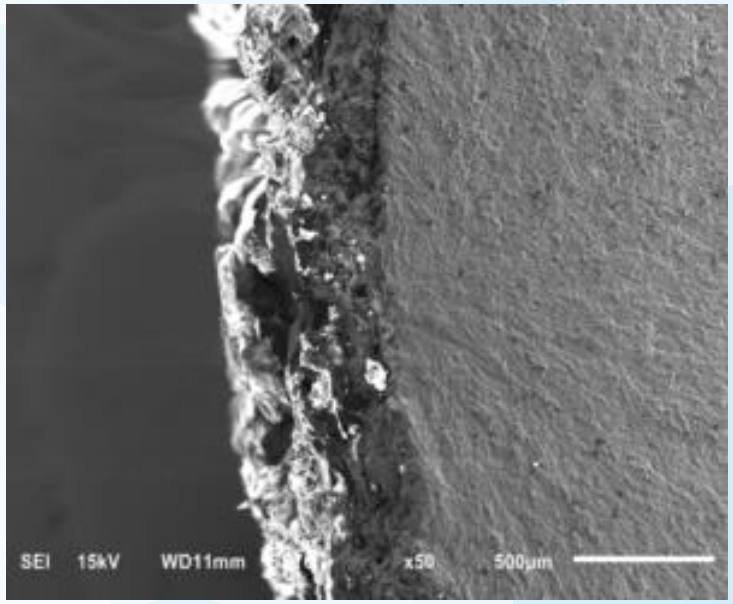
Wear-through — abrasion or erosion consumes the layer

Thermal fatigue cracking — CTE mismatch cracks the coating on cycling

Interdiffusion embrittlement — brittle intermetallics grow at temperature

Metallurgical Coatings: Corrosion

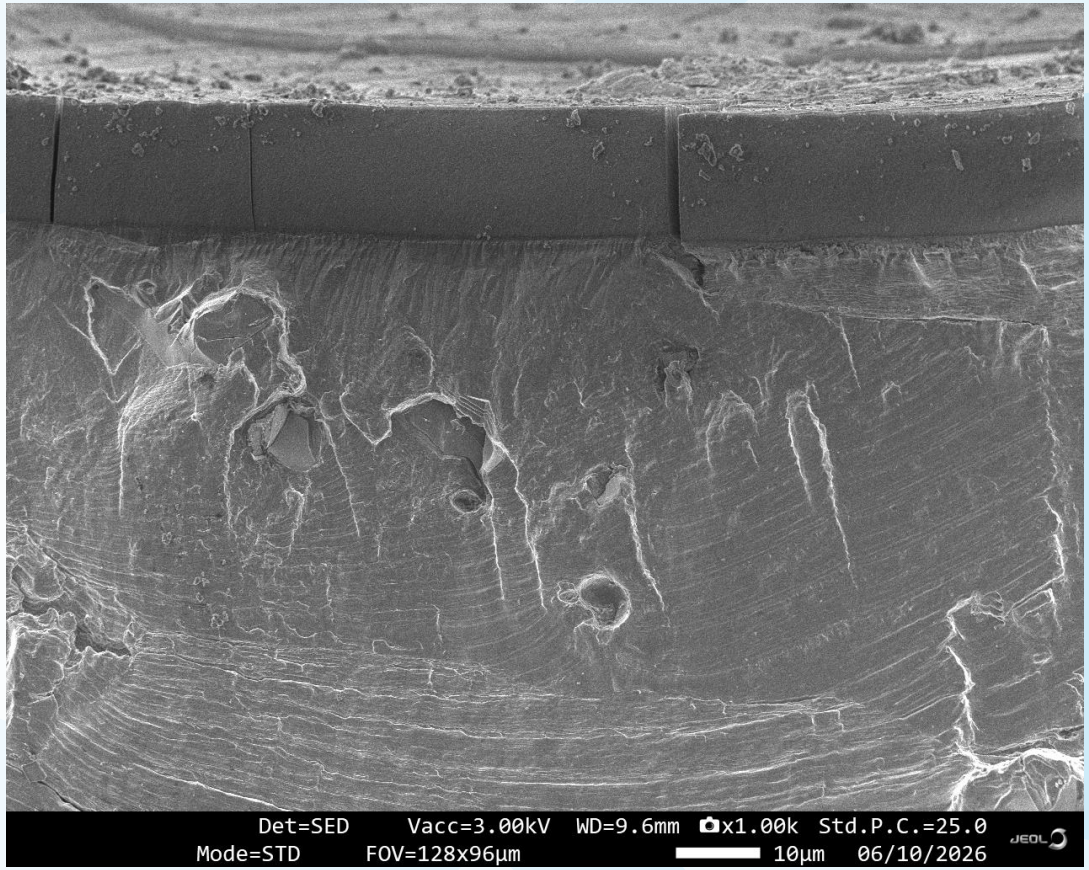
- **As-received exam** – Document blistering, rust, delamination before destructive work
- **Cross-section metallography** – Thickness, porosity, interface condition, substrate attack
- **SEM/EDS** – Corrosion product composition; interface contaminants (Cl, S, P, F)
- **XRD & FTIR** – Corrosion product phases; binder degradation
- **Root cause** – Surface prep, thickness, damage, or environment





Metallurgical Coatings: Cracking

- **As-received exam** – Document crack pattern (mud cracking, isolated, network), location, orientation
- **Cross-section metallography** – Crack depth/path, layer thicknesses, porosity, substrate penetration
- **SEM** – Crack origin and morphology; fractography of crack faces
- **EDS** – Contaminants in crack; confirm crack age (corrosion products inside)
- **XRD / FTIR** – Brittle intermetallic phases; binder embrittlement or UV degradation
- **Root cause** – Excess thickness, cure issues, residual stress, CTE mismatch, or substrate deflection



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Fracture Analysis

Fracture Analysis: The Basics

Definition

Fracture — separation of a component into pieces under stress

Fractography — interpreting fracture-surface features to establish origin, mode, and root cause

The surface is a record — features preserve where cracking started, how it grew, and the final failure event

Keys to the Analysis

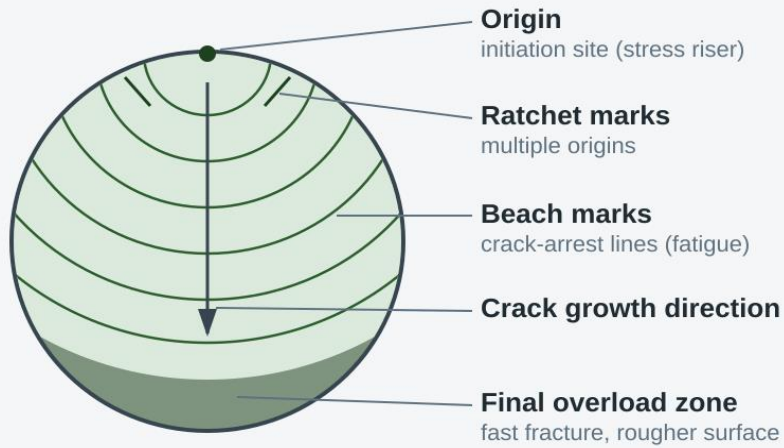
Locate the origin — chevrons, radial and beach marks point back to it

Identify the mode — ductile, brittle, fatigue, or environmental

Determine the loading — tension, bending, torsion; static or cyclic

Preserve the evidence — never mate fracture faces back together

Anatomy of a Fatigue Fracture (Shaft)



Classic fatigue failure: the crack initiates at a surface stress riser, grows cycle by cycle (beach marks), and the remaining ligament fails by fast overload.

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Fracture Analysis: Terminology

Fracture Modes

Ductile — tearing with plastic deformation; dimpled surface

Brittle — rapid, low-energy fracture; little deformation

Fatigue — progressive cracking under cyclic loading

Environmental — SCC, hydrogen embrittlement, creep, corrosion fatigue

Macroscopic Features

Beach marks — crack-arrest lines radiating from a fatigue origin

Chevron marks — V-patterns pointing back to the origin

Ratchet marks — steps between multiple initiation sites

Shear lip — 45-degree rim of final ductile separation

Radial marks — fan-like ridges spreading from a brittle origin

Microscopic (SEM) Features

Dimples — microvoid coalescence; ductile rupture

Striations — one ridge per load cycle; fatigue

Cleavage facets — flat transgranular planes; brittle

Intergranular facets — grain-boundary fracture (HE, SCC, embrittlement)

Secondary cracks — branching off the main fracture path

Analysis Terms

Origin — initiation site; locate first, examine closest

Stress riser — notch, defect, or geometry concentrating stress

Fracture toughness — material resistance to crack propagation

Overload — final fast fracture of the remaining section

Residual stress — locked-in stress aiding or opposing cracking

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Fracture Analysis: Macro vs. Micro

Macroscopic (Visual / Stereomicroscope)

Chevron marks — converge on the fracture origin

Beach marks — indicate fatigue; map the crack-growth history

Ratchet marks — multiple origins; high stress or stress concentration

Shear lips & necking — ductile behavior; final overload

Flat, granular surface — brittle fracture with little deformation

Surface condition — corrosion products, oxidation, temper colors

Deformation pattern — bending direction, torsional twist, misalignment

Microscopic (SEM / Metallography)

Striations — cycle-by-cycle fatigue growth; spacing gives growth rate

Dimples — ductile microvoid coalescence; shape shows load direction

Cleavage — transgranular brittle fracture along crystal planes

Intergranular fracture — embrittlement, SCC, or hydrogen damage

Inclusions / defects at origin — EDS identifies composition

Secondary cracking — branching typical of SCC

Microstructure at origin — metallography reveals heat treatment, HAZ, decarburization

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Case Study: Fracture Analysis of Bow Riser



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Case Study: Fracture Analysis of Bow Riser

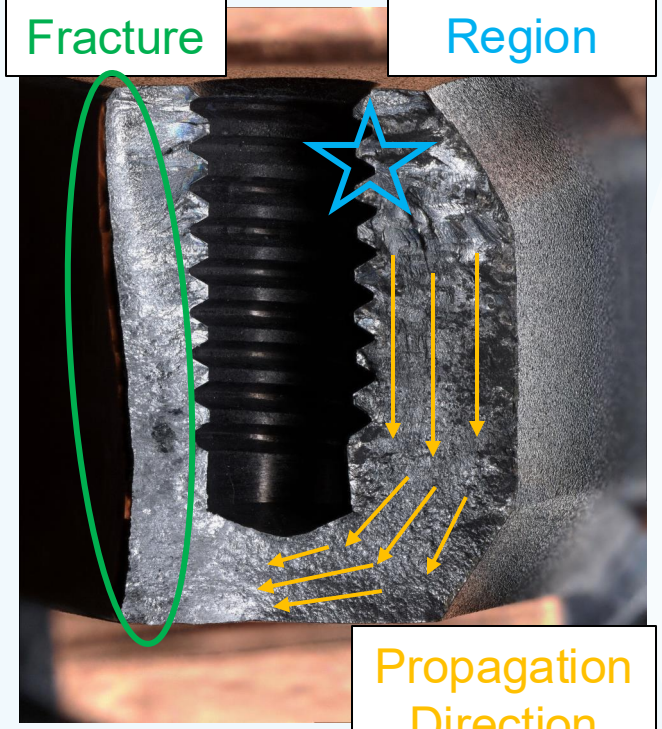


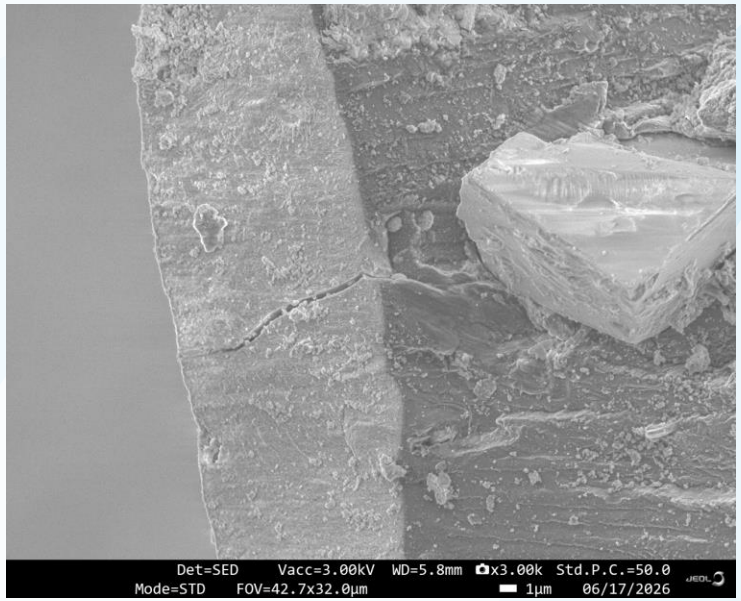




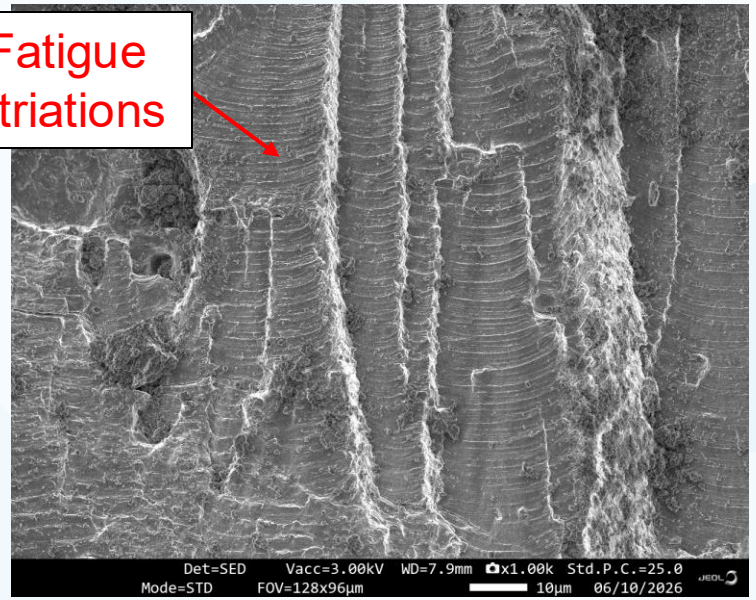
Close-up photographs of the fractured region of the bow riser.

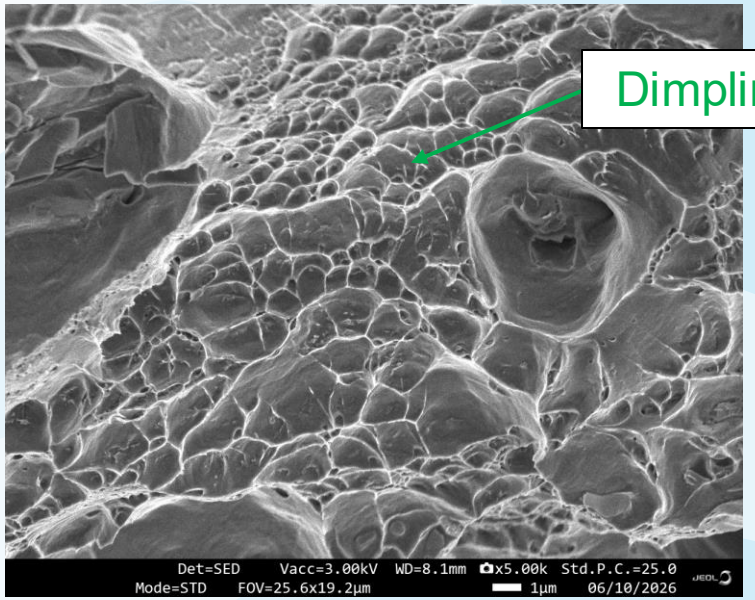
Case Study: Fracture Analysis of Bow Riser





Initiation Site





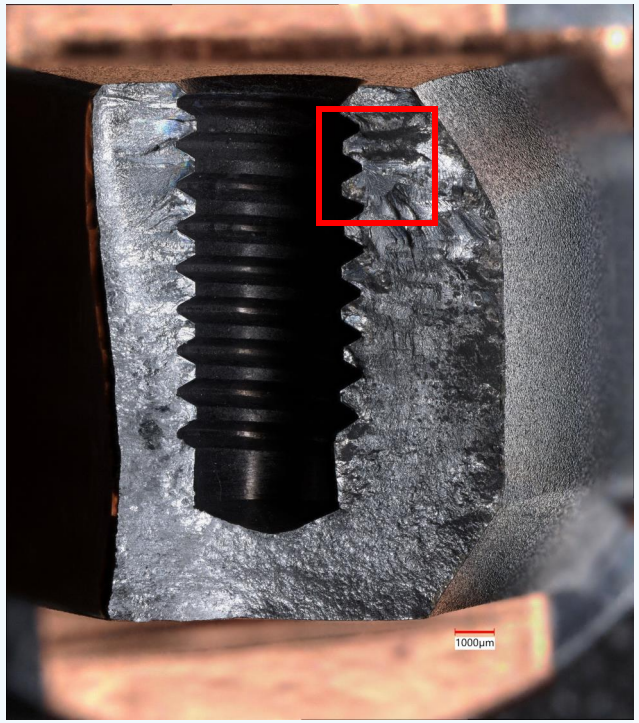
Case Study: Fracture Analysis of Bow Riser



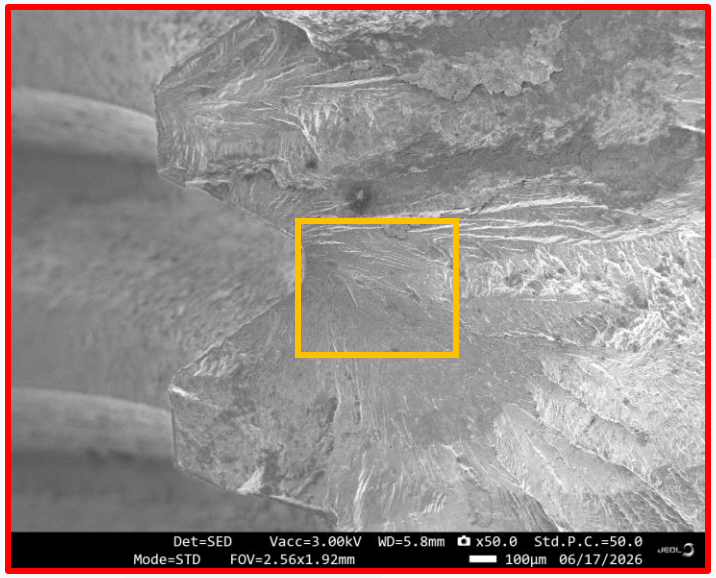


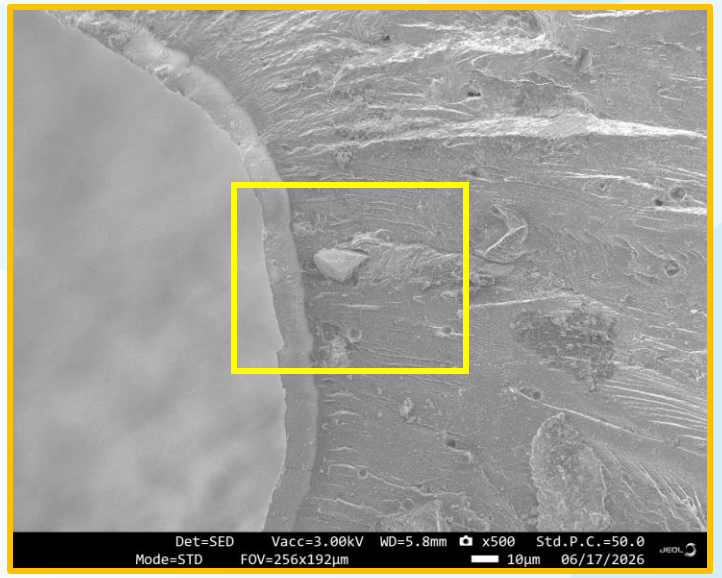
Optical stiches of both fracture surfaces from the bow riser.

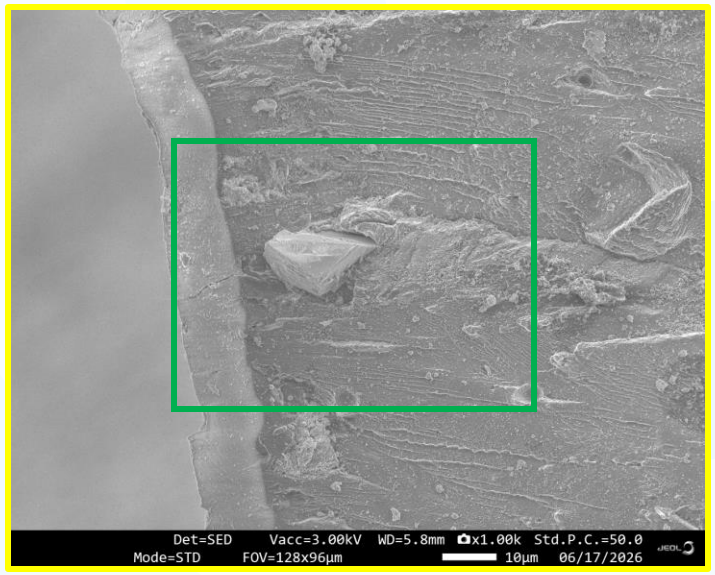
Case Study: Fracture Analysis of Bow Riser

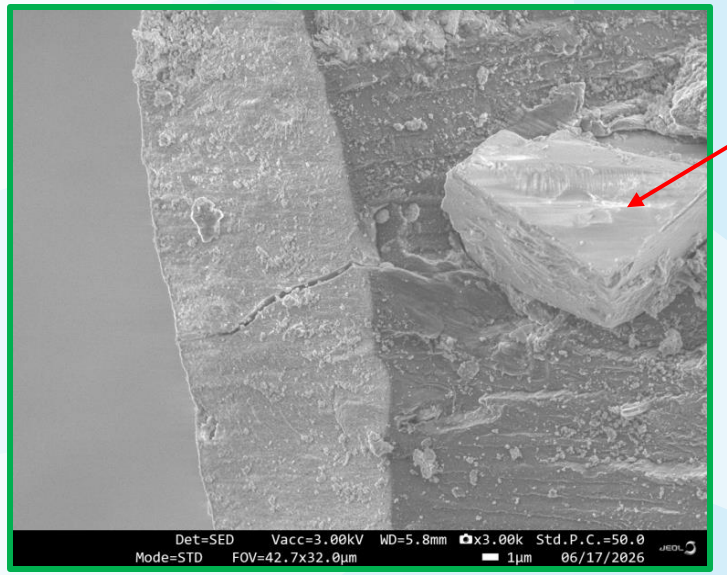


SEM images of fracture surface A showing the proposed initiation site of the failure.



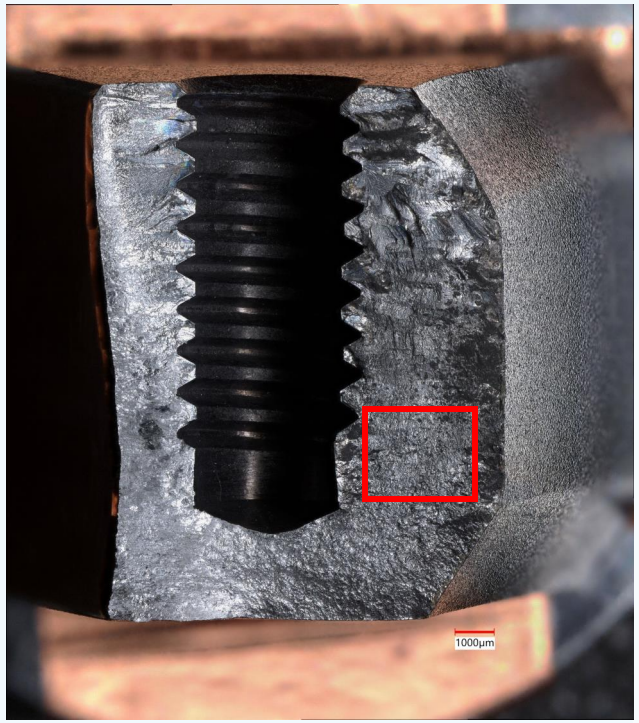




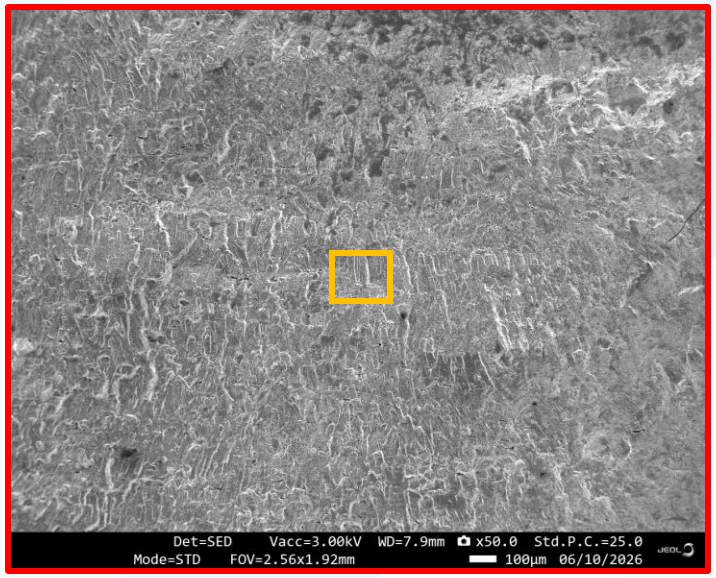


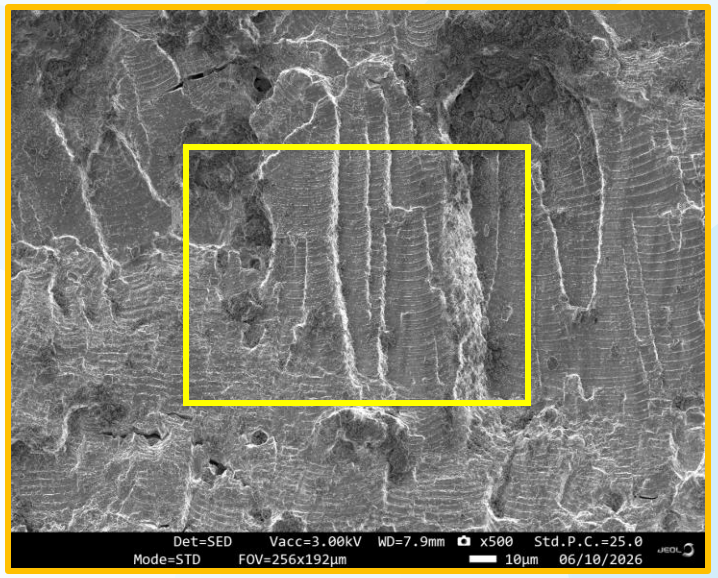
Inclusion

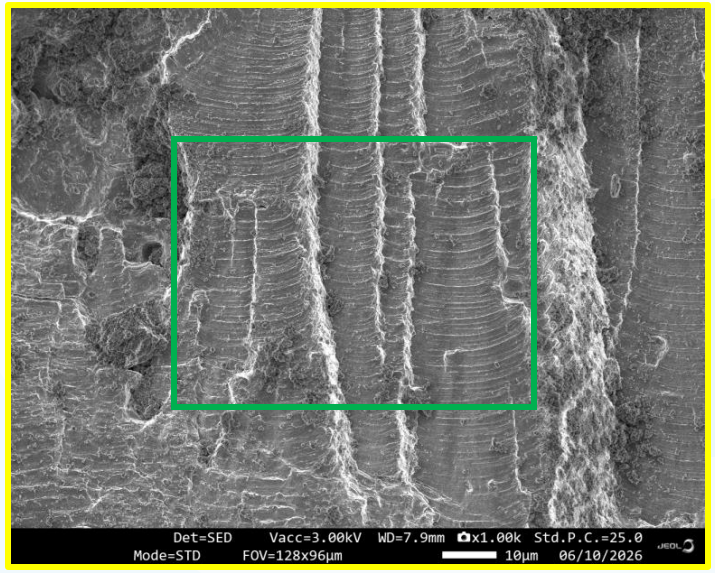
Case Study: Fracture Analysis of Bow Riser

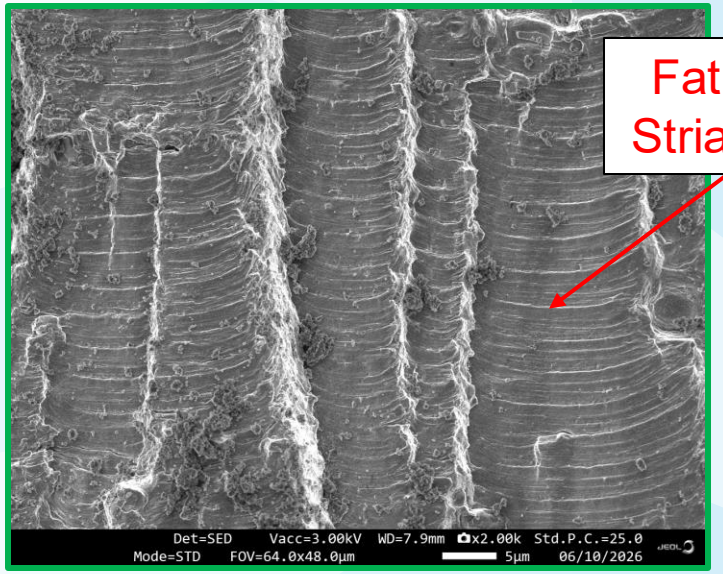


SEM images of fracture surface A showing the bottom portion of the threaded region.

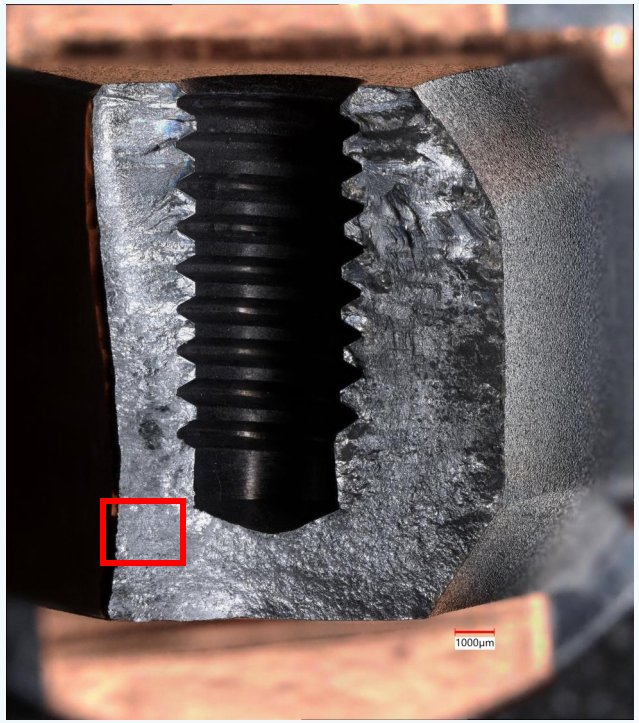




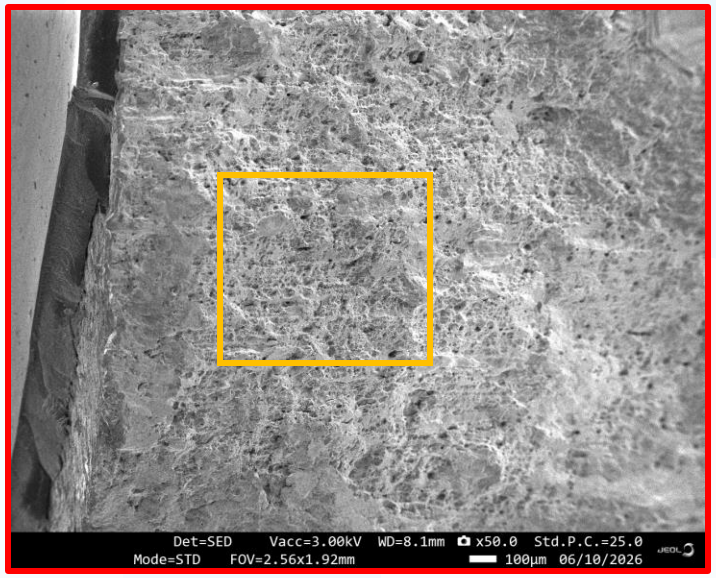


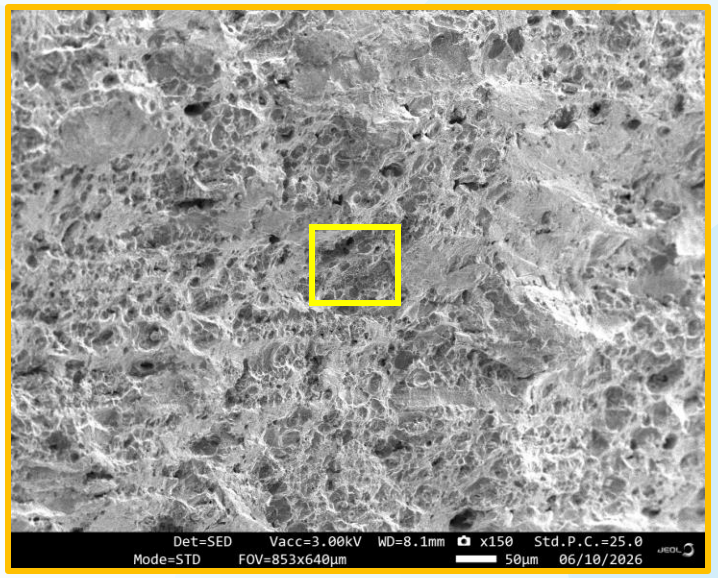


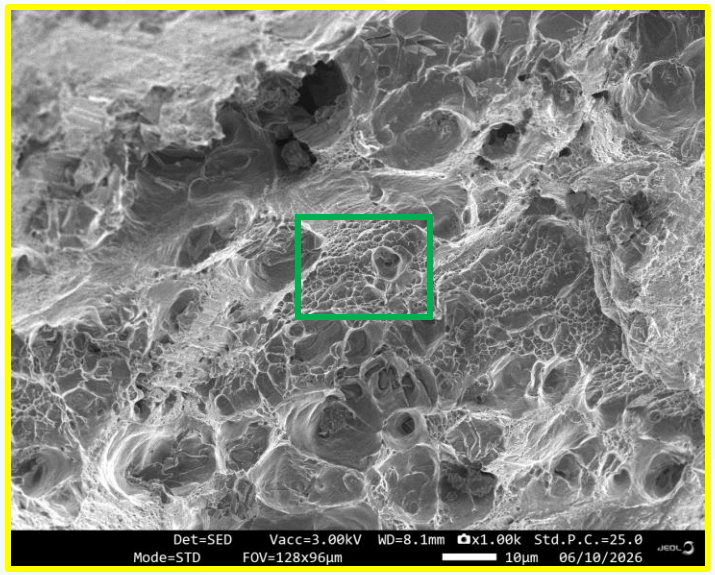
Case Study: Fracture Analysis of Bow Riser

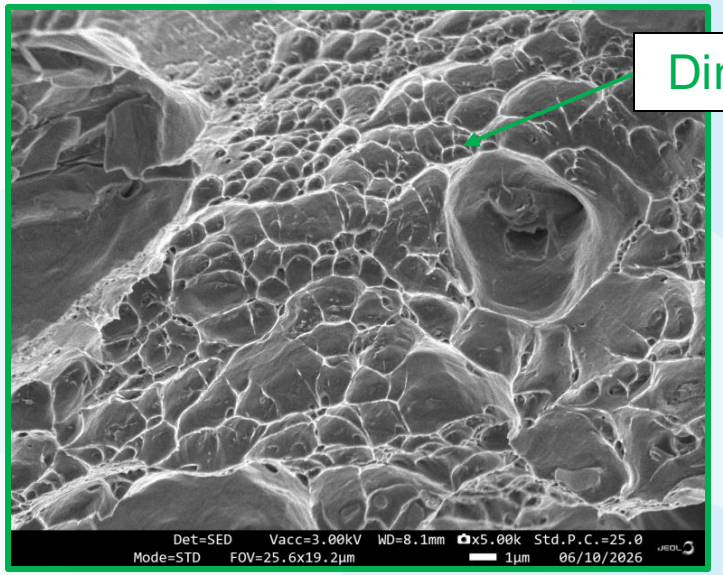


SEM images of fracture surface A showing the bottom portion of the threaded region.









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Q&A Session

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Thank you!

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