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PERFORMANCE REVIEW INSTITUTE



- centres of vocational Excellence in aerospace & defence for advanced manufacturing
- AILEEN addresses the **shortage of skilled personnel** for the Aerospace & Defence Sectors by setting up **CoVEs** for Advanced Manufacturing (AM), supporting the recovery of the Aerospace sector, developing innovative methodologies and tools, with the nomination of the first Centres of Vocational Excellence in AM, to guarantee specialized sectoral training, and the transfer of excellence knowledge and activities in the field of education and training.

AILEEN Project



Non-Destructive Testing in Additive Manufacturing for Metals and Polymers



- **Non-Destructive Testing in Additive Manufacturing for Metals and Polymers**
- **Target:** Additive Manufacturing, Welding and NDT Engineers
- **Objectives:** Develop the knowledge and skills necessary for the application of Non-Destructive Testing (NDT) methods in Additive Manufacturing (AM) for metals and polymers.
- **Precedence:** Basic knowledge of materials science, manufacturing processes, additive manufacturing, and general NDT principles.
- **Entry Level:** Level 4
- **Overall Duration:** 1 day (7 hours)

Trainers



- Prof. Dr. Ulaş Yaman
- Orcan Kolankaya
- Dr. Tuğçe Kaleli Alay
- İbrahim Aydın
- Başak Güneş

Non-Destructive Testing in Additive Manufacturing for Metals and Polymers



Topics	Hours
Introduction to NDT in Additive Manufacturing and Regulatory Standards	1.5
NDT in Additive Manufacturing	2
Strategies for Inspection in Additive Manufacturing	1.5
Case Studies Review	2

Examination



- February 6, 2026 at 17:00
- 14 Questions
- Multiple-choice
- 30 minutes

Certificate of Completion



CERTIFICATE OF COMPLETION

AILEEN PILOT COURSE

Country, City | timeframe

This certificate is awarded to

for the completion of **insert course name here** organized through the Erasmus+ project AILEEN (Project No. 101103507).

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PRI Qualification





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Laser
AKADEMIE



ASTURIAS HUB
DEFENSA



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FAN 3D



FAN 3D



Brunel
University
London

Non-Destructive Testing in Additive Manufacturing

Introduction

Prof. Dr. Ulaş Yaman

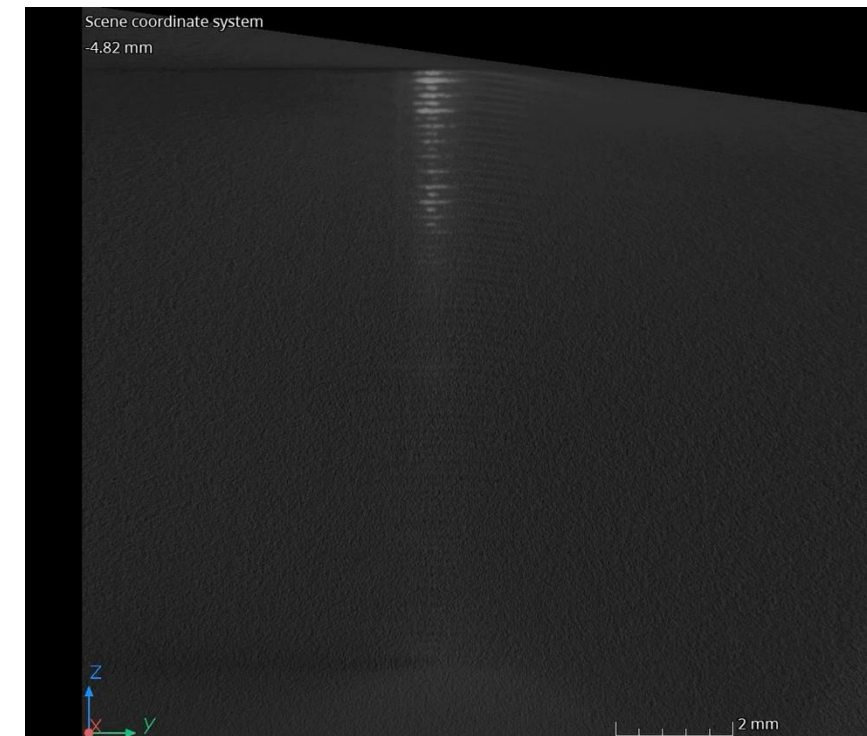
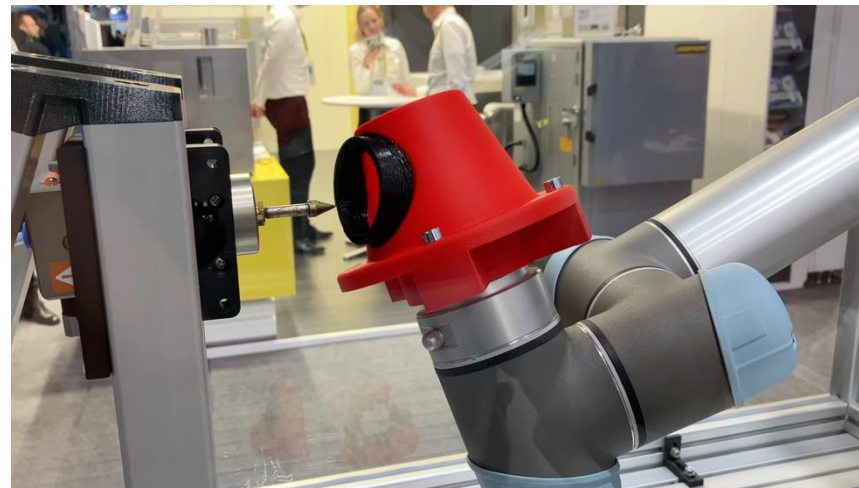
Welding Technology and NDT Center

Middle East Technical University

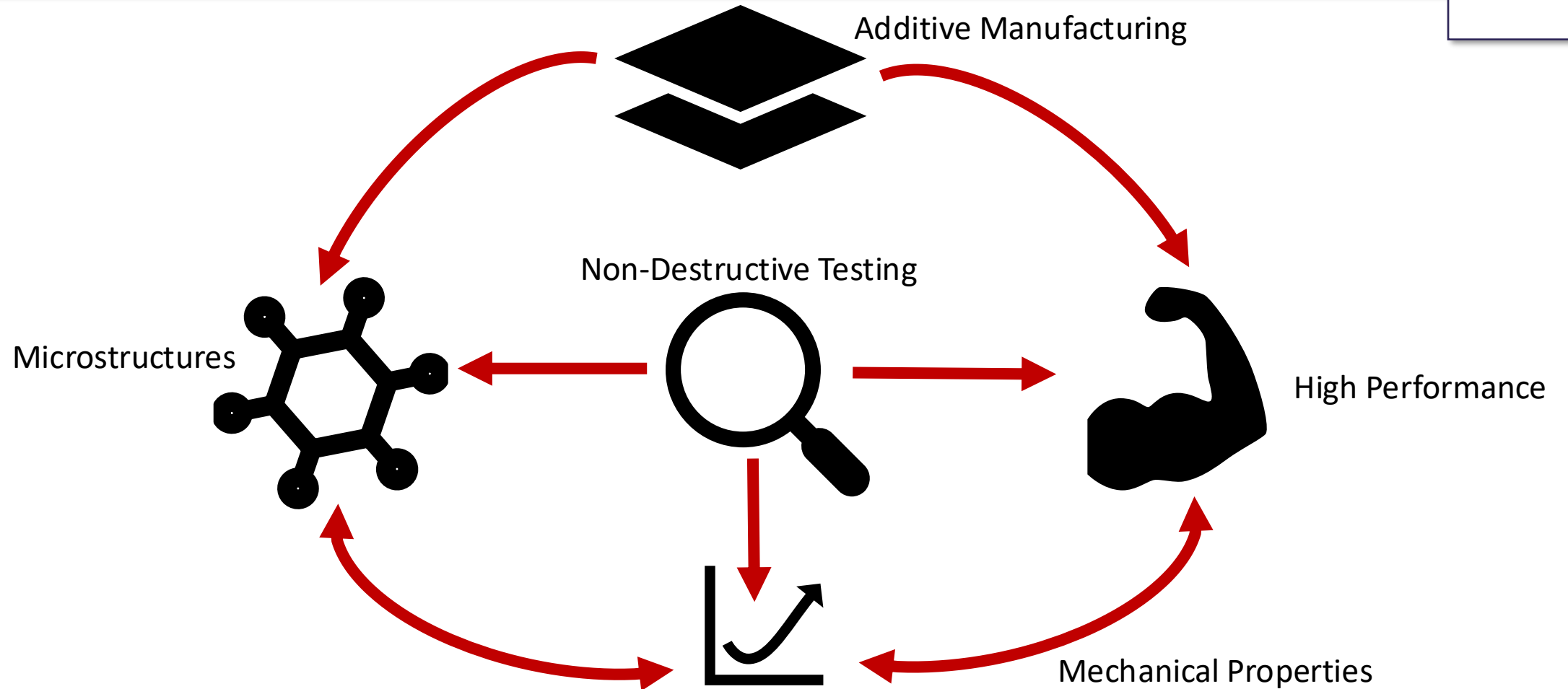
Outline



- Introduction
- Additive Manufacturing Technologies
- Defects in Additive Manufacturing
- Evaluations



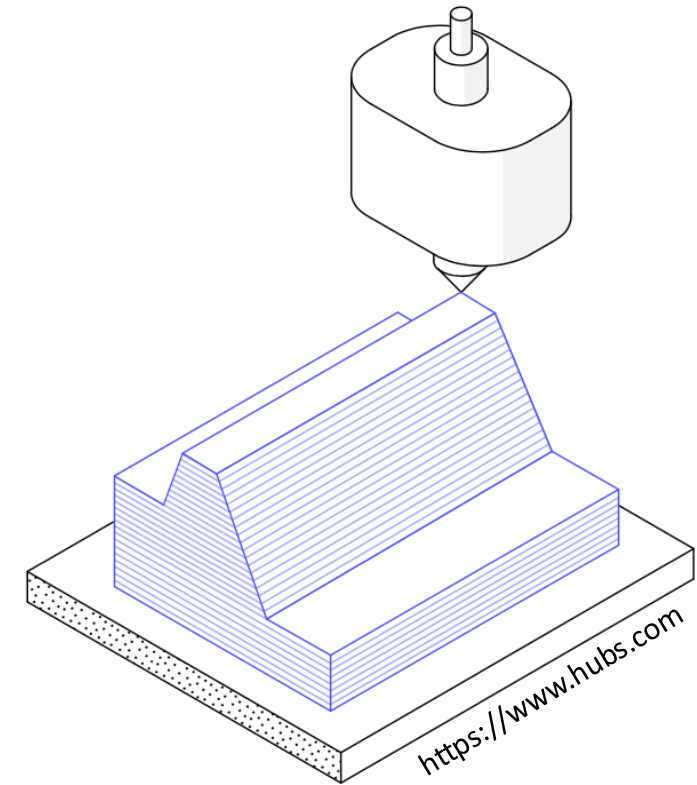
Introduction



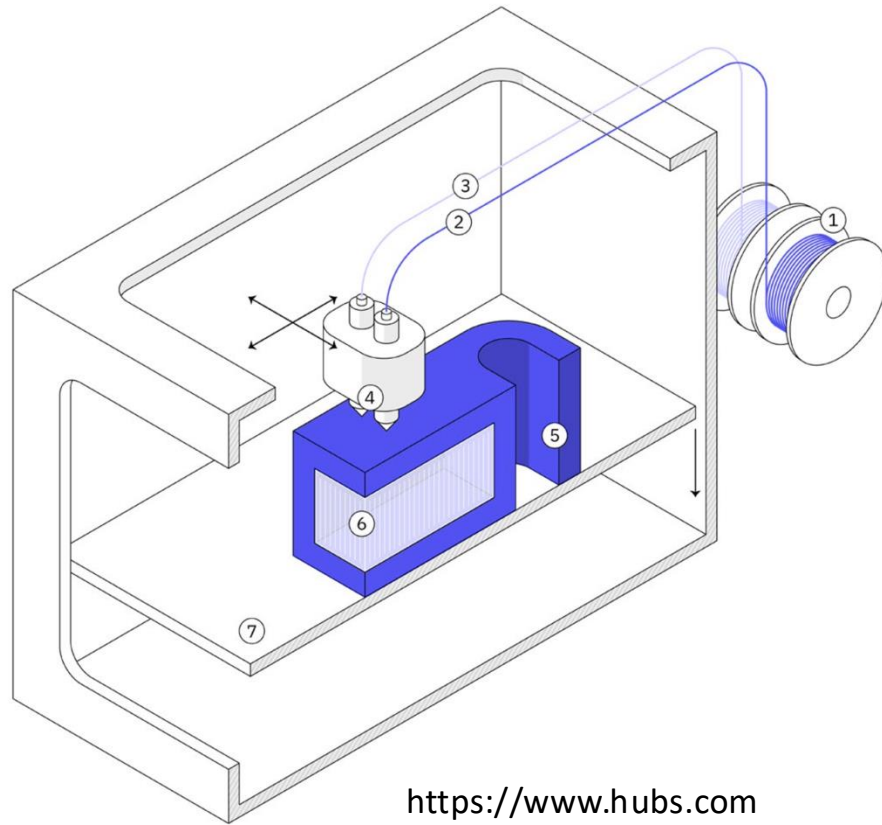
Additive Manufacturing Technologies



- ISO and ASTM
- 7 main additive manufacturing approaches
 - Material Extrusion
 - Vat Photopolymerization
 - Material Jetting
 - Powder Bed Fusion
 - Binder Jetting
 - Directed Energy Deposition
 - Sheet Lamination



Material Extrusion



<https://www.hubs.com>

- Fused Filament Fabrication (FFF)
- Extrusion
- Nozzle head
- Support structures
- Most common
- Cheapest
- PLA, ABS, PETT, etc.
- Concrete 3D Printers
- Bio-printers

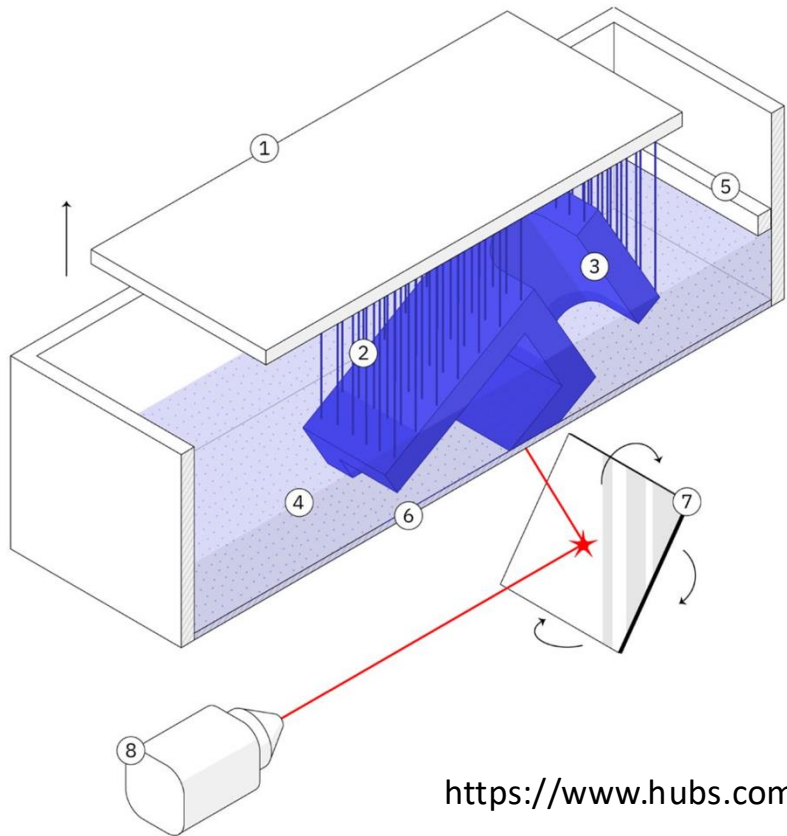
Material Extrusion



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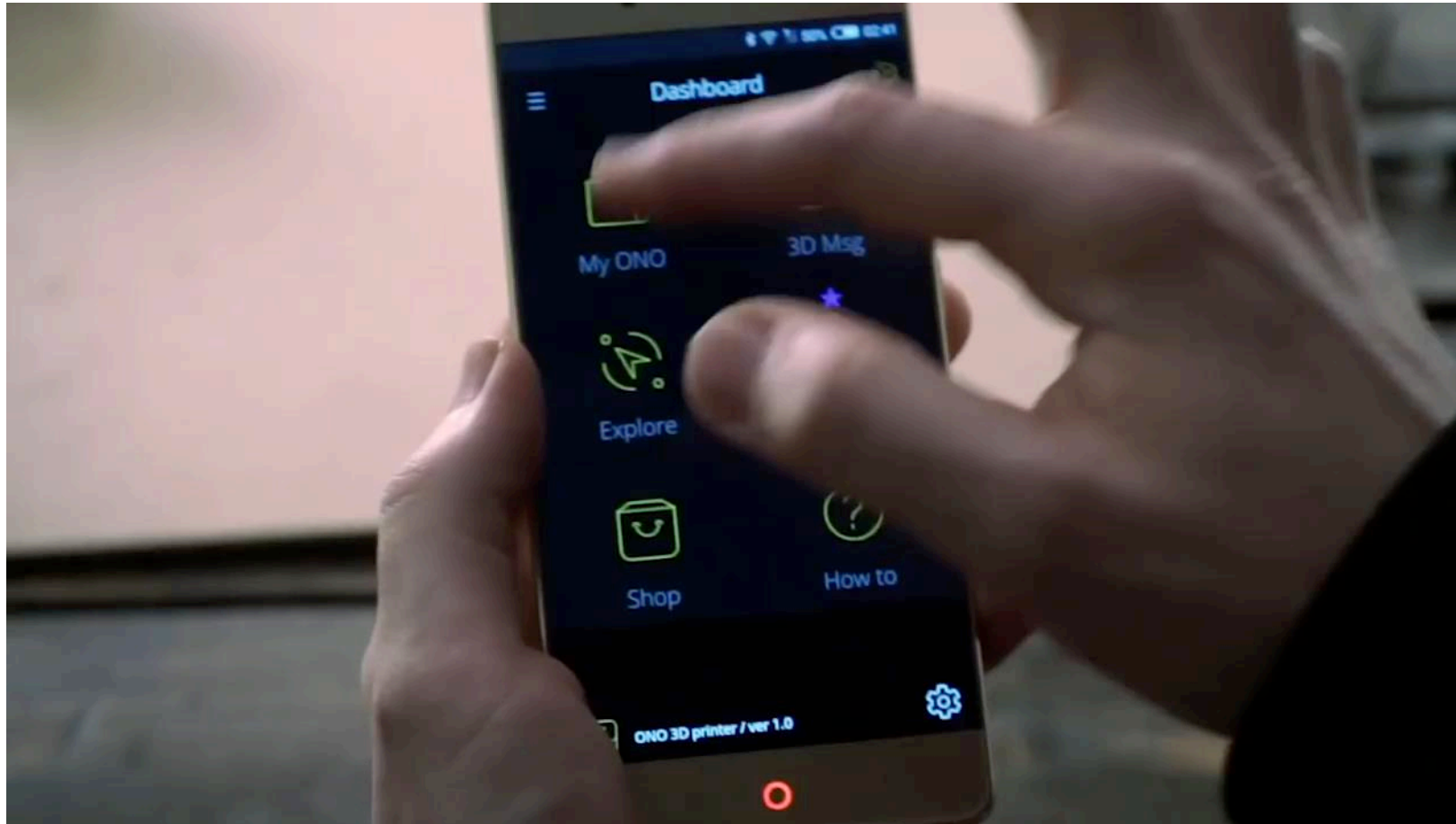
Vat Photopolymerization



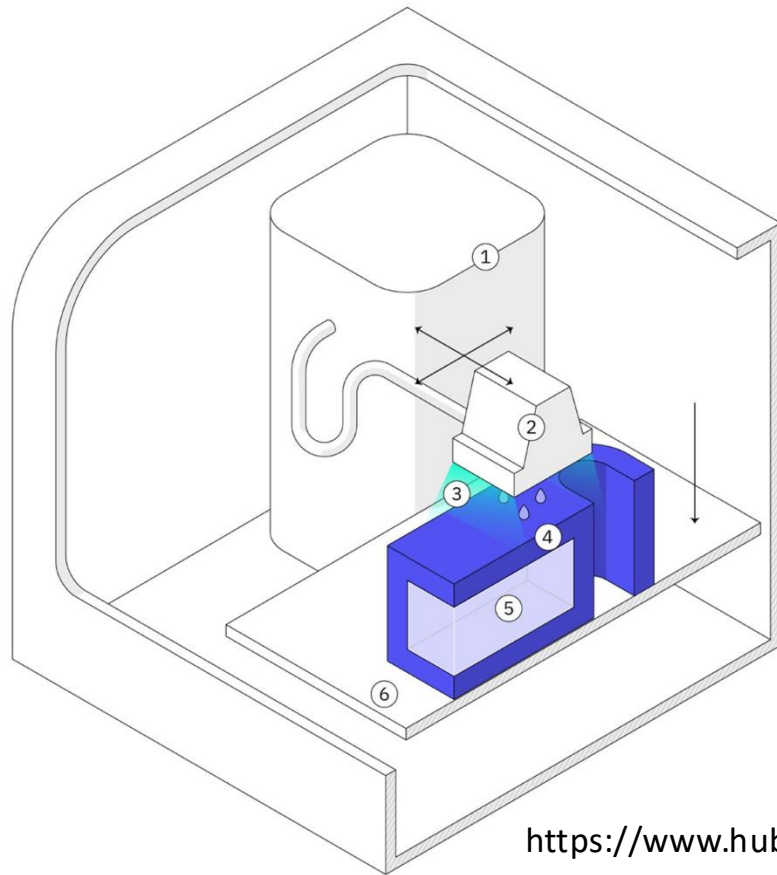
<https://www.hubs.com>

- Stereolithography (SLA)
- Photopolymers, resins
- Various materials
- Support structures
- Laser
- High accuracy and surface quality
- Resin in the tank
- CLIP and DLP methods
 - Light source

Vat Photopolymerization



Material Jetting



<https://www.hubs.com>

- Polyjet
- Multijet
- Photopolymers, resins
- Colored artifacts
- High resolution
- Various materials
- Expensive
- More sustainable

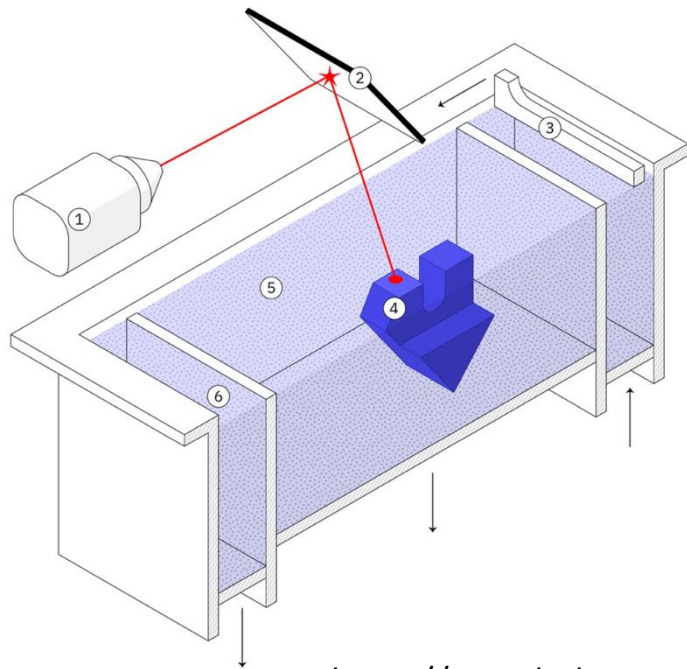
Material Jetting



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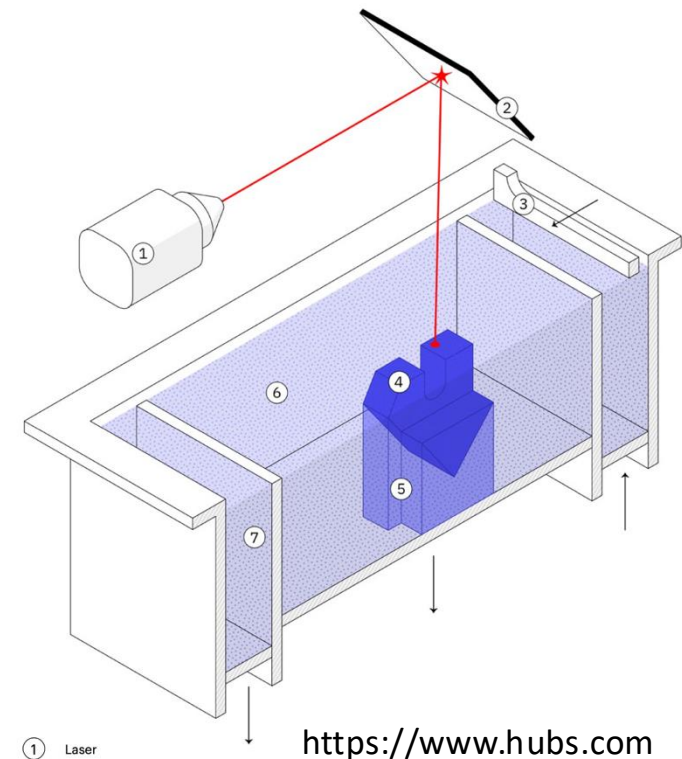


Powder Bed Fusion



<https://www.hubs.com>

- Sintering or Melting
- Powders of
 - Polymers
 - Metals
- Laser(s)
- Support structures
- Recycling of powders
- Low surface quality



<https://www.hubs.com>

Powder Bed Fusion

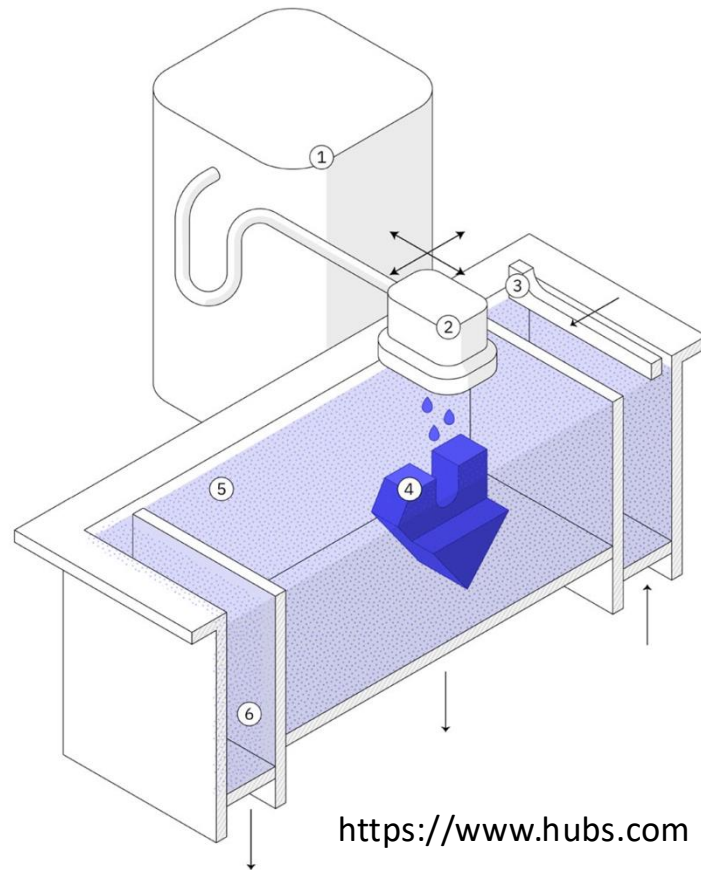


BLT-S1500 26-Laser

FORMING PROCESS

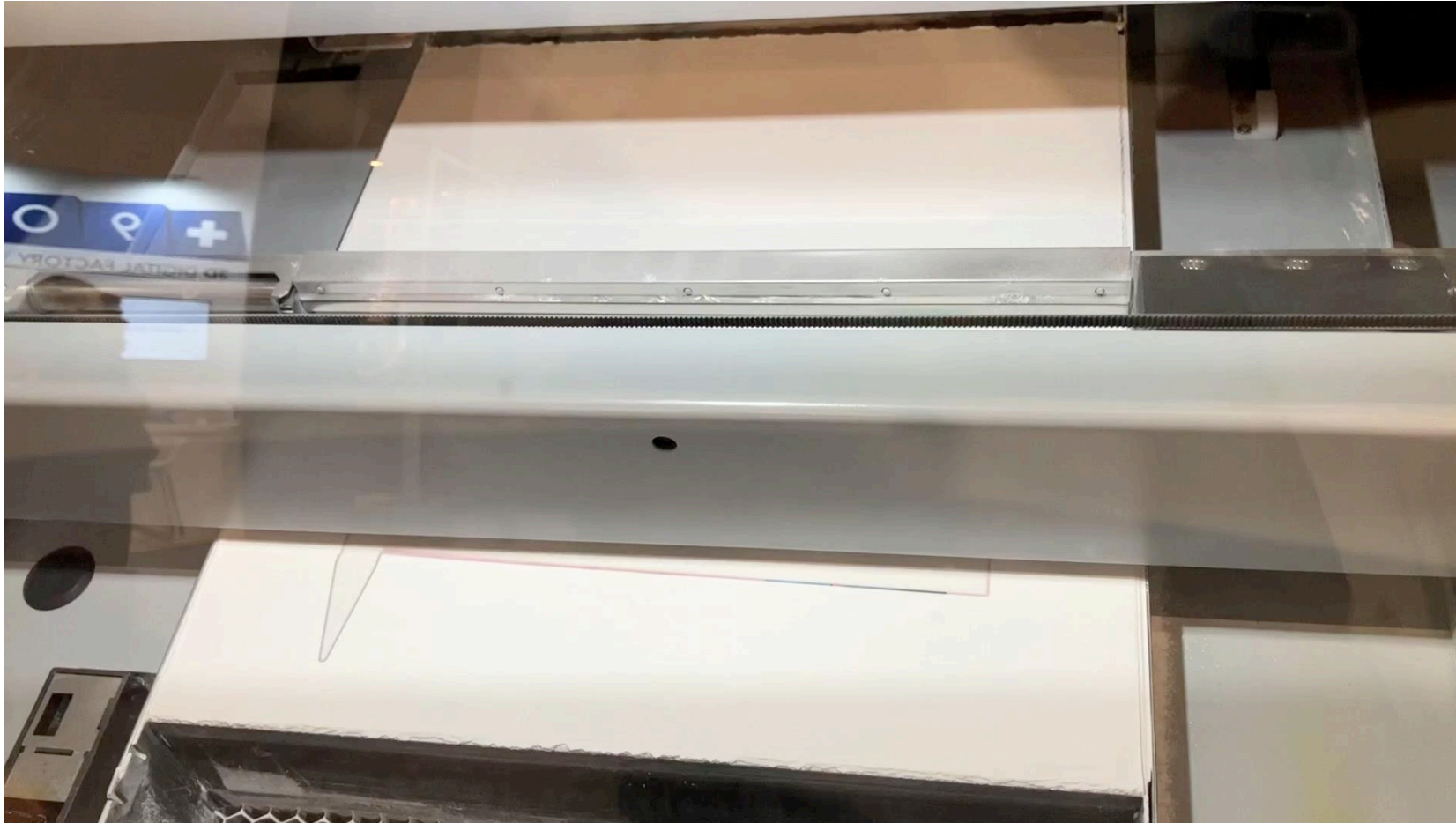


Binder Jetting



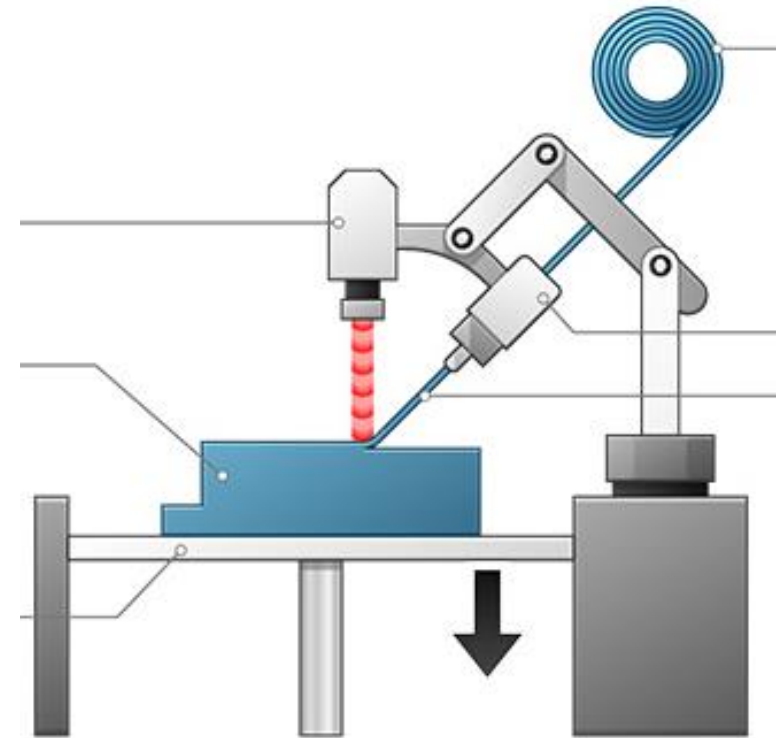
- Colored artifacts
- Larger and complicated pieces
- Lower mechanical properties
- Secondary operations
 - Infiltration
- High surface roughness
- Plastics, metals, ceramics, sand, etc.

Binder Jetting



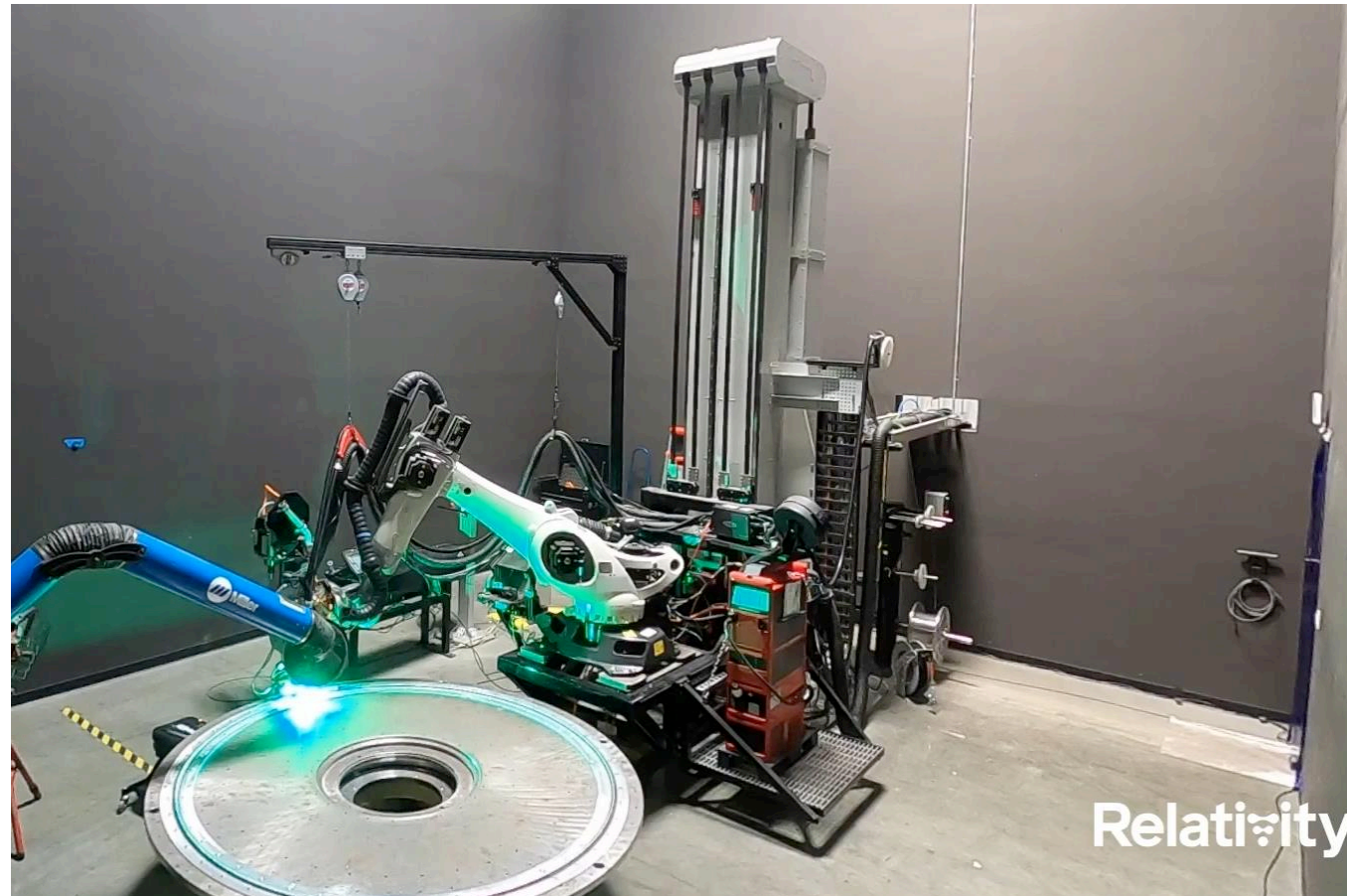
Directed Energy Deposition

- Stronger parts
- Various metals (powder or wire)
- Larger parts
- Repairing
- Coating
- Expensive
- High surface roughness
- High density



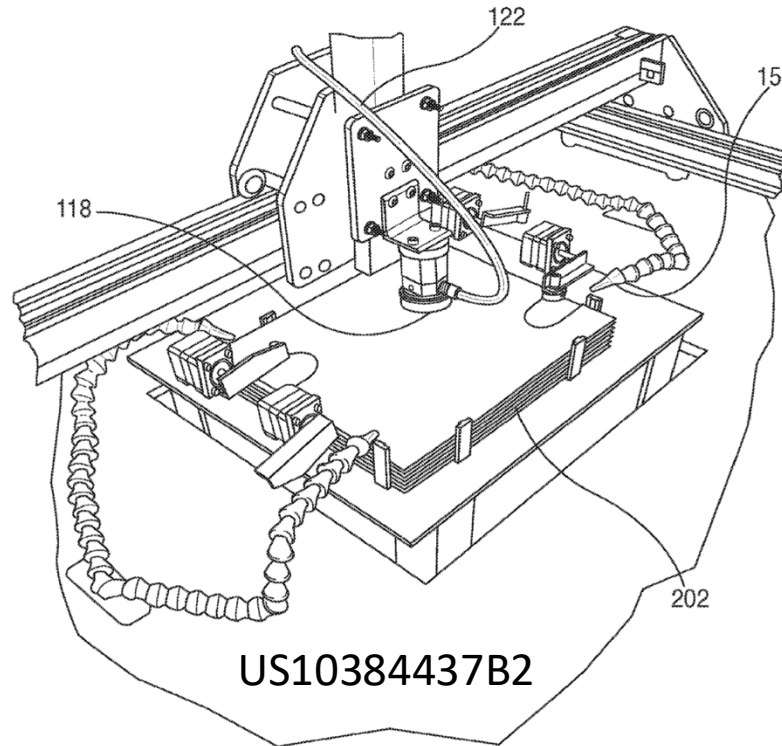
<https://www.3dnatives.com>

Directed Energy Deposition



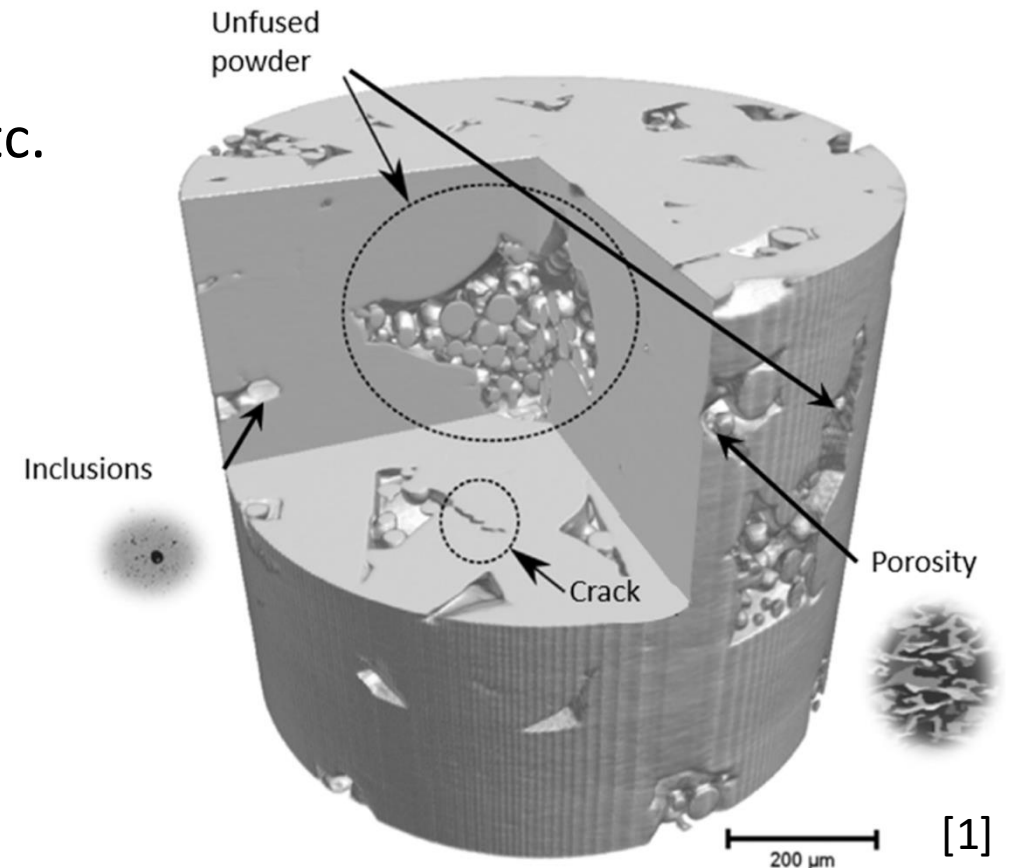
Sheet Lamination

- Sheets of
 - Papers
 - Metals
 - Composites
- Laser, knife, cutting tool
- Fusion between layers
 - Polymers
 - Ultrasonic welding



Defects in Additively Manufactured Parts

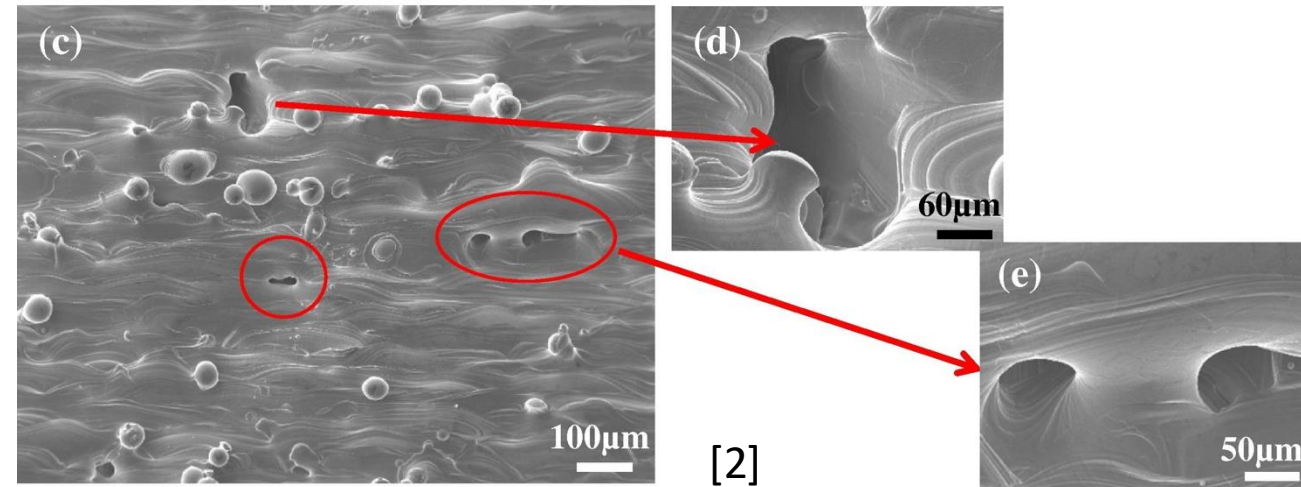
- Variables in Additive Manufacturing
 - Laser power, scan speed, focal diameter, etc.
 - Path planning
 - Support structures
 - Material impurities
- Porosity
- Cracks
- Unfused Powders
- Inclusions



Defects in Additively Manufactured Parts – Porosities



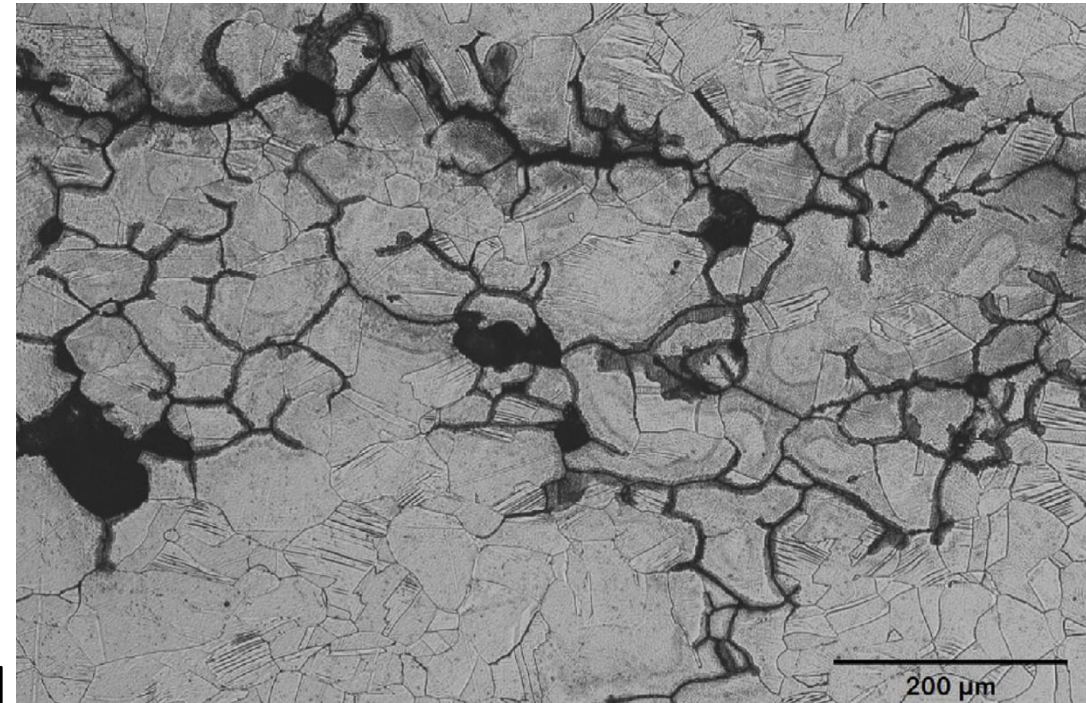
- Defects found in sintering and melting AM processes
 - Insufficient melting
 - Entrapped gases
- Microporosities below powder size
 - Pores inside the source powder
- Manufacturing parameters should be optimized.



Defects in Additively Manufactured Parts – Cracks

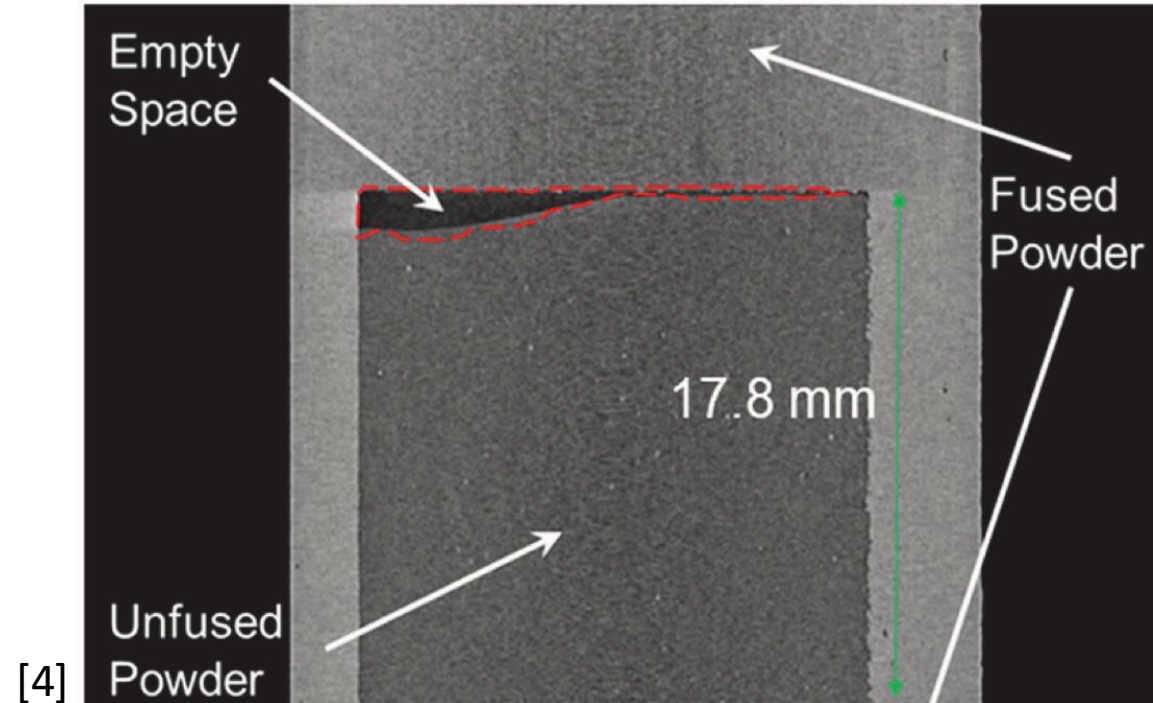
- Residual stresses
 - Melting issues
 - Manufacturing variables
- Removal of support structures
- Stress concentration
 - Maybe eliminated during design

[3]



Defects in Additively Manufactured Parts – Powders

- Structure of the powders directly affects the part.
- Defects in powder manufacturing
- Determination of unfused powders is quite difficult with conventional approaches.
 - Novel non-destructive methods!

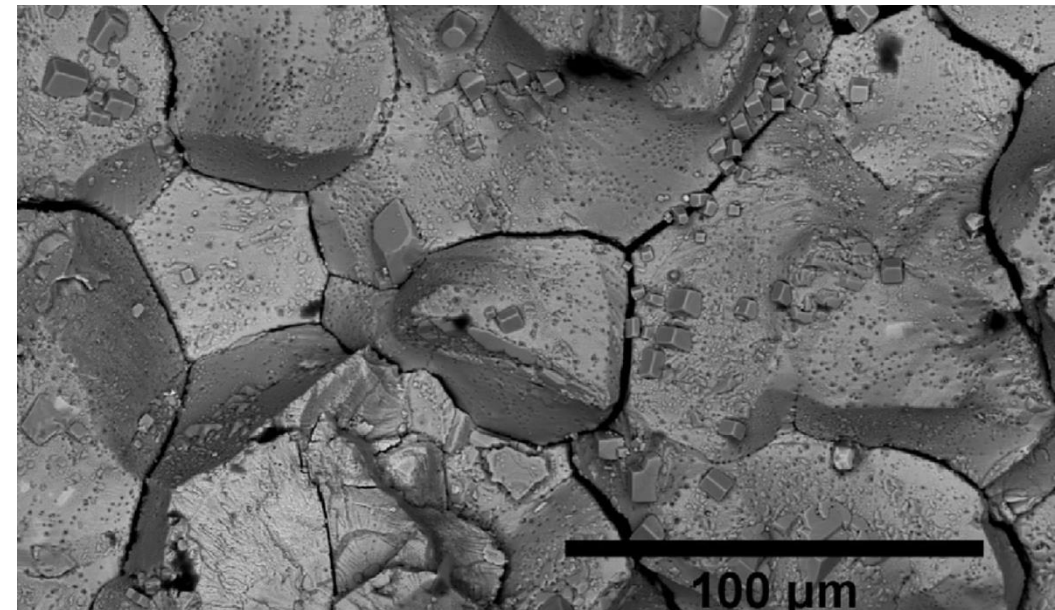


Defects in Additively Manufactured Parts – Inclusions



- Affect the final properties of the manufactured parts.
- Desirable inclusions
 - Improve mechanical properties
- Undesirable inclusions
 - Defects in main material
 - Manufacturing defects
 - Inter metallic forms
 - Novel non-destructive methods!

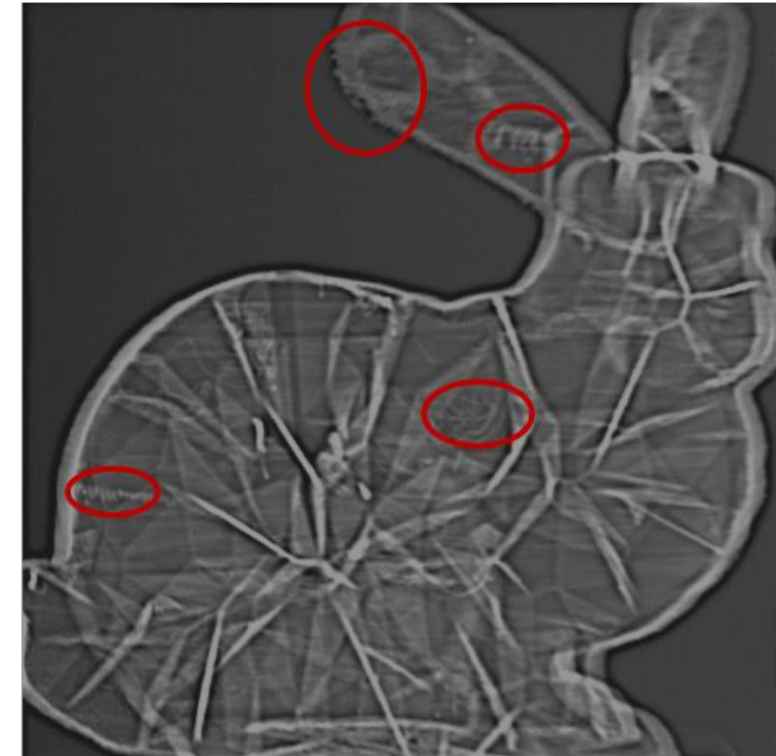
[3]



Evaluations



- Novel NDT approaches for Additive Manufacturing
- Methods for complicated geometries
- Standards for inspection and technologies
 - Acceptance criteria
 - Reference parts
- In-situ inspection
- Qualification and certification



References



- 1) Kim, F. H., et al. "Investigation of pore structure in cobalt chrome additively manufactured parts using X-ray computed tomography and three-dimensional image analysis." *Additive Manufacturing* 17 (2017): 23-38.
- 2) Qiu, Chunlei, et al. "On the role of melt flow into the surface structure and porosity development during selective laser melting." *Acta Materialia* 96 (2015): 72-79.
- 3) Lou, Xiaoyuan, Peter L. Andresen, and Raul B. Rebak. "Oxide inclusions in laser additive manufactured stainless steel and their effects on impact toughness and stress corrosion cracking behavior." *Journal of Nuclear Materials* 499 (2018): 182-190.
- 4) Scott-Emuakpor, Onome, et al. "Determining unfused powder threshold for optimal inherent damping with additive manufacturing." *Additive Manufacturing* 38 (2021): 101739.



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Non-Destructive Testing (NDT) in Additive Manufacturing

*Section 1.1: Introduction to NDT and Regulatory
Standards*

ORCAN KOLANKAYA



Session 1.1 Agenda (90 minutes)

- Part 1: Introduction to NDT in AM (~20 min)
- Part 2: AM Processes and Defects (~15 min)
- Part 3: Standards Overview - Four Categories (~10 min)
- Part 4: Personnel Certification Standards (~15 min)
- Part 5: Method-Specific Standards (~5 min)
- Part 6: AM-Specific NDT Standards (~15 min)
- Part 7: Industry-Specific Standards (~10 min)





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Part 1

Introduction to NDT in Additive Manufacturing



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What is Non-Destructive Testing (NDT)?

- Examination methods that do not damage the test object
- Evaluates properties without affecting future usefulness
- Also known as:
 - NDE - Non-Destructive Evaluation
 - NDI - Non-Destructive Inspection
 - NDEx - Non-Destructive Examination
- Enables 100% inspection of production parts
- Essential for quality assurance in safety-critical industries



NDT Methods - Overview



Surface Methods

- Visual Testing (VT)
- Penetrant Testing (PT/FPI)
- Magnetic Particle Testing (MT)
- Eddy Current Testing (ET)
- Detect surface-breaking defects

Volumetric Methods

- Ultrasonic Testing (UT/PAUT/TOFD)
- Radiographic Testing (RT)
- Computed Tomography (CT)
- Infrared Thermography (IRT)
- Detect internal defects

Why NDT in Aerospace & Defence?

- Safety-critical applications - failure is not an option
- Regulatory requirements mandate inspection
- High-value components - destructive testing not economical
- In-service inspection requirements
- Traceability and documentation requirements
- Quality assurance throughout product lifecycle



Why is NDT Critical for Additive Manufacturing?

- AM introduces unique defect types not found in traditional manufacturing
- Complex internal geometries are difficult to access
- Layer-by-layer process creates potential for internal flaws
- Material properties can vary within a single part
- Limited process history compared to conventional methods
- Qualification and certification requirements still evolving



Limited Process History of AM



Conventional manufacturing (casting, forging, machining) has decades of accumulated data:

- Well-documented failure modes and defect types
- Established statistical databases on material behavior
- Proven acceptance criteria based on historical performance
- Known correlations between process parameters and outcomes
- Mature process controls validated over many production cycles

Additive Manufacturing lacks this historical foundation:

- Relatively new technology (industrial metal AM ~15-20 years)
- Fewer parts in service, less field data on long-term performance
- Process-property relationships still being characterized
- Limited statistical data for reliability predictions
- Acceptance criteria often borrowed from casting/welding standards (may not be fully appropriate)

Why this makes NDT critical:

Without extensive process history, manufacturers cannot rely on statistical confidence alone to guarantee part quality. NDT compensates for this uncertainty by:

1. Direct verification - Each part is inspected rather than relying on process statistics
2. Building the knowledge base - NDT findings contribute to understanding AM-specific defect populations
3. Risk mitigation - Until process history matures, inspection provides safety assurance
4. Qualification support - NDT data helps establish the process history that AM currently lacks

Essentially, NDT fills the confidence gap that decades of experience provide for conventional methods.

NDT Challenges Specific to AM

- Surface roughness interferes with contact methods (PT, UT)
- Complex geometries limit accessibility for inspection
- Anisotropic microstructure affects ultrasonic propagation
- New defect types require new acceptance criteria
- Lack of standardized reference specimens
- In-process vs post-process inspection decisions
- Cost-benefit of inspection vs. part value



Destructive vs Non-Destructive Testing



Destructive Testing (DT)

- Destroys or alters specimen
- Tensile, hardness, fatigue testing
- Metallographic examination
- Provides direct material properties
- Statistical sampling only
- Cannot inspect production parts

Non-Destructive Testing (NDT)

- Preserves the test object
- Can test 100% of production
- Repeatable inspections
- In-service inspection possible
- Multiple methods available
- Requires correlation to DT results



DT and NDT: Complementary Approaches

- DT establishes baseline material properties
- NDT verifies production quality against baseline
- AM qualification typically requires both:
 - Witness specimens tested destructively
 - Production parts inspected non-destructively
 - Statistical process control links both approaches
- NDT cannot replace DT for material characterization
- DT cannot provide 100% production inspection



Purpose of the Witness Specimens



Witness specimens are tested destructively to establish and verify material properties alongside production parts. They serve as a bridge between DT and NDT in AM qualification:

- 1. Baseline validation** - Witness specimens (built alongside production parts using the same process parameters) are destroyed through tensile, hardness, fatigue, or metallographic testing to confirm the material properties of that specific build
- 2. Process verification** - Since you cannot destructively test actual production parts, witness specimens provide evidence that the build achieved the expected material characteristics
- 3. Statistical process control** - The results from witness specimens link destructive test data to the non-destructive inspection performed on production parts, enabling correlation between NDT indications and actual material quality



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Part 2

AM Processes and Typical Defects



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Metal AM Process Categories



Powder Bed Fusion (PBF)

- Laser PBF (L-PBF/SLM/DMLS)
- Electron Beam PBF (EB-PBF/EBM)
- Fine features, high resolution
- Limited build size
- Powder management critical

Directed Energy Deposition (DED)

- Laser DED (LENS, LMD)
- Electron Beam DED (EBAM)
- Wire Arc AM (WAAM)
- Larger build volumes
- Higher deposition rates
- Lower resolution



Powder Bed Fusion (PBF) - Process Details

- Thin layer of powder spread across build platform
- Energy source (laser/e-beam) selectively melts powder
- Platform lowers, new powder layer applied
- Process repeats layer-by-layer
- Typical layer thickness: 20-100 μm
- Build environment: Inert gas (L-PBF) or vacuum (EB-PBF)



Directed Energy Deposition (DED) - Process Details

- Material fed directly into melt pool
- Feedstock: Powder or wire
- Energy source creates melt pool on substrate
- Material added and solidifies
- Can build on existing parts (repair applications)
- Higher deposition rates, lower resolution than PBF



AM Defects: Porosity

- Gas Porosity:
 - Spherical voids from trapped gas
 - Caused by dissolved gases in powder or atmosphere
 - Typically small ($<100\ \mu\text{m}$)
- Keyhole Porosity:
 - Irregular shaped voids
 - Caused by excessive energy density
 - Deep, unstable melt pool collapses
- Lack of Fusion (LOF) Porosity:
 - Irregular, elongated voids between layers
 - Caused by insufficient energy/overlap
 - Most critical defect type for mechanical properties
- Detection: CT (most effective), RT, UT



AM Defects: Cracks and Delamination

- Hot Cracking (Solidification Cracking):
 - Occurs during solidification
 - Related to alloy composition and thermal gradients
- Cold Cracking:
 - Occurs after solidification
 - Related to residual stress and hydrogen
- Delamination:
 - Separation between layers
 - Caused by insufficient bonding or residual stress
- Detection: PT, MT (surface), UT, CT (internal)



AM Defects: Other Types

- Inclusions - Foreign particles trapped in material (oxides etc.)
- Surface roughness - Inherent to layer-by-layer process
- Dimensional inaccuracies - Shrinkage, warping, distortion
- Residual stress - Can cause cracking or distortion
- Contamination - Powder cross-contamination, oxidation
- Support structure remnants - Incomplete removal



Defect Detection Method Summary



Defect Type

- Surface porosity → PT, VT
- Internal porosity → CT, RT, UT
- Surface cracks → PT, MT, ET
- Internal cracks → UT, CT
- Lack of fusion → CT, UT
- Inclusions → CT, RT

Considerations

- Surface finish affects PT/MT
- CT best for complex geometry
- UT challenging for rough surfaces
- RT limited by geometry
- Method selection per standard
- Often multiple methods required



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Part 3

Standards Overview (in four Categories)



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Learning Objectives

- Understand the fundamentals of AM and its applications in aerospace/defence
- Comprehend how regulatory standards apply to NDT
- Learn the importance of NDT for safety-critical compliance
- Identify the four categories of NDT standards
- Know the key requirements of each standard
- Understand relationships between different standards



Why Standards Matter in NDT for AM

- Ensure consistent inspection quality worldwide
- Define minimum competency requirements for personnel
- Establish procedures and acceptance criteria
- Enable mutual recognition between organizations
- Support regulatory compliance (EASA, FAA, etc.)
- Facilitate supply chain qualification
- Reduce liability and ensure traceability



What are EASA, FAA, etc.?

These are government regulatory agencies that oversee aviation and aerospace safety. They have legal authority to certify aircraft, components, and the organizations that manufacture them.

FAA - Federal Aviation Administration

- Country: United States
- Role: Regulates all aspects of civil aviation in the US
- Relevance to NDT/AM:
 - Issues airworthiness certificates for aircraft and components
 - Approves manufacturing processes including AM
 - Requires NDT for safety-critical parts
 - References standards like NAS 410 for personnel certification

EASA - European Union Aviation Safety Agency

- Region: European Union
- Role: EU-wide aviation safety authority (similar to FAA)
- Relevance to NDT/AM:
 - Certifies aircraft and components for European market
 - Approves Design Organizations (DOA) and Production Organizations (POA)
 - Requires compliance with EN standards (EN 4179, etc.)
 - Mutual recognition agreements with FAA

For Space/Defence:

- NASA - National Aeronautics and Space Administration (US)
- ESA - European Space Agency
- DoD - US Department of Defense (military specifications)

Why Standards Support Regulatory Compliance? Regulatory agencies do not write detailed NDT procedures themselves. Instead, they:

1. Reference industry standards - FAA/EASA accept ISO 9712, NAS 410, EN 4179 as proof of personnel competence
2. Require certified processes - NADCAP accreditation demonstrates compliance
3. Mandate traceability - Standards provide the framework for documentation
4. Enable approval - Following recognized standards simplifies the certification process



NDT Standards - Four Categories

- 1. Personnel Certification Standards
 - WHO can perform NDT - qualification and certification
- 2. Method-Specific Standards
 - HOW to perform NDT - procedures and techniques
- 3. AM-Specific NDT Standards
 - NDT specifically FOR additive manufacturing
- 4. Industry-Specific Standards
 - REQUIREMENTS for aerospace, space, defence applications



How Standards Work Together

- Personnel standards ensure qualified inspectors
- Method standards define how to inspect
- AM standards address unique AM challenges
- Industry standards set acceptance requirements
- Example workflow:
 - Certified inspector (ISO 9712/EN 4179)
 - Following procedure (EN ISO 17635)
 - Using AM-specific guidance (ISO/ASTM 52905)
 - Meeting industry requirements (NASA-STD-5009)





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Category 1

Personnel Certification Standards (Who Can Perform NDT?)



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Personnel Certification - Why It Matters

- NDT results depend heavily on operator skill
- Certification ensures minimum competency
- Three-level system widely adopted:
 - Level 1: Perform tests under supervision
 - Level 2: Independent testing and reporting (accept/reject)
 - Level 3: Full technical responsibility, method development
- Certification requires training + experience + examination
- Periodic recertification required



ISO 9712:2021 - International Standard

- Full title: Qualification and certification of NDT personnel
- International baseline for personnel certification
- Applies to manufacturing, in-service, and all industrial sectors
- Covers all major NDT methods:
 - AT, ET, LT, MT, PT, RT, TT, UT, VT
 - Plus method-specific techniques (RT-Digital, RT-Film etc.)
- Third-party certification (independent certification bodies)



ISO 9712:2021 - Certification Levels



- Level 1:
 - Set up equipment per written instructions
 - Perform tests and record results
 - Report results per written criteria
 - Cannot interpret or evaluate results independently
- Level 2:
 - Select technique for the test method
 - Set up and verify equipment settings
 - Perform and supervise tests
 - Interpret and evaluate results per standards
 - Prepare written NDT instructions
 - Supervise Level 1 personnel
- Level 3:
 - Assume full responsibility for testing facility
 - Establish and validate techniques and procedures
 - Interpret standards, codes, and specifications
 - Designate methods, techniques, and procedures
 - Train and examine Level 1 and 2 personnel

ISO 9712:2021 - Certification Requirements



- Training hours (minimum per method):
 - Level 1: 40 hours | Level 2: 80 hours | Level 3: 40 hours additional
- Experience (months working under supervision):
 - Level 1: 3-12 months | Level 2: 9-24 months | Level 3: 24-48 months
- Examination: General, specific, practical
- Vision requirements: Near vision acuity, colour perception
- Validity: 5 years, with annual confirmation
- Recertification: Every 5 years (re-examination or continuous)

NAS 410 - Aerospace NDT Personnel (US)



- National Aerospace Standard by AIA (Aerospace Industries Association)
- Current revision: NAS 410 Rev 5
- Employer-based certification (Written Practice required)
- Specifically for aerospace manufacturing and maintenance
- Technically equivalent to EN 4179
- Accepted by major aerospace OEMs worldwide

OEM stands for Original Equipment Manufacturer. In the aerospace context, this refers to the major aircraft and aerospace equipment manufacturers such as:

- Aircraft manufacturers: Boeing, Airbus, Lockheed Martin, Northrop Grumman, Bombardier, Embraer
- Engine manufacturers: GE Aviation, Pratt & Whitney, Rolls-Royce, Safran
- Other aerospace system manufacturers: Honeywell, Collins Aerospace, etc

NAS 410 - Personnel Levels

- Trainee: Under direct supervision, no independent testing
- Level 1 Limited: Specific tasks only, limited scope
- Level 1: Perform calibration, testing per approved data
- Level 2: Set up, interpret, evaluate, train Level 1
- Level 3: Responsible for NDT operations, develop procedures
- Auditor Level 3: Additional audit qualifications



NAS 410 - NDT Methods Covered

- Eddy Current Testing (ET)
- Magnetic Particle Testing (MT)
- Liquid Penetrant Testing (PT)
- Radiographic Testing including CT (Computed Tomography) (RT)
- Ultrasonic Testing including PAUT (UT)
- Additional: Infrared Thermography (IR), Shearography (SH)
- Leak Testing (LT), Visual Testing (VT)



NAS 410 - Written Practice

- Employer must establish a Written Practice document
- Defines company's NDT personnel program
- Must address:
 - Organizational structure and responsibilities
 - Training requirements and records
 - Experience requirements
 - Examination requirements (general, specific, practical)
 - Certification and recertification procedures
 - Vision requirements and testing frequency
- Written Practice subject to customer/NADCAP audit



What is NADCAP? (USA)

NADCAP stands for National Aerospace and Defense Contractors Accreditation Program. It is:

- An industry-managed accreditation program for aerospace and defense suppliers
- Administered by the Performance Review Institute (PRI, USA)
- A standardized approach for aerospace companies to audit and approve their suppliers' special processes, including NDT (Non-Destructive Testing)



EN 4179:2021 - Aerospace Series (Europe)

- European standard for aerospace NDT personnel
- Full title: Qualification and approval of personnel for NDT
- Harmonized with NAS 410 - mutual recognition
- Published by CEN (European Committee for Standardization)
- Adopted as national standard in EU member states
- Required for aerospace suppliers in Europe



EN 4179:2021 - Key Features

- Employer-based qualification (Written Practice required)
- Same level structure as NAS 410
- Recognition of outside agency certifications (ISO 9712 certificate holders)
- Prime contractor can extend certification to suppliers (NDT personnel at the small supplier are certified by the prime contractor, not by the supplier themselves)
- NADCAP accreditation demonstrates compliance
(NADCAP serves as the third-party audit mechanism that verifies whether aerospace suppliers properly implement their Written Practice documents and comply with NAS 410/EN 4179 requirements for NDT personnel certification.)
- Specific requirements for limited certifications



EN 4179 vs NAS 410 Comparison



EN 4179:2021

- European aerospace standard
- CEN (European Committee for Standardization) publication
- Employer-based certification
- Same technical requirements
- Required in EU supply chain
- NADCAP accepted

NAS 410

- US aerospace standard
- AIA publication
- Employer-based certification
- Same technical requirements
- Required in US supply chain
- NADCAP accepted



EN 473:2008 - Historical Reference

- Former European standard for NDT personnel certification
- Superseded by EN ISO 9712 (adoption of ISO 9712)
- Was third-party certification (like ISO 9712)
- Important for understanding legacy certifications
- Some personnel still hold EN 473 certificates
- Transition: EN 473 certificates recognized until expiry



Personnel Certification Standards Summary



Third-Party Certification

- ISO 9712:2021
- Independent certification body
- International recognition
- General industry use
- Transferable between employers
- Audit by third party

Employer-Based Certification

- NAS 410 / EN 4179
- Company Written Practice
- Aerospace-specific
- NADCAP audited
- Employer controls certification

Comparison of All



	NAS 410 / EN 4179	ISO 9712
Certification type	Employer-based	Third-party (e.g METU PSM)
Requirements set by	Employer's Written Practice*	Certification body (e.g METU PSM)
Transferability	Limited (employer-specific)	Transferable between employers
Oversight	Customer/NADCAP audits	Third Party Accreditation body (e.g TURKAK)

* NAS 410 sets minimum requirements that employers must meet or exceed



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Category 2

Method-Specific Standards (How to Perform NDT ?)



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Method-Specific Standards - Overview

- Define HOW to perform NDT methods
- Cover equipment, procedures, reporting
- Provide guidance on method selection
- Reference acceptance criteria from other standards
- EN ISO 17635 is key for method selection guidance
- Individual method standards exist for each NDT method



EN ISO 17635 - NDT of Welds

- Full title: Non-destructive testing of welds - General rules for metallic materials
- Provides guidelines for selecting NDT methods
- Originally for welding, but principles apply to AM
- AM involves similar fusion/melting processes
- Key reference for method selection decisions



EN ISO 17635 - Method Selection Criteria

- Factors to consider when selecting NDT method:
 - Type of defect expected (surface vs volumetric)
 - Material type and thickness
 - Joint configuration and accessibility
 - Required detection sensitivity
 - Production stage (pre-weld, during, post-weld)
- Standard provides selection tables based on:
 - Quality level required (ISO 5817)
 - Joint type and geometry
 - Defect type of concern
- Recommends combination of methods for complete coverage



EN ISO 17635 - Surface Inspection Methods

- Visual Testing (VT) - Always the first method
- Penetrant Testing (PT):
 - For non-ferromagnetic materials
 - Open surface discontinuities only
 - Requires clean, relatively smooth surface
- Magnetic Particle Testing (MT):
 - For ferromagnetic materials only
 - Surface and near-surface defects
 - Can work through thin coatings
- Selection based on material type and defect sensitivity required



EN ISO 17635 - Volumetric Inspection Methods



- Radiographic Testing (RT):
 - Good for volumetric defects (porosity, inclusions)
 - Less sensitive to planar defects parallel to beam
 - Provides permanent record
 - Safety considerations (radiation)
- Ultrasonic Testing (UT):
 - Good for planar defects (cracks, lack of fusion)
 - Can determine defect depth and size
 - Contact or immersion coupling required
 - Operator skill dependent
- Selection based on defect orientation and geometry

EN ISO 17635 - Relevance to AM

- AM has similar fusion characteristics to welding
- Method selection principles directly applicable
- Additional AM considerations:
 - Surface roughness affects PT and contact UT
 - Complex geometries limit RT and UT access
 - Internal channels may require CT (Tomography)
 - Layer-by-layer defects similar to lack of fusion
- Standard being referenced in AM-specific standards





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Category 3

AM-Specific NDT Standards NDT for Additive Manufacturing



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AM-Specific NDT Standards - Overview

- Developed specifically for AM inspection challenges
- Published by ISO/ASTM joint committee (ISO TC 261 / ASTM F42)
- Address gaps not covered by traditional NDT standards
- Standards categories:
 - Defect detection methods
 - Intentional flaw seeding for validation
 - Imperfection classification
- Several still in development (DIS = Draft International Standard)



ISO/ASTM 52905:2023 - Defect Detection

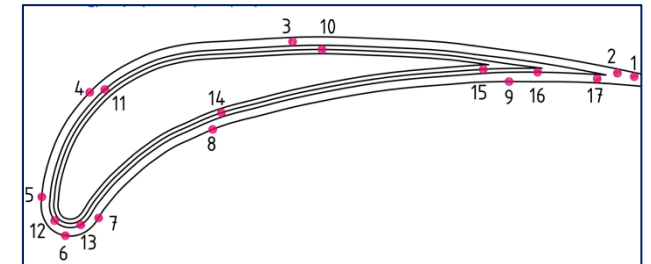
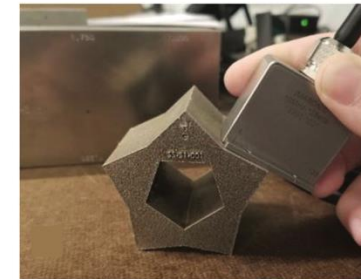
- Full title: AM of metals - NDE - Defect detection in parts
- Technical Report (TR) providing guidance
- Comprehensive review of NDT methods for metal AM
- Evaluates existing welding/casting standards for AM
- Proposes systematic approach to AM inspection
- Key reference for AM NDT implementation



ISO/ASTM 52905 - Two-Level NDT Approach



- Level 1: Initial Quality Indicator (IQI)
 - Use 'Star artefact' or similar reference part
 - Verifies process capability
 - Quick check of overall quality
 - Go/no-go for further inspection
- Level 2: A la carte approach (*Parçanın gerçek Geometrisine Sahip Tasarım*)
 - Targeted inspection for specific defect types
 - Based on process risk assessment
 - Select methods based on expected defects
 - More detailed characterization
- This two-level approach optimizes inspection effort
- Standard provides guidance on method selection for each level



ISO/ASTM 52905 - NDT Methods Evaluated

- Computed Tomography (CT) - Highest potential for AM
- Ultrasonic Testing (UT/PAUT) - Good for planar defects
- Radiographic Testing (RT) - Established, limitations noted
- Penetrant Testing (PT) - Surface only, roughness issues
- Eddy Current Testing (ET) - Surface/near-surface
- Visual Testing (VT) - Always applicable
- Other: Thermography, Resonance Testing



ISO/ASTM 52905 - Why CT is Emphasized?

- CT provides complete 3D volumetric data
- Can inspect complex internal geometries
- Dimensional verification against CAD
- Defect location, size, and distribution
- Limitations addressed in standard:
 - Part size vs resolution tradeoff
 - The Core Problem:
 - CT scanners have detectors with a fixed number of pixels (e.g., 2000×2000)
 - The voxel (3D pixel) size = Part diameter ÷ Number of pixels
 - Larger parts = larger voxels = lower resolution = smaller defects become invisible
 - Scan time and cost
 - Material density limitations
 - Artefacts from high-density materials (excessive exposure, scattering etc.)
- CT often the 'gold standard' for AM part qualification



ISO/ASTM 52906:2022 - Intentionally Seeding Flaws

- Full title: AM - NDE - Intentionally seeding flaws in metallic parts
- Guidance for creating test specimens with known defects
- Purpose: Validate NDT method capabilities
- Critical for establishing detection limits
- Supports POD (Probability of Detection) studies



ISO/ASTM 52906 - Flaw Seeding Approaches

- CAD-based seeding:
 - Design defects directly into CAD geometry
 - Known size, shape, location
 - Repeatable for reference specimens
- Process manipulation:
 - Alter process parameters to create defects
 - e.g., reduce power, increase speed, skip layers
 - Creates 'natural' defect morphology
 - Less precise control of defect characteristics
- Mechanical introduction:
 - Post-process introduction of flaws
 - e.g., drilling holes, EDM notches
 - Known geometry but artificial morphology
- Standard provides guidance on each approach



ISO/ASTM 52906 - Applications

- Develop and validate NDT procedures for AM
- Establish minimum detectable flaw size
- Create reference standards for equipment calibration
- Support POD studies for critical applications
- Compare NDT method capabilities
- Train inspectors on AM-specific defect appearances



ASTM E3166 - NDE of Metal AM Aerospace Parts

- Standard Guide for post-build NDE of AM aerospace parts
- Published by ASTM Committee E07 on NDT
- Covers multiple NDT methods:
 - Computed Tomography (CT)
 - Penetrant Testing (PT)
 - Eddy Current Testing (ET)
 - Optical Metrology
 - Radiographic Testing (RT)
 - Infrared Thermography (IRT)
 - Ultrasonic Testing (UT)
- Materials: Al, Ti, Ni-based, Co-Cr, stainless steels
- Processes: PBF and DED



ASTM E3166 - Key Points

- Addresses parts in different states:
 - As-built (no post-processing)
 - Intermediately machined
 - Fully finished
- Does NOT recommend specific accept-reject criteria!
- References existing ASTM NDT standards
- Considers surface condition effects on inspection
- Provides method-specific guidance for AM parts



ISO/ASTM DIS 52948 - Imperfections in PBF

- Draft International Standard (under development)
- Full title: AM of metals - NDE - Imperfection classification in PBF parts
- Covers both laser and electron beam PBF:
 - L-PBF (Laser Powder Bed Fusion)
 - EB-PBF (Electron Beam Powder Bed Fusion)
- Provides systematic defect classification
- Includes visual and metallographic illustrations



ISO/ASTM 52948 - Imperfection Categories

- Cracks - Hot cracking, cold cracking, delamination
- Porosity - Gas porosity, keyhole porosity
- Lack of Fusion - Between layers, between tracks
- Inclusions - Oxide, carbide, foreign material
- Surface imperfections - Roughness, balling, spatter
- Shape/dimensional - Warping, shrinkage, distortion
- Classification based on formation mechanism and appearance



ISO/ASTM DIS 52969 - Imperfections in DED

- Draft International Standard (under development)
- Full title: AM of metals - NDE - Classification of imperfections in DED parts
- Complements ISO/ASTM 52948 for DED processes
- Covers various DED variants:
 - Laser DED (powder and wire feed)
 - Electron Beam DED
 - Wire Arc AM (WAAM)
- Classification based on formation mechanisms



ISO/ASTM 52969 - DED-Specific Considerations

- DED has different defect characteristics than PBF:
 - Larger melt pool, different thermal history
 - Wire feed: different porosity mechanisms
 - Larger layer heights, coarser features
 - Interface defects in repair applications
 - Substrate/deposit interface issues
- Standard addresses DED-specific defect morphology
- Important for selecting appropriate NDT methods



AM-Specific Standards Summary



Published Standards

- ISO/ASTM 52905:2023
 - Defect detection guidance
- ISO/ASTM 52906:2022
 - Intentional flaw seeding
- ASTM E3166
 - Aerospace AM inspection guide

Draft Standards

- ISO/ASTM DIS 52948
 - PBF imperfection classification
- ISO/ASTM DIS 52969
 - DED imperfection classification
- (Under ISO TC 261 / ASTM F42)



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Category 4

Industry-Specific Standards Aerospace, Space, Defence



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Industry-Specific Standards - Overview

- Set requirements for specific sectors/applications
- Define acceptance criteria for safety-critical parts
- Often more stringent than general standards
- May require specific NDT methods/coverage
- Three key sources covered here:
 - NASA - US space and aerospace
 - ECSS - European space applications
 - Other: MIL-STD, customer specifications
- These define WHAT must be achieved with NDT



NASA-STD-5009B - NDE Requirements

- Full title: NDE Requirements for Fracture-Critical Metallic Components
- Current revision: 2019 (Rev B)
- Applies to NASA human-rated spaceflight hardware
- Supports fracture control program (NASA-STD-5019A)
- Defines minimum NDE requirements for safety-critical parts
- Contains 96 verifiable requirements



NASA-STD-5009B - NDE Requirements



These requirements typically cover areas such as:

- NDE method selection criteria
- Personnel qualification requirements
- Minimum detectable flaw sizes for each method
- Procedure documentation requirements
- Equipment calibration standards
- Probability of Detection (POD) requirements
- Traceability and record-keeping

When a contractor or supplier works on NASA fracture-critical hardware, they must demonstrate compliance with each of these 96 requirements (NER1-NER96) through a verification matrix or compliance checklist. This structured approach ensures nothing is missed and provides clear audit trails for safety-critical spaceflight components.

NASA-STD-5009B - Applicability

- Applies to fracture-critical metallic components
- Materials covered:
 - Aluminum alloys
 - Steels
 - Titanium alloys
 - Nickel-based superalloys
- Component categories:
 - Structural components
 - Pressure vessels and lines
 - Rotating machinery
 - Mechanisms
- Verification of compliance required for all 96 requirements
(objective evidence that demonstrates you have met the requirement)
E.g NER 3 - Inspections by certified personnel -> Review personnel certification records against NAS 41



NASA-STD-5009B - Standard vs Special NDE



- Standard NDE:
 - Established methods with documented capabilities
 - PT, MT, ET, UT, RT per defined procedures
 - Known Probability of Detection (POD)
 - Minimum detectable flaw sizes specified
- Special NDE:
 - When Standard NDE is insufficient
 - Enhanced procedures required
 - Must demonstrate adequate detection capability
 - Requires engineering approval
- Selection based on criticality and inspection capability

NASA-STD-5009B - Detection Requirements

- Specifies minimum detectable crack sizes by method:
 - PT: 0.125 inch surface crack (typical)
 - ET: Varies by setup and material
 - UT: Flaw size related to reference reflector (ERS)
 - RT: Based on image quality indicators
- POD (Probability of Detection) requirements
- Typically 90% POD at 95% confidence for critical flaws
- Different requirements for different material/method combinations



NASA/TM-2014-218560 - NDE of AM Report

- Technical Memorandum: State-of-the-Discipline Report
- Published November 2014
- Multi-center NASA effort (MSFC, LaRC, GRC)
- Comprehensive review of NDE for AM at that time
- Identified gaps and needs for AM inspection
- Foundation for subsequent standards development



NASA/TM-2014-218560 - Key Findings



- Identified critical gaps in NDE for AM:
 - Critical defects not fully characterized
 - Lack of physical reference standards
 - Inspection procedures not established
 - In-process monitoring needs definition
 - Accept/reject criteria undefined
- Recommended developments:
 - Develop AM-specific reference standards
 - Establish POD data for AM defects
 - Create inspection procedures for complex geometries
 - Develop in-process monitoring capabilities
- Report influenced subsequent AM-NDE standards

EN 16602-70-15:2021 (ECSS) - Space Product Assurance

- European Cooperation for Space Standardization (ECSS)
- Full title: Space product assurance - Non-destructive testing
- Comprehensive NDT standard for space projects
- Applies to ESA and European space industry
- Covers both metallic and composite materials
- Personnel certification per ISO 9712 or EN 4179



EN 16602-70-15 - NDT Methods Covered

- Visual Testing (VT)
- Leak Testing (LT)
- Penetrant Testing (PT)
- Eddy Current Testing (ET)
- Magnetic Particle Testing (MT)
- Radiographic Testing (RT) including CT
- Ultrasonic Testing (UT)
- Proof Testing



EN 16602-70-15 - Key Requirements

- NDT procedures must be qualified
- Personnel must be certified (ISO 9712 or EN 4179)
- Equipment calibration and verification required
- Traceability of all inspection records
- Specific requirements for flight hardware
- Defines inspection levels based on criticality



Industry Standards Summary



NASA Standards

- NASA-STD-5009B
 - Fracture-critical components
 - Defines detection requirements
- NASA/TM-2014-218560
 - State-of-discipline report
 - Identified AM-NDE gaps

ECSS Standard

- EN 16602-70-15:2021
 - Space product assurance
 - All NDT methods covered
 - European space applications
 - Personnel per ISO 9712/EN 4179



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Summary

Key Takeaways

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Standards Categories - Summary

- 1. Personnel Certification - Who can perform NDT
 - ISO 9712 (international), NAS 410/EN 4179 (aerospace)
- 2. Method-Specific - How to perform NDT
 - EN ISO 17635 (method selection for welds)
- 3. AM-Specific - NDT for additive manufacturing
 - ISO/ASTM 52905, 52906, ASTM E3166, DIS 52948, DIS 52969
- 4. Industry-Specific - Aerospace, space, defence requirements
 - NASA-STD-5009B, NASA/TM, EN 16602-70-15 (ECSS)



Standards Quick Reference



Personnel Certification

- ISO 9712:2021 - International
- NAS 410 - Aerospace (US)
- EN 4179:2021 - Aerospace (EU)
- EN 473:2008 - Legacy

AM & Industry Specific

- ISO/ASTM 52905 - Defect detection
- ISO/ASTM 52906 - Flaw seeding
- ASTM E3166 - AM aerospace
- NASA-STD-5009B - Fracture-critical

Key Messages

- NDT is essential for AM part qualification
- Standards ensure consistent quality and safety
- Personnel certification ensures competent inspectors
- AM-specific standards address unique challenges
- CT is the 'gold standard' for AM internal inspection
- Standards continue to evolve with AM technology
- Compliance with standards supports regulatory approval



Looking Ahead - Next Sessions

- Section 1.2: NDT Methods in Detail (2.5 hours)
 - Individual method principles and applications
 - Equipment and procedures
 - Advantages and limitations for AM
- Section 1.3: Inspection Strategies (1.5 hours)
 - Post-build vs in-process inspection
 - Method selection strategies
- Section 1.4: Case Studies (1.5 hours)
 - Real-world NDT applications
 - Problem-solving exercises
- Total course: 7 contact hours
- Build on standards knowledge with practical application



References (1/2)

- ISO 9712:2021 - Qualification and certification of NDT personnel
- NAS 410 Rev 5 - NDT Personnel Certification
- EN 4179:2021 - Aerospace series - NDT personnel qualification
- EN 473:2008 - NDT Personnel qualification (superseded)
- EN ISO 17635 - NDT of welds - General rules
- ISO/ASTM 52905:2023 - AM - NDE - Defect detection
- ISO/ASTM 52906:2022 - AM - NDE - Intentionally seeding flaws



References (2/2)

- ASTM E3166 - NDE of Metal AM Aerospace Parts
- ISO/ASTM DIS 52948 - Imperfections in PBF parts
- ISO/ASTM DIS 52969 - Imperfections in DED parts
- NASA-STD-5009B - NDE for Fracture-Critical Components
- NASA/TM-2014-218560 - NDE of AM State-of-Discipline Report
- EN 16602-70-15:2021 - Space product assurance - NDT





Thank You

Section 1.1: Introduction to NDT and Standards

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NON-DESTRUCTIVE TESTING METHODS

Dr. Tuğçe KALELİ ALAY



WHAT IS NON-DESTRUCTIVE TESTING (NDT) ?



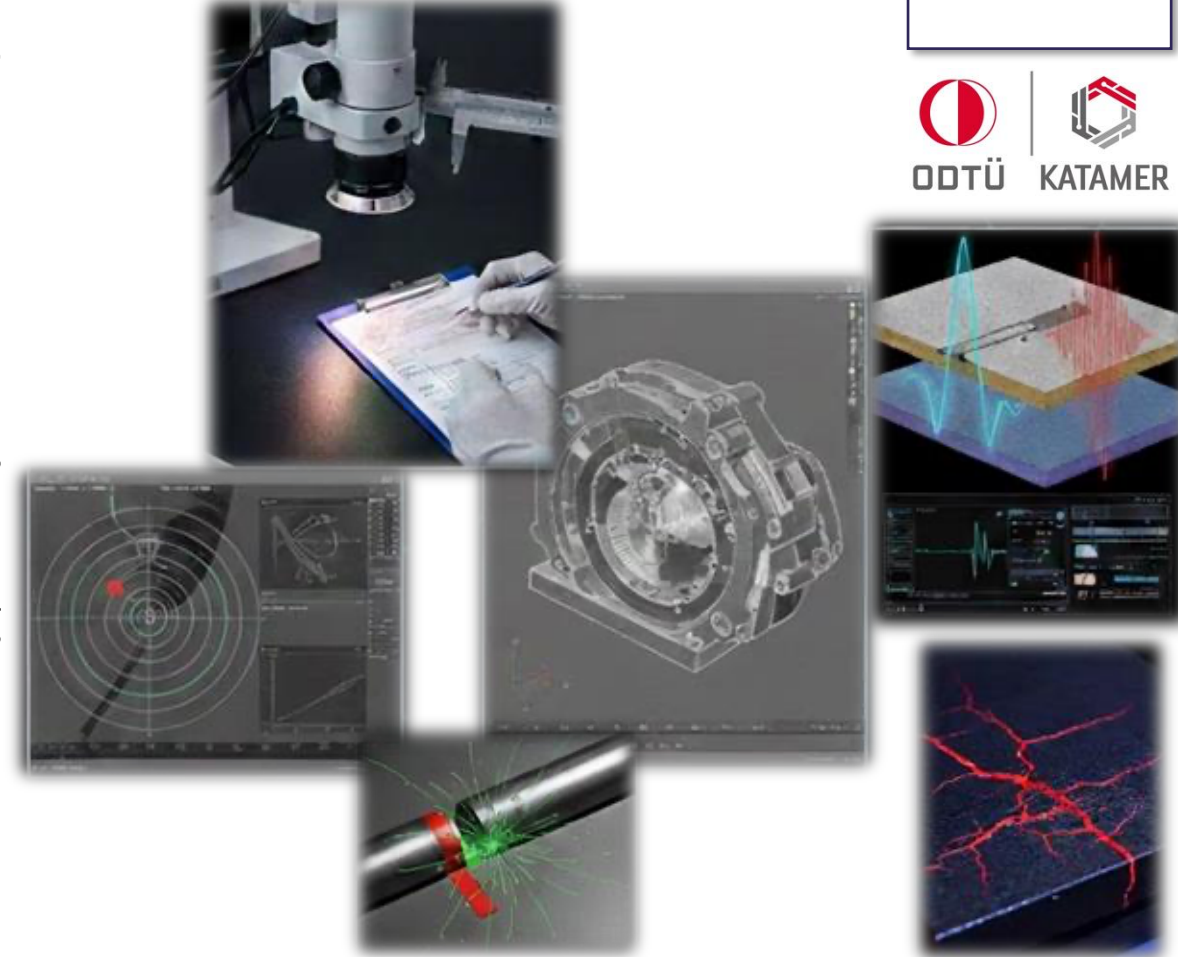
🚀 Non-Destructive Testing (NDT) allows us to detect discontinuities on the surface or inside the material without damaging the material.

🚀 The biggest advantage is that it maintains the usability of the part under test.

🚀 There are no additional production costs as the tested part does not deteriorate.

🚀 It can be applied during production or during service.

🚀 Rapid and repeatable tests can be performed.



DESTRUCTIVE TESTING(DT) AND NON-DESTRUCTIVE TESTING (NDT)

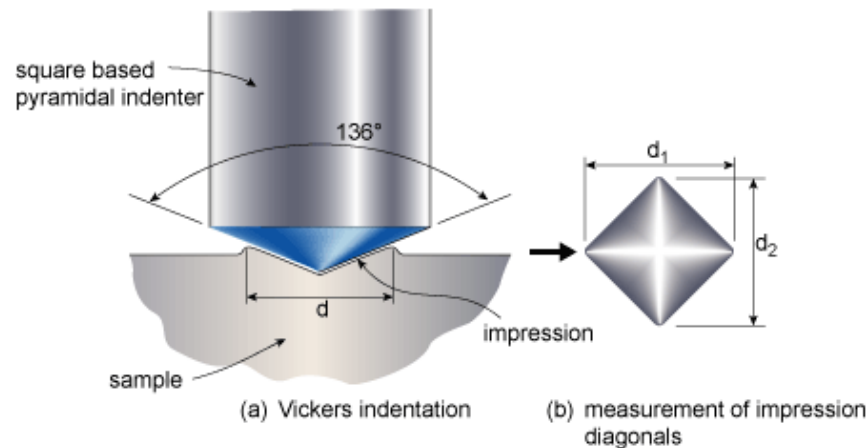


Destructive Testing (DT) is a testing methodology where a material or component is subjected to a load or environment that eventually causes it to fail or be permanently altered.

Unlike NDT, DT is designed to determine the mechanical limits and material properties of a part.

DESTRUCTIVE TESTS

- Tensile test
- Bending experiment
- Hardness test
- Notch impact experiment
- Macro review
- Micro-examination
- Fracture toughness test



NON-DESTRUCTIVE TESTING METHODS



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SURFACE INSPECTION METHODS

-  Visual Inspection (VT)
-  Penetrant Inspection (PI/PT)
-  Magnetic Particle Inspection (MPI/MT)
-  Eddy Currents Testing (ET)

- ✓ Magnetic Flux Leakage (MFL)
- ✓ Acoustic Emission Test (AT)
- ✓ Leakage Test (LT)

VOLUMETRIC INSPECTION METHODS



Ultrasonic Testing (UT)

- *PAUT (Phased Array UT)
- *ToFD (Time of Flight Diffraction)
- *TFM (Total Focusing Method)



Radiographic Examination (RT)

- *Film Radiography (RT-F)
- *Digital Radiography (RT-D) : CR , DDA
- *Computed Tomography (CT)

VISUAL INSPECTION (VT)



📏 **Performing dimensional analysis:** Checking whether the materials are in the desired dimensions at any manufacturing stage

👁️ **Detecting surface defects:** Identifying cracks, pores, burrs, and surface irregularities.

🔦 **Providing fast and easy inspection:** The most basic and widely used non-destructive testing method.

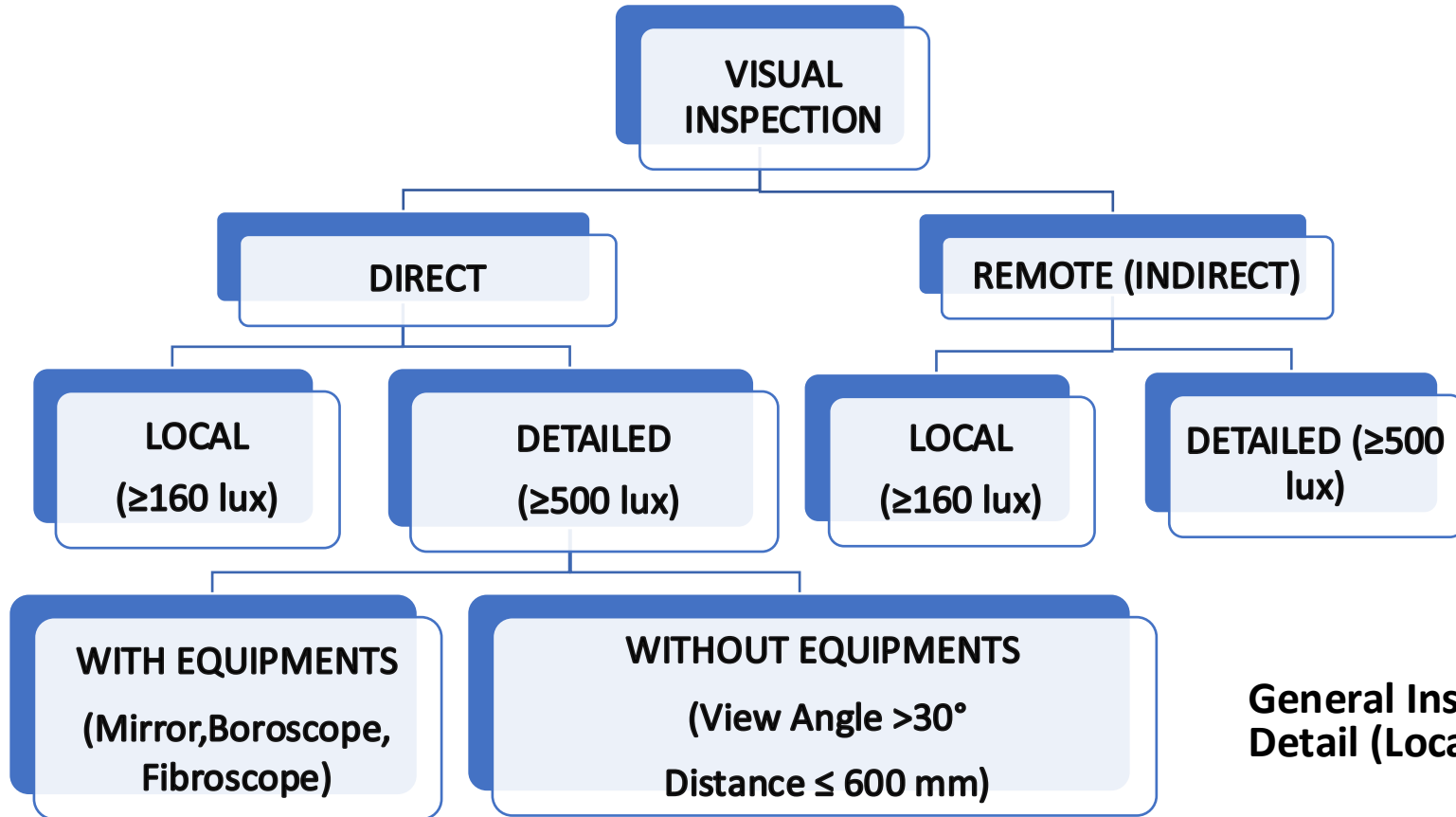
📏 **Checking production quality:** Evaluating whether welded or cast parts meet standards.

🔧 **Performing preventive maintenance:** Detecting early damage that may occur during the operation.



VISUAL INSPECTION (VT)

BASIC CONCEPTS



EN ISO 13018 Standard: Visual Inspection Basic Principles

General Inspection: Illumination intensity min. 160 lux
Detail (Local) Inspection: Min. 500 lux for lighting intensity

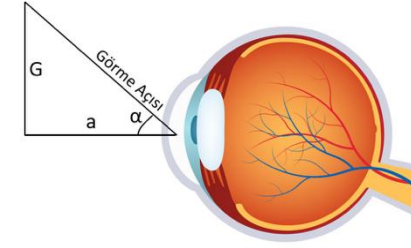
VISUAL INSPECTION (VT)

BASIC CONCEPTS



1. Direct Visual Inspection

- If the distance between the examination surface and the eye is ≤ 600 mm and the direction of view is more than 30° , direct visual examination is performed.
- If the inspection part is not reachable (>600 mm improper position, toxic environment, radiation, etc.) and if the gaze direction is $< 30^\circ$, direct inspection is performed using auxiliary tools.



VISUAL INSPECTION (VT)

BASIC CONCEPTS



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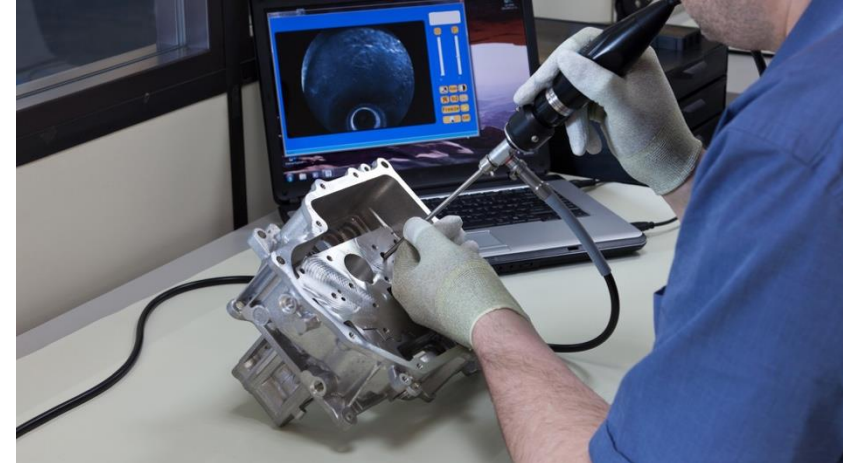
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2. Remote (Indirect) Visual Inspection

- Instead of light, the image is transformed into another form of energy.
- A photograph examined in an indirect examination may be an image shown instantly. Additional processes such as magnification, image intensification and measurement may be needed.



VISUAL INPECTION (VT)

DIMENSIONAL MEASUREMENT

- Ruler, caliper, micrometer, digital measuring tools, templates, jigs, etc. are used to check whether the materials are within the dimensional tolerances
- Especially in welded manufacturing, welding gauges are very important.



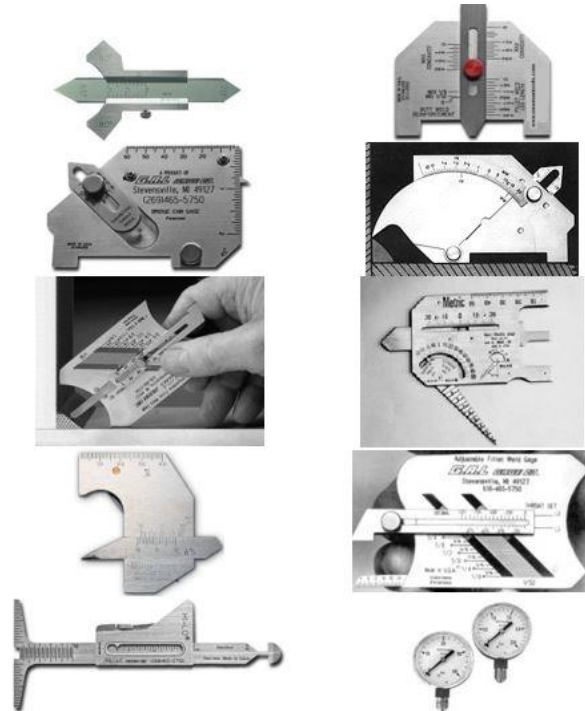
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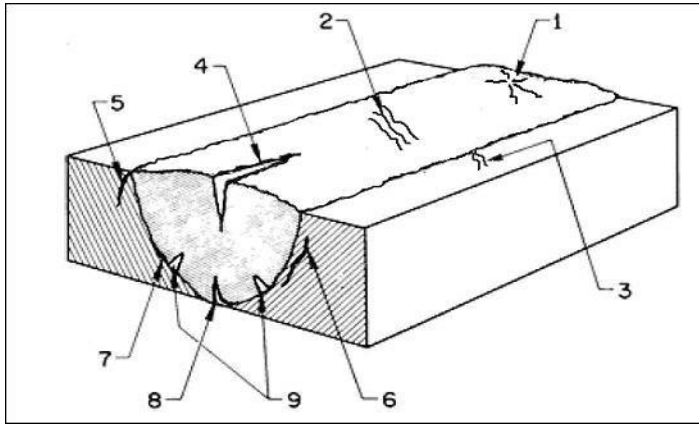
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VISUAL INSPECTION (VT)

DISCONTINUITIES

- After all manufacturing methods, areas that disrupt the integrity of the material and on its surface are formed. These regions are called **discontinuities**.
- If there is discontinuity that exceeds the critical dimensions, it is called a **defect/error**.

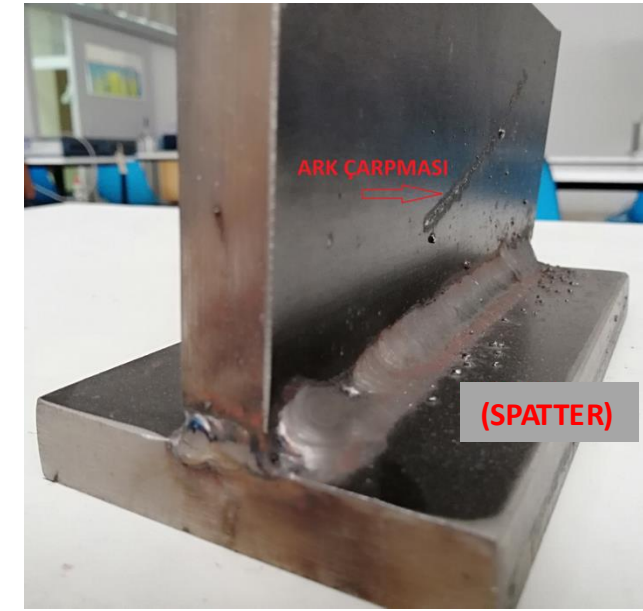
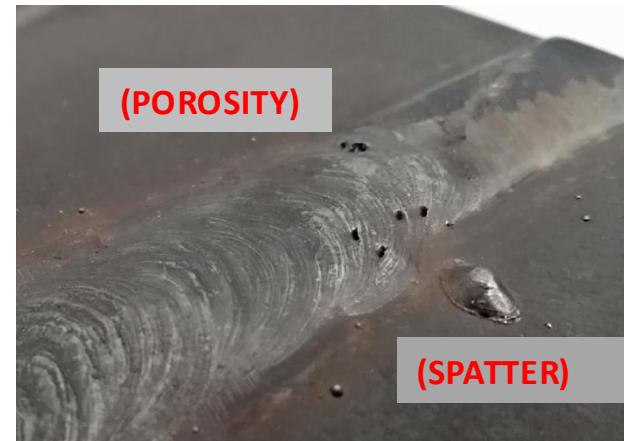
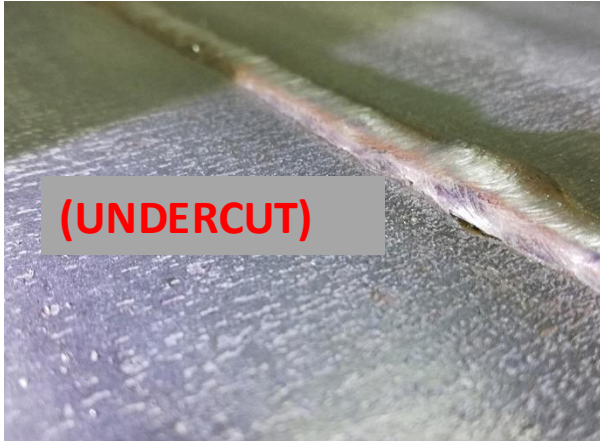


VISUAL INSPECTION (VT)

DISCONTINUITIES

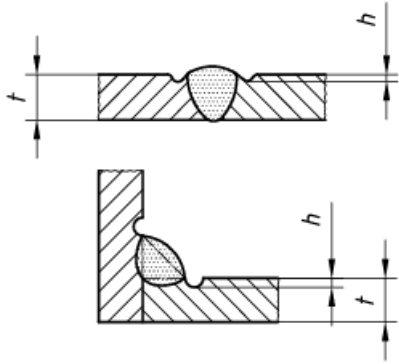
Typical defects after welded manufacturing

- Pore, spatter, crack, combustion groove, excessive weld metal (cap) height, root groove, insufficient penetration, inadequate melting, overlap, undercut, arc strike, linear misalignment, angular misalignment, etc.

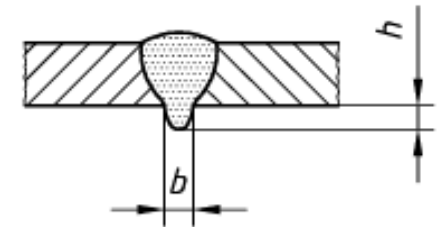
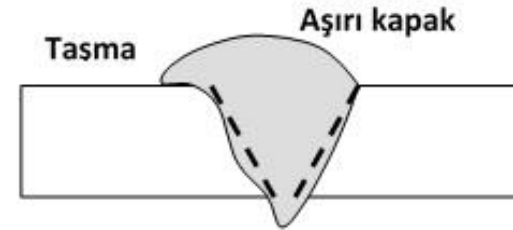
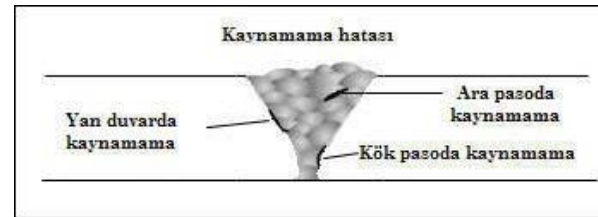
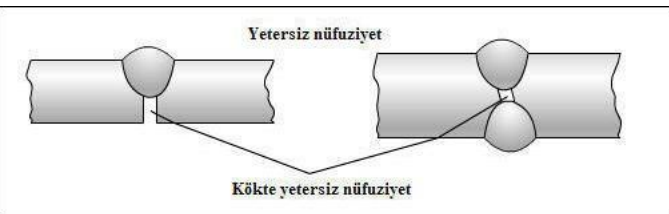
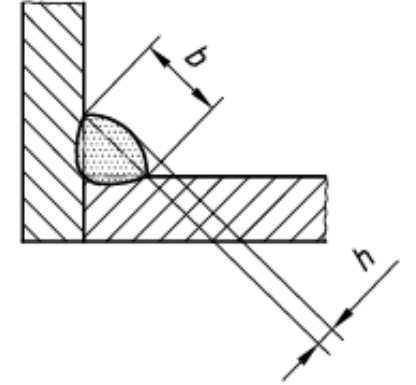


VISUAL INSPECTION (VT)

Symptoms found after weld inspection are made according to the criteria of the relevant quality level **EN ISO 5817**.



t mm	Limits for imperfections for quality levels		
	D	C	B
0,5 to 3	Short imperfections: $h \leq 0,2 t$	Short imperfections: $h \leq 0,1 t$	Not permitted
> 3	$h \leq 0,2 t$, but max. 1 mm	$h \leq 0,1 t$, but max. 0,5 mm	$h \leq 0,05 t$, but max. 0,5 mm

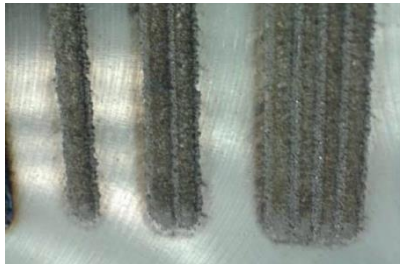


VISUAL INSPECTION (VT) in AM

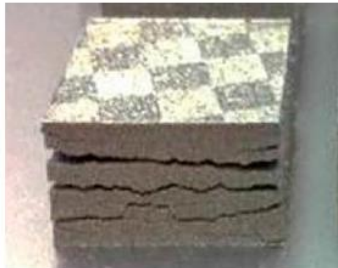
DISCONTINUITIES



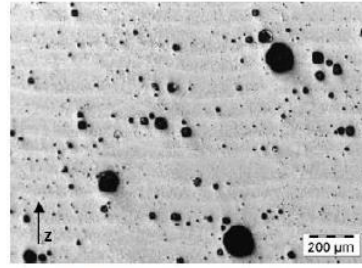
Typical defects on surface after metal AM (not specific for AM)



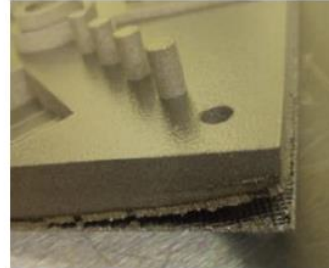
Poor Surface Finish



Delamination



Gas porosity

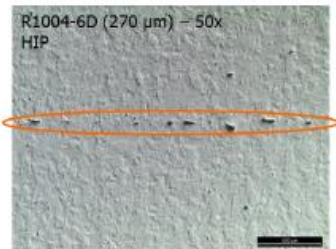


Dimensions/warping

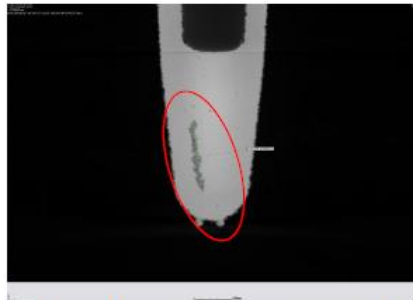


b) Cracks on the support interface

Typical defects on surface after AM, (specific for AM)



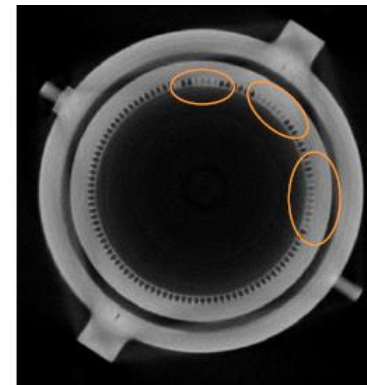
Layer defect
(horizontal LOF)



Cross-layer defect (vertical LOF)



Unconsolidated powder



Trapped powder



a) Colouring appearing in the downskin area



b) Colouring in a part above the supports

Source: ISO/ASTM JG59 DTR 52905, 'Additive Manufacturing —Non-Destructive Testing and Evaluation —Standard Guideline for Defect Detection in Metallic Parts'

VISUAL INSPECTION (VT) in AM

DISCONTINUITIES



TABLE 1 Nondestructive Test Detection of Typical Additive Manufacturing Flaws^{A,B}

Flaw/Artifact ^C	Observed in PBF or DED?	Why?	Post-Process Detection	Comment
Porosity	both	Poor selection of parameters, moisture or contamination of feed material or process environment, inadequate handling, storage, vaporization of minor alloying constituents depending on material feedstock. Errors in precision of beam delivery.	Depending on sample geometry and size of porosity, may be detected using CT/ET ^G /IRT/PCRT/RT/UT	HIP recoverable (may not be fully recoverable)
Voids	both	Powder run out, changes in the energy density of the impinging beam creating keyhole melting or vaporization conditions that entrap voids or create spatter (spherical molten ejecta) leaving holes, and voids that may be covered by subsequent layers of fused materials. System drift or calibration issues may come into play to create conditions of LOF. Bridging of powder in the hopper/poor flow properties.	Depending on sample geometry and size of voids, may be detected using CT/ET ^G /IRT/PCRT/RT/UT	HIP recoverable depending on size (not fully recoverable regardless)
Layer flaws	Unique to AM ^F	Interruption to powder supply, optics systems errors (laser) or errors in data. Contamination of build environment purity (inert gas interruption) or other process interruption such as changing the filament emitter within an electron beam gun. Powder supply blending or mixing between one batch and another, a new lot of filler wire, etc.	Depending on sample geometry and size of flaw, may be detected using CT/ET ^G /PCRT/RT/UT	HIP recoverable depending on size (not fully recoverable regardless)



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VISUAL INSPECTION (VT) in AM

DISCONTINUITIES

Cross-layer flaws	Unique to AM ^F	Poor selection of parameters, contamination or degradation of the processing environment. Discoloration (for example, DED-PA of Ti alloys) as detected visually can indicate a process out of control. Error in the precision of the beam delivery.	Depending on sample geometry and size of flaw, may be detected using CT/ET ^G /PCRT/RT/UT	HIP recoverable depending on size (not fully recoverable regardless)
Under melted material/ unconsolidated powder (LOF) Cracking ^D	both Unique to AM ^F	Poor selection of parameters, poorly developed and controlled process or a process out of control creating a poorly resolved flaw state. Errors in the precision of beam delivery. AM PBF failure to clean one alloy powder completely from the build environment prior to processing another, DED large assemblies extensive solidification stresses present within large buildups, There is a host of metallurgical issues associated with crack susceptibility. Extremely large range of potential thermal and mechanical conditions present, across all AM processes, that may lead to cracking are poorly characterized.	Most probably CT, and PCRT, detectability depends on sample geometry and size Depending on sample geometry and size of crack, may be detected using CT/IRT/PCRT/ET ^G /RT/UT	Only fixable during the process ...
Reduced mechanical properties	both	New powder out of spec or degraded through reuse, poorly developed/controlled process, interruption of feedstock supply. Residual stresses produced by rapid cooling, in a state of pre-stress, thus reducing the effective structural load that can be applied on the part, or causing structural weaknesses in a part in regions that have lower mechanical properties compared with the rest of the part.	Check powder (X-ray diffraction) at end of process and mechanical properties of finished part, stress related reduced properties can be detected using PCRT	...
Poor dimensional accuracy	both	Scaling/offset factors are effected by part geometry, beam intensity, and the density of the powder bed or build platform shift. SLM –scan head/optics problems. EBM – presence of EMF interference.	Usually easy (visually), as part has step on surface, but localized defects may require laser CMM and internal deviations with CT compared with CAD.	...



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VISUAL INSPECTION (VT) in AM

DISCONTINUITIES



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TABLE 3 Application of NDT to Detect Additive Manufacturing Discontinuity Classes^A

Discontinuity Class	Covered in this Guide							Not Covered in this Guide				VT
	CT/RT/ CR/DR	ET	MET ^B	PCRT	PT	IRT	UT	AE	LT	NR	MT	
Surface	X ^C	X ^D	X	...	X ^D	...	...	...	...	...	...	X
Porosity	X	X ^D	...	X	X ^D	...	X	...	...	...	...	X
Cracking	X ^E	X ^D	...	X	X ^D	X	X	X	X ^F	...	X	X ^G
Lack of Fusion	X ^E	X ^D	...	X	X ^D	X	X	X	...	...	X	...
Part Dimensions	X	...	X	...	...	...	...	...	...	X ^H	...	...
Density ^I	X ^J	...	...	X	...	...	...	...	...	...	...	...
Inclusions	X ^K	X ^D	...	X	...	X	X	...	...	...	...	...
Discoloration	...	...	...	...	...	...	...	...	...	...	...	X
Residual Stress	...	X ^{D,L}	X	X	...	...	...	...	...	X	...	...
Hermetic Sealing	...	...	...	...	...	...	...	...	X ^F	...	...	...

^A Abbreviations used: ... = not applicable, AE = Acoustic Emission, CR = Computed Radiography, CT = Computed Tomography, DR = Digital Radiology, ET = Eddy Current Testing, IRT = Infrared Thermography, LT = Leak Testing, MET = Metrology, MT = Magnetic Particle Testing, NR = Neutron Radiography, PCRT = Process Compensated Resonance Testing, PT = Penetrant Testing, RT = Radiographic Testing, UT = Ultrasonic Testing, and VT = Visual Testing.

^B Includes Digital Imaging.

^C Especially helpful when characterizing internal passageways or cavities (complex geometry parts) for underfill and overfill, or other internal features not accessible to MET, PT, or VT (including borescopy).

^D Applicable if on surface.

^E Radiographic methods are not optimal for detecting tight laminar features like cracking and LOF, which typically do not exhibit enough density change.

^F If large enough to cause a leak or pressure drop across the part.

^G Macroscopic cracks only.

^H Conventional neutron radiography (NR) allows determination of internal and external dimensions.

^I Pycnometry (Archimedes principle).

^J Density variations will only show up in imaged regions having equivalent thickness.

^K If inclusions are large enough and sufficient scattering contrast exists.

^L Residual stress can be assessed if resulting from surface post-processing (for example, peening).

Windows'u Etkin
Windows'u etkinleştirm

VISUAL INSPECTION (VT) in AM

DISCONTINUITIES



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According to ASTM 52905 ;

- Certain AM flaws (i.e., **voids and porosity**) can occur in most or all AM parts (non process specific), and can be characterized and evaluated using existing methods **for welded (EN ISO 17635, EN ISO 5817, EN ISO 10042) or cast parts (ISO 11971)**
- Other AM flaws (i.e, **layer, cross layer, unconsolidated and trapped powder**) are unique to PBF, and new or better NDT detection methods are needed.

		Non- NDT	Common in DED & PBF	Covered by current standards	Unique to AM
DED					
	Poor surface finish				
	Porosity				
	Incomplete fusion				
	Lack of geometrical accuracy/steps in part				
	Undercuts				
	Non-uniform weld bead and fusion characteristic				
	Hole or void				
	Non-metallic inclusions				
	Cracking				
PBF					
	Unconsolidated powder				
	Lack of geometrical accuracy/steps in part				
	Reduced mechanical properties				
	Inclusions				
	Void				
	Layer				
	Cross layer				
	Porosity				
	Poor surface finish				
	Trapped powder				

Develop new or better NDT methods

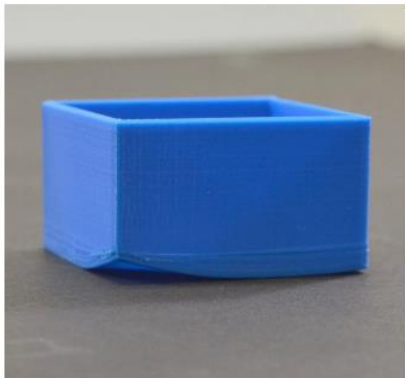
Source: ISO/ASTM JG59 DTR 52905, 'Additive Manufacturing —Non-Destructive Testing and Evaluation —Standard Guideline for Defect Detection in Metallic Parts'

VISUAL INSPECTION (VT) in AM

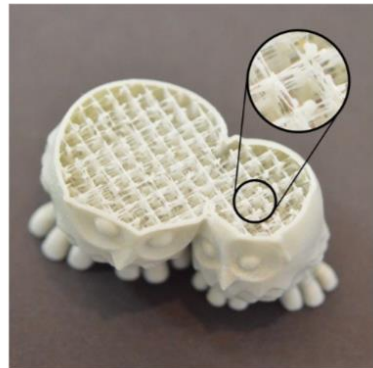
DISCONTINUITIES



Typical defects on surface after polymer AM



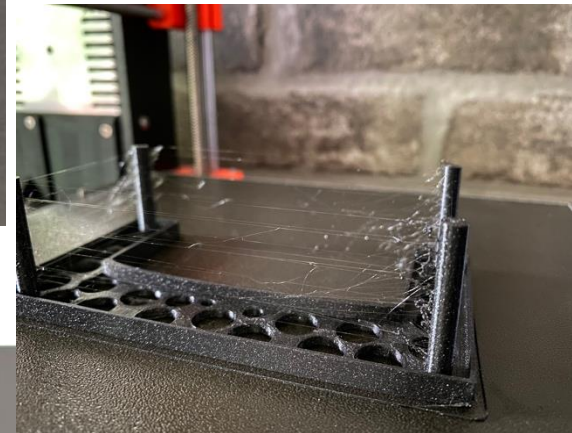
Warping



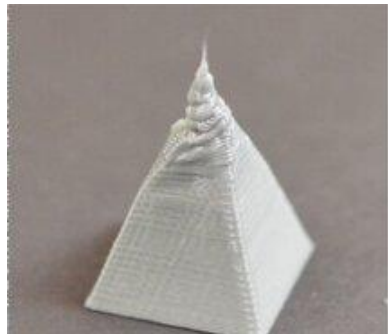
Weak Infill



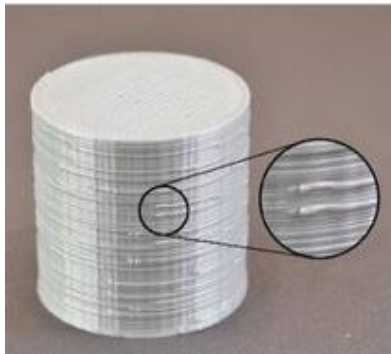
Layer Separation



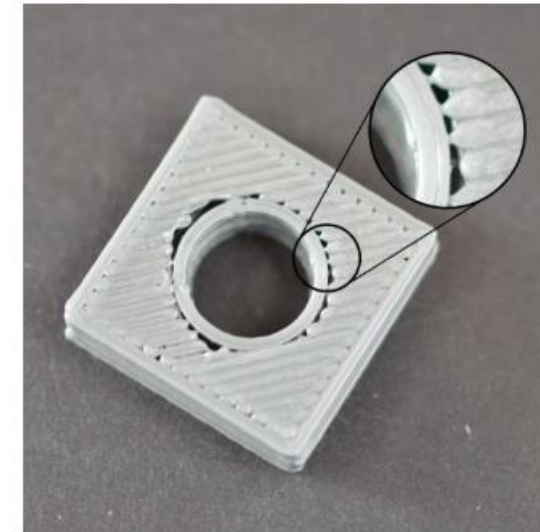
Stringing



Overheating effect



blobs and zits



Gaps Between Infill and Outline

DRAWBACKS OF VISUAL INSPECTION (VT)



⚠ Technical Limitations

- It can't see the inner flaws
- High surface roughness makes defect-roughness discrimination difficult
- Small microcracks can be overlooked

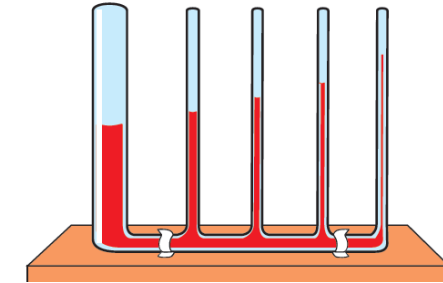
⚠ Operational Limitations

- Operator-dependent
- Sensitive to lighting and viewing angle
- Access is restricted in complex geometries

In additive manufacturing, visual testing is essential for surface quality and process monitoring, but it must always be complemented by volumetric NDT methods for internal defect detection.

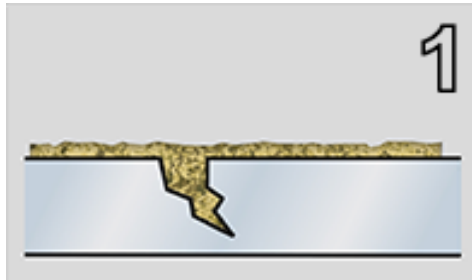
PENETRANT INSPECTION (PI/PT)

- Surface-breaking defects invisible to the naked eye
- **Discontinuity size $\neq$ actual defect size**
- It can be applied to almost all kinds of materials, provided that their surfaces are extremely non-porous
- To ensure that a fluidized penetrant fluid is penetrated into discontinuities on the inspection surface and then drawn back to the surface by the developer to become visible
- Penetrates by capillary action
- The general rules for this method are defined in various standards
- EN ISO 3452-1 and ASTM E1417

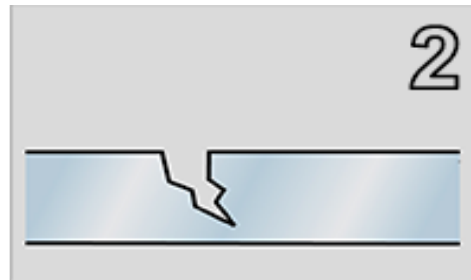


PENETRANT INSPECTION (PI/PT)

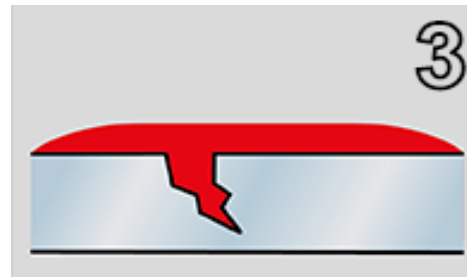
According to 3452-1, the stages of the inspection are as follows, and each stage is mandatory.



Pre-Cleaning



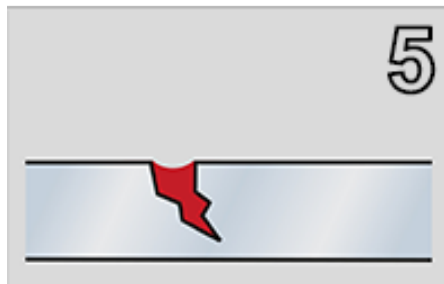
Visual Inspection and
control of inspection
conditions



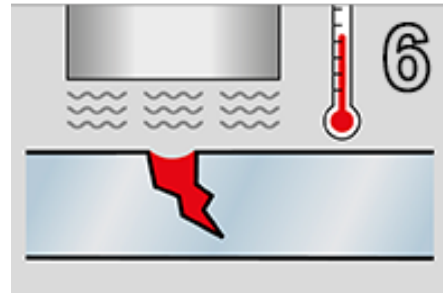
Penetrant application
and dwell time



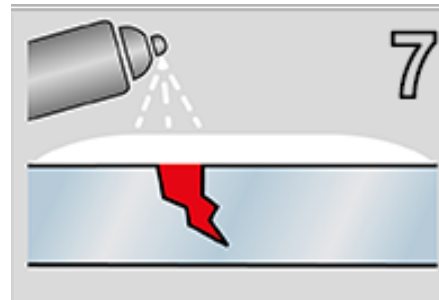
Intermediate
washing



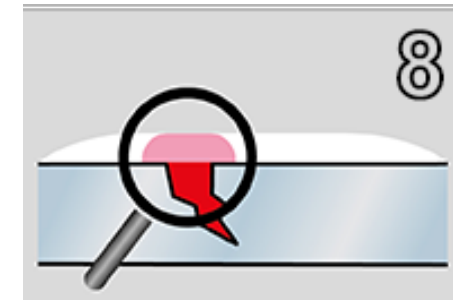
Removal of all penetrant



Drying (if necessary)



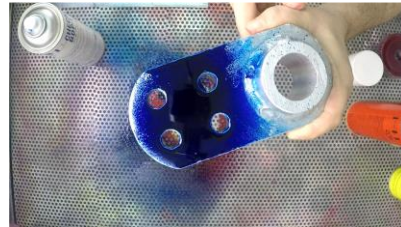
Developer application



Final Inspection

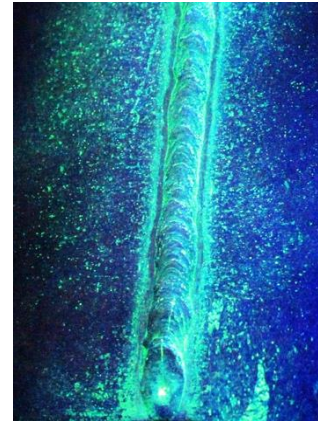
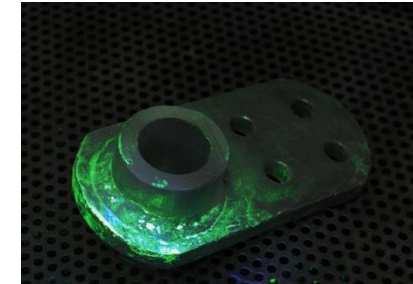
DYE PENETRANT

- Dye penetrants can be produced in red or blue color.
- It is called a Type II penetrant
- It should be worked in min. 500 lux ambient lighting.



FLORESCENT PENETRANT

- They usually glow green under UV light.
- It is called Type I penetrant
- Min. 10 W/m² UV light intensity max. It should have 20 lux center lighting



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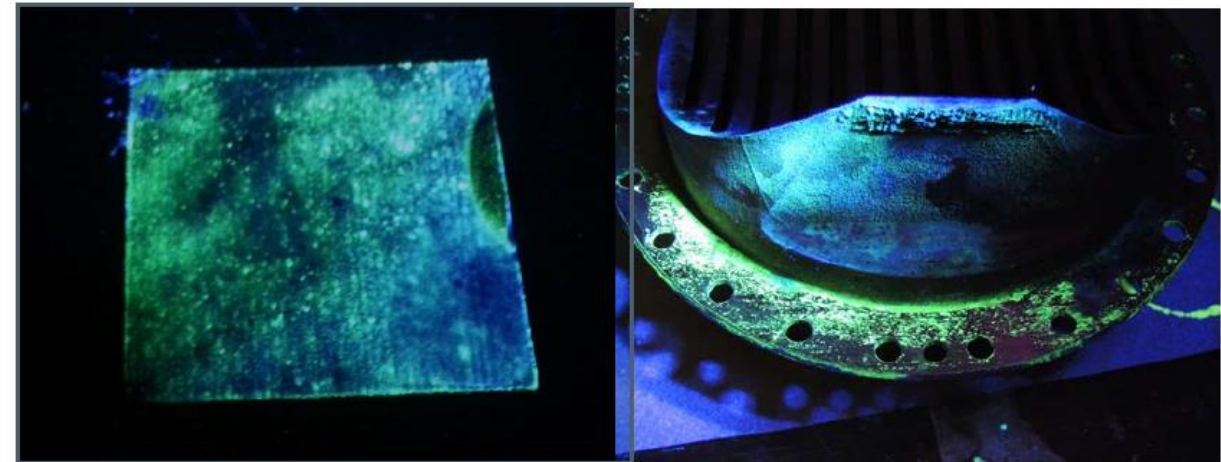
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PENETRANT INSPECTION in AM

- In AM, PT is effective for detecting surface-breaking defects in metal parts, but its reliability strongly depends on surface condition and post-processing.
- **For DED (Metal);**
 - Lack of fusion open to the surface
 - Surface cracks caused by cooling
 - Repair and coating zones
- **For LPBF (Metal);**
 - Post-processing (machining, polishing)
 - Control of cracks and porosity opened on the surface



Penetrant testing of a Ti-6Al-4V block under development for a liquid rocket gaseous hydrogen/liquid oxygen (GH₂/LOX) injector (left) and a Pogo-Z baffle (right) showing high background noise due to as-manufactured surface roughness

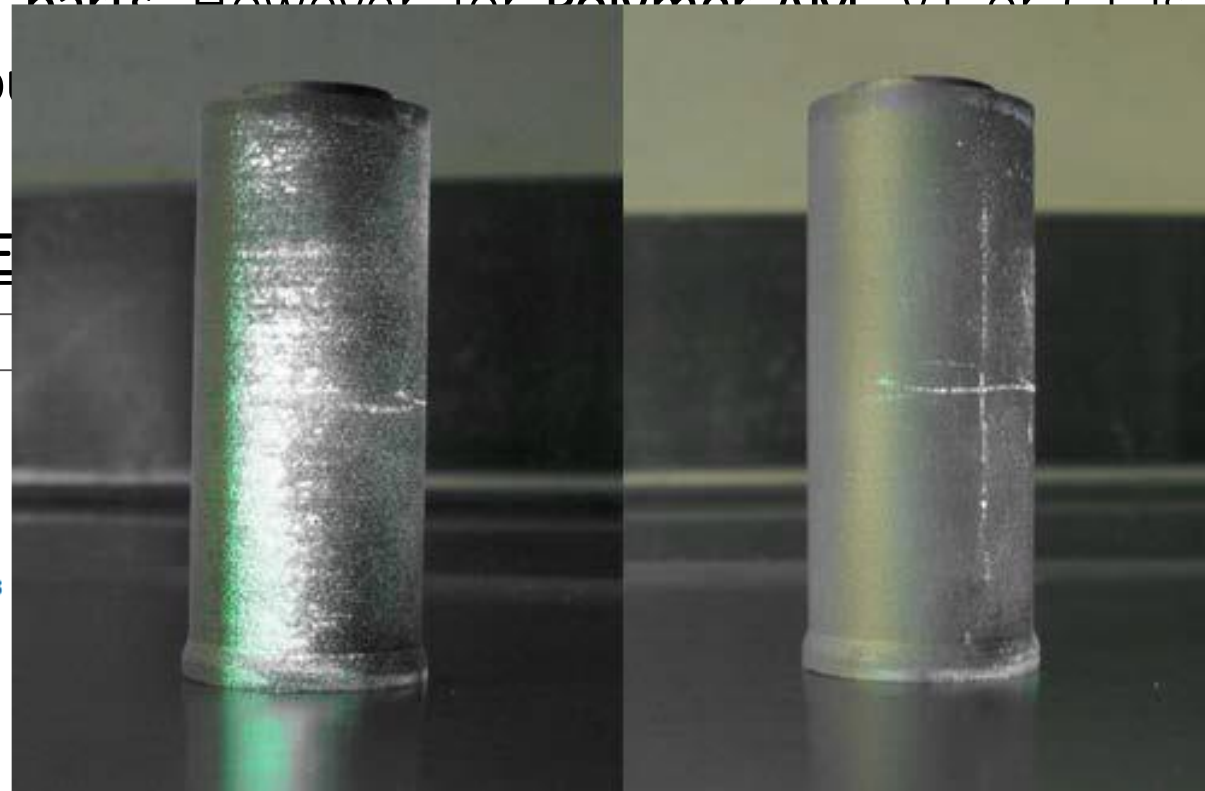
Source: NASA/TM—2014–218560, Nondestructive Evaluation of Additive Manufacturing

DRAWBACKS of PENETRANT INSPECTION in AM

- The PT method is important for verifying the open surface defects after machining (finishing) on **Metal AM** parts. However, for **Polymer AM**, VT or CT is much safer than PT due to the porosity.

According to ASTM:52905 for Metal DE

- It states as a legal basis that the application of PT on **"as-built"** surfaces will give erroneous results and that surface cleaning/treatment is **mandatory**.



Applicability to AM flaws	
3	able. As-built component with surface which is not suitable for penetrant inspection.
	able. As-built component with surface which is not suitable for magnetic particle inspection.
	likely that most surface flaws are eliminated by machining the
	romagnetic materials. It is not most surface flaws can be eliminated by machining the surface.

MAGNETIC PARTICLE TESTING (MT)



- It is based on the principle of magnetizing the discontinuities in ferromagnetic materials by various methods and as a result, the 'LEAKAGE FLUX' formed around the discontinuities is detected with magnetic powders applied during the inspection.

RELATIVE MAGNETIC PERMEABILITY ≥ 100

*Iron, Ni, Co and their alloys are ferromagnetic

** Austenitic Stainless steel, Ti, Al, Cu, brass etc. are non-ferromagnetic

On the surface and near-surface

Tangential Field Strength measure: 2-6 kA/m

MAGNETIC PARTICLE TESTING (MT)



- It is based on the principle of magnetizing the discontinuities in ferromagnetic materials by various methods and as a result, the 'LEAKAGE FLUX' formed around the discontinuities is detected with magnetic powders applied during the inspection.

1. Magnetization by Passing Current Through Part
2. Magnetization by Passing a Magnetic Field through the Part
 - Passing current through insulated conductor (Magnetization with Auxiliary Conductor)
 - Magnetizing adjacent to part with insulated conductor
 - Portable Magnet (Yoke type magnetization)
 - Fixed Poles
 - Fixed coil
 - Flexible cable coil
3. Combined Magnetization

MAGNETIC PARTICLE TESTING (MT)



- It is based on the principle of magnetizing the discontinuities in ferromagnetic materials by various methods and as a result, the 'LEAKAGE FLUX' formed around the discontinuities is detected with magnetic powders applied during the inspection.



Types of Inspection Environments

1. Dry Magnetic Powders
(Black, green, red, etc.)
2. Wet Magnetic Powders
(Florescent, Black Magnetic Powder)

MAGNETIC PARTICLE TESTING (MT)



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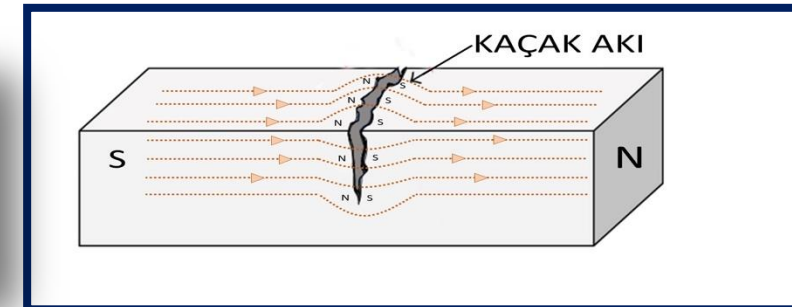
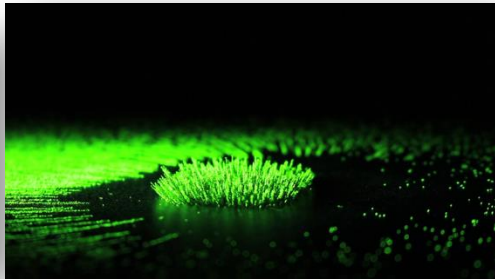
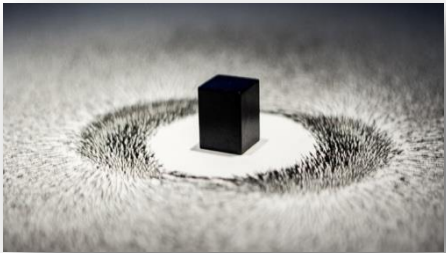


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- It is based on the principle of magnetizing the discontinuities in ferromagnetic materials by various methods and as a result, the 'LEAKAGE FLUX' formed around the discontinuities is detected with magnetic powders applied during the inspection.

EN ISO 9934-1

Magnetic Particle Inspection-General Principles



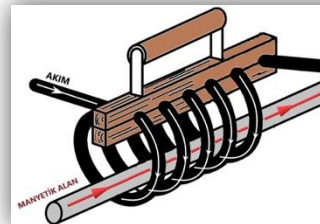
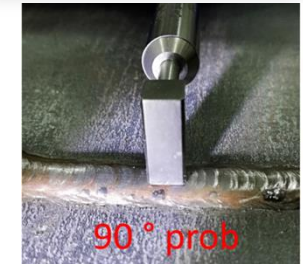
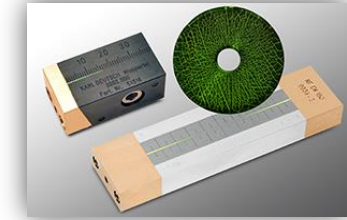
MAGNETIC PARTICLE TESTING (MT)



EN ISO 9934-1 Magnetic Particle Inspection-General Principles

Sequence of operations when performing magnetic particle inspection:

1. Pre-cleaning, preparation of the inspection surface and visual inspection
2. If magnetization has been done beforehand, demagnetization
3. Control of review conditions
4. Control of the inspection environment
5. Control of magnetization arrangement, field direction and intensity
6. Defining the boundaries of the inspection zone
7. Application of magnetization and inspection medium to the surface
8. Review and registration
9. Demagnetization
10. Final cleaning



MAGNETIC PARTICLE TESTING (MT)



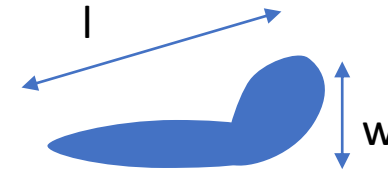
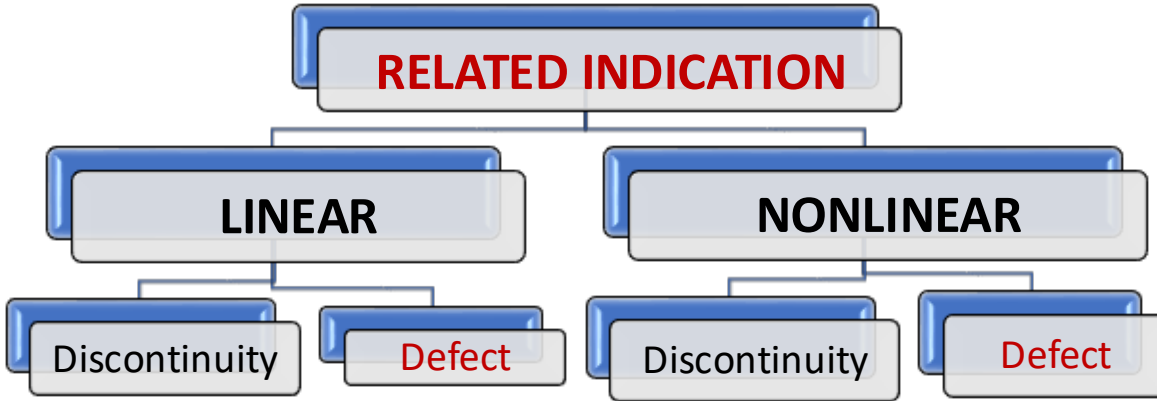
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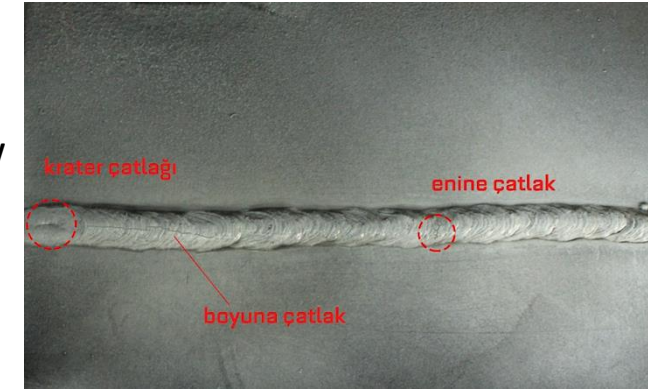
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L : length
W: width

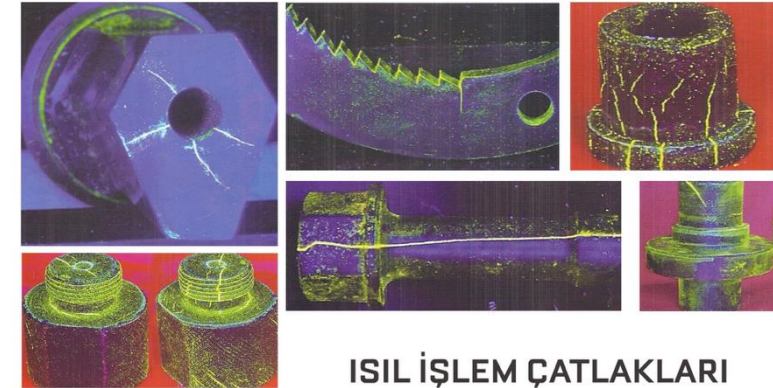


Indication whose length is more than 3 times its width. ($L > 3W$)

Indication whose length is less than or equal to 3 times its width. ($L \leq 3W$)



© CEphoto, Uwe Aranas



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MAGNETIC PARTICLE TESTING (MT) in AM

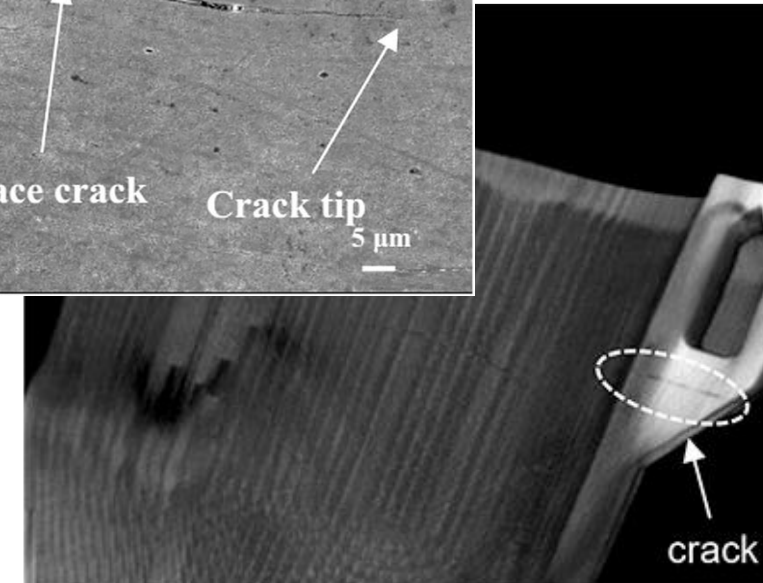
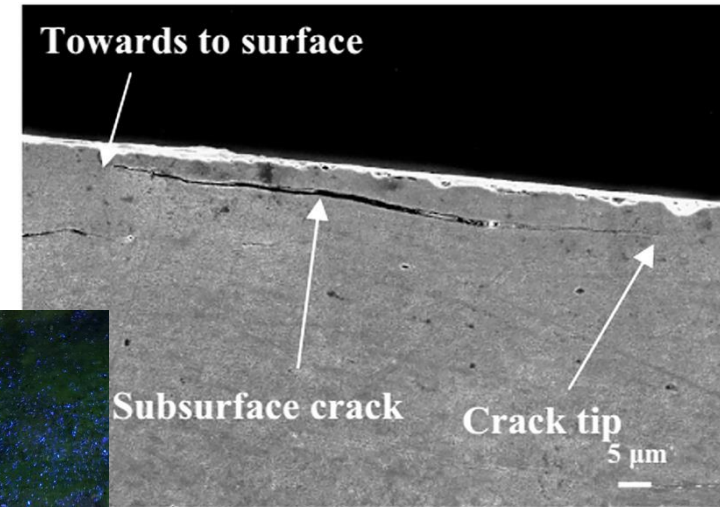
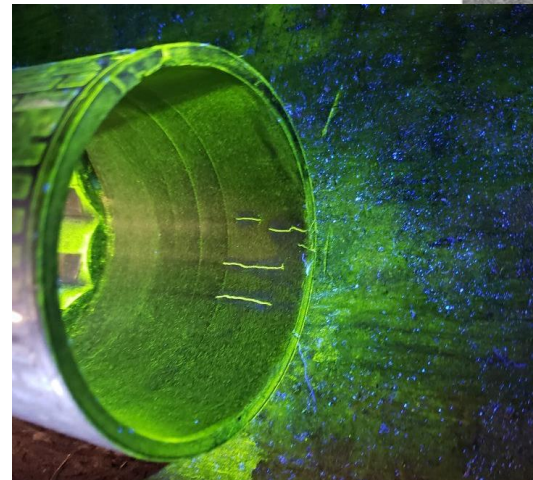


Steel and ferromagnetic alloys, especially those produced by LPBF and DED, during production , are prone to **surface and near-surface cracks, lack of fusion** due to :

- ✓ High thermal gradients,
- ✓ Repeated thermal cycles,
- ✓ Directional solidification
- ✓ Residual stresses

The reasons why MT is preferred in AM parts are quite strong:

- ✓ High sensitivity to surface cracks
- ✓ Being a fast and low-cost method
- ✓ Applicable to complex geometries (on accessible surfaces)
- ✓ Operationally simpler than UT or CT



DRAWBACKS of MAGNETIC PARTICLE TESTING (MT)

MT has some serious limitations in additive manufacturing:

- X It can only be used for ferromagnetic materials → Al, Ti, Ni-based superalloys.
- X Not detect volumetric defects → UT or CT is required for internal porosity, closed lack-of-fusion, gas cavities.
- X Very sensitive to surface roughness → As-built AM parts can be problematic for MT.
- X It is dependent on operator experience → Discontinuity-defect distinction requires attention.



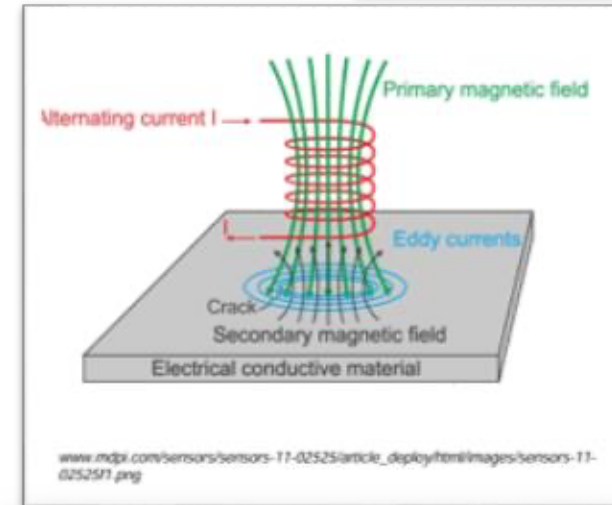
EDDY CURRENT TESTING (ET)



It is a surface inspection method in which the principles of Electromagnetism are used to detect discontinuities on the surface or just below the surface.

When a probe with alternating current through it is brought closer to the material, a magnetic field is created in varying directions within the winding. This directionally changing magnetic field induces circular eddy currents on the material surface (Lenz's law)

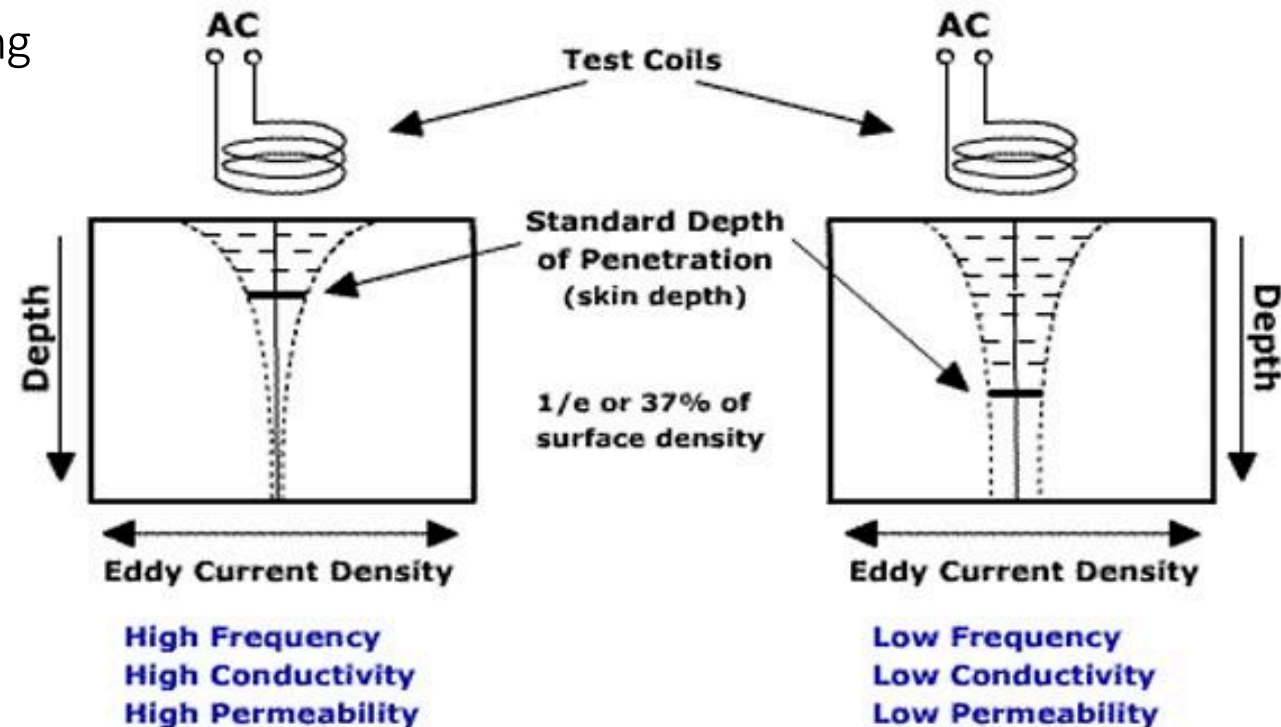
A discontinuity on the surface causes changes in the phase and intensity of this eddy current, and these changes are transmitted to the screen by the winding on the test probe or by a second receiving probe.



EDDY CURRENT TESTING (ET)



- The material's electrical conductivity, magnetic permeability, and the frequency of the alternating current used all affect its penetration depth
- As the frequency increases, the depth decreases
- In materials with high electrical conductivity, the eddy current density on the surface is very high and the sensitivity on the surface is high. But this negatively affects the depth of influence.
- High magnetic permeability also reduces penetration depth.

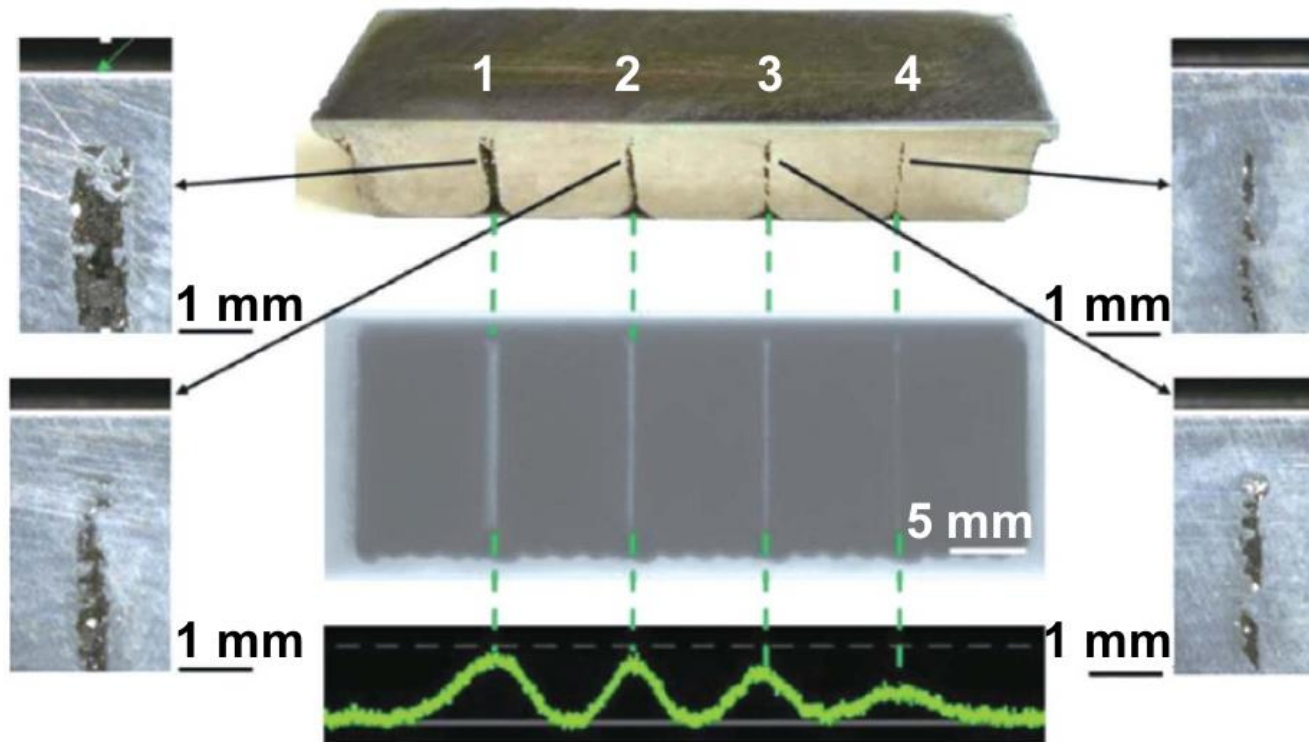


EDDY CURRENT TESTING (ET)



- + Eddy current inspection is used to detect very small faults (up to 0.5 mm) close to the surface.
- + The inspection speed is high. It is very suitable for the control of semi-finished products and mass production.
- + Since it does not require contact with the surface, it can also be applied to high-temperature materials, rough surfaces, surfaces with restricted surface access or coatings, and parts with complex geometries.
- + The equipment can be easily transported
- + **It does not require surface preparation (pre-cleaning, contact fluid, etc.)**
- + Material characterization can be done by measuring electrical conductivity

EDDY CURRENT TESTING (ET) in AM

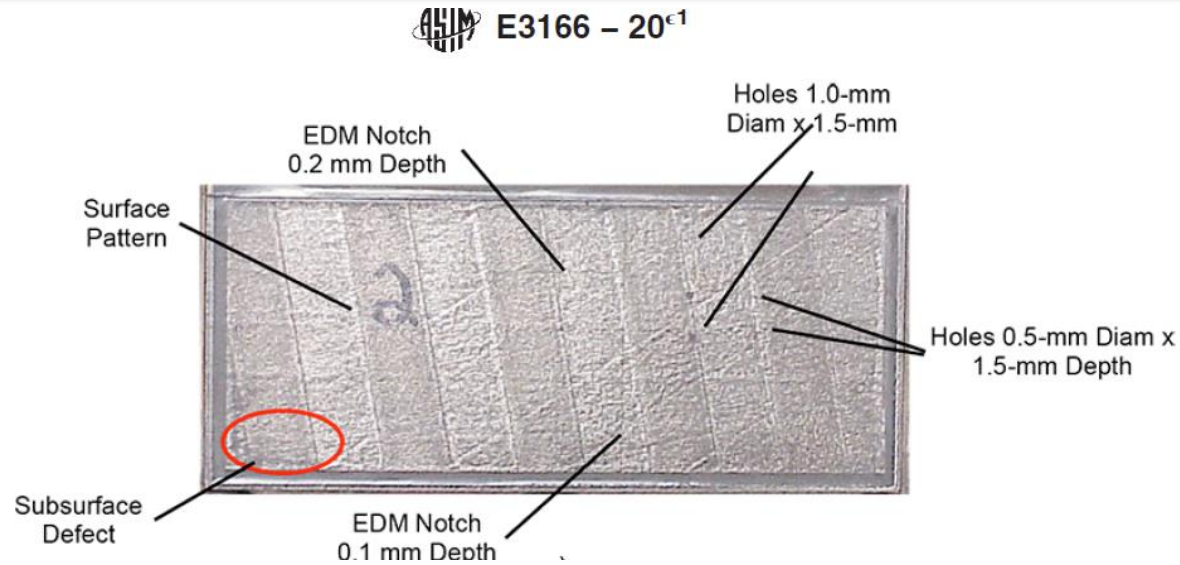


Sectional views of internal defects of variable sizes within a Ti-6Al-4V component processed by additive/subtractive hybrid manufacturing (ASHM) and the corresponding EC reactance signal perturbation due to defects

EDDY CURRENT TESTING (ET) in AM

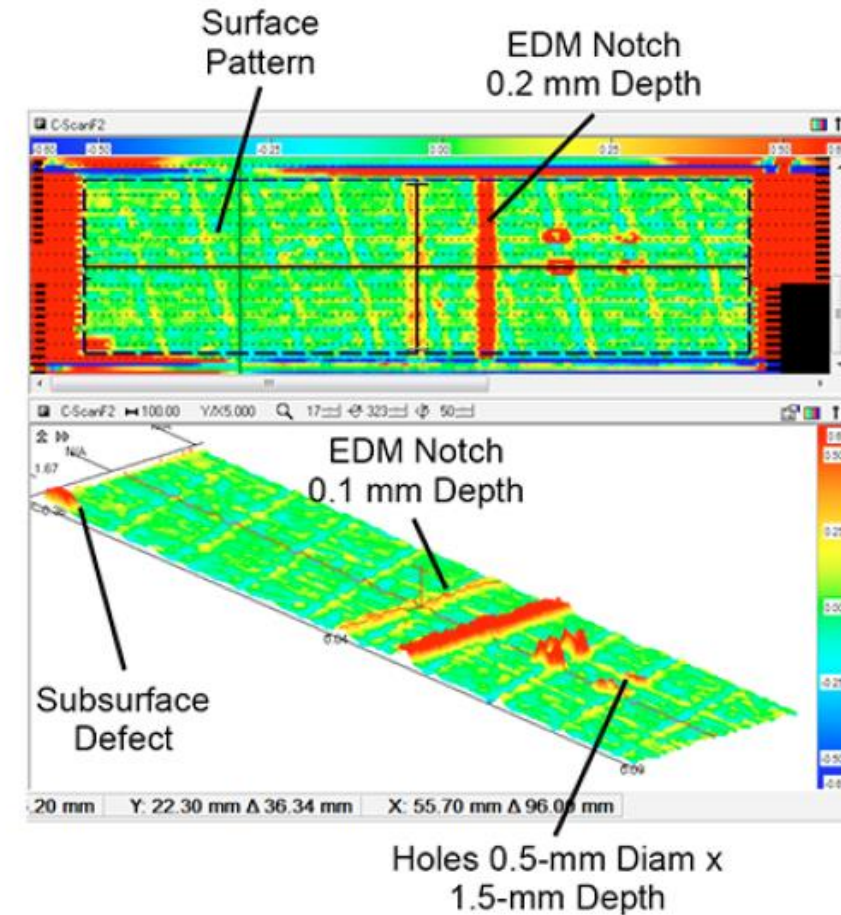


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Additively Manufactured UNS N06625 Part

Source: ASTM 3166: Standard Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build



Array Eddy Current Plots: (a) Specimen; (b) 1.5 MHz, Vertical Component C-scan

DRAWBACKS of EDDY CURRENT TESTING (ET)

- Eddy current inspection is only suitable for comparable measurements. It requires intensive and careful calibration work before testing.
- It is affected by the magnetic properties of the test material. Challenges occur during the testing of ferromagnetic materials.
- **It cannot detect defects parallel to the surface.**
- Its depth of penetration is limited.
- It requires serious training and experience.



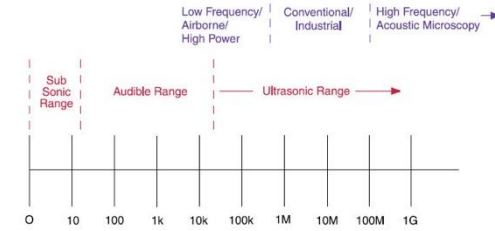
ULTRASONIC TESTING (UT)



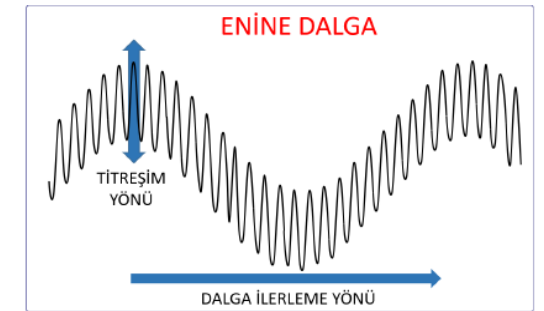
Infrasound waves : < 20 Hz

Audible Sound : 20 Hz – 20000 Hz

ULTRASOUND : > 20000 Hz or 20 KHz



- Ultrasonic vibrations travel in waveform, but they need an elastic medium for progress; such as solid or liquid media.
- If the direction of travel of ultrasonic waves and atomic vibrations are in the same direction, longitudinal (compression) and transverse (shear, shear) ultrasonic sound waves are formed
- Their rate of progress depends on the density of their environment and the forces that bind the atoms together.



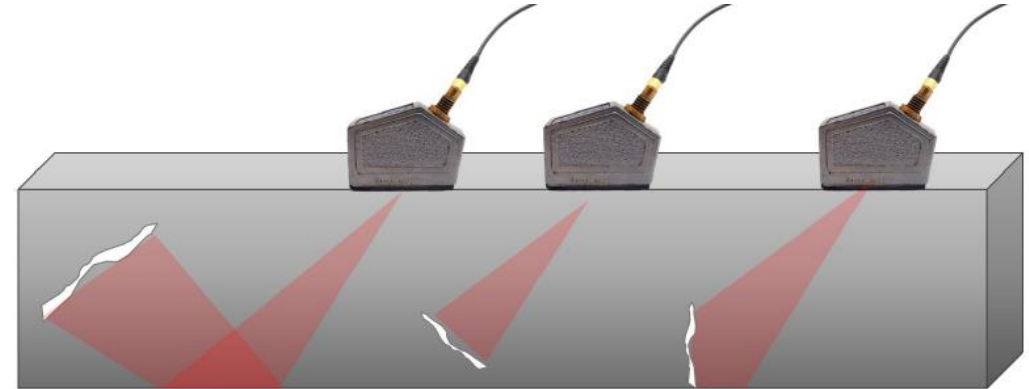
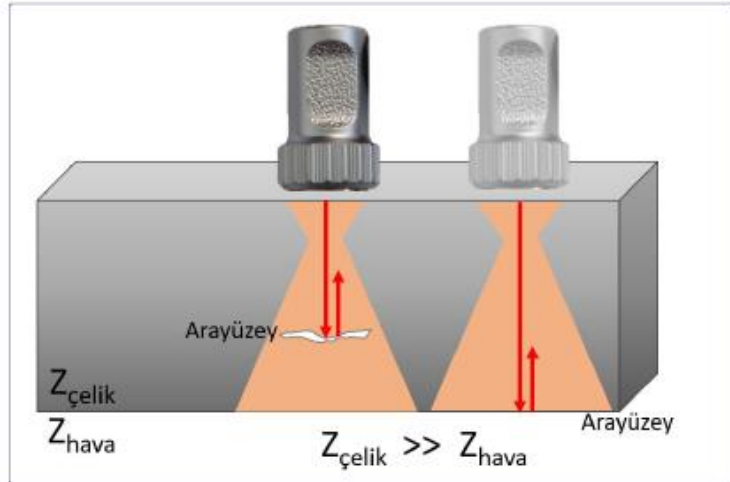
ULTRASONIC TESTING (UT)

- The piezoelectric (PZT) crystals inside the probe convert the electric current into mechanical sound waves and produce high-frequency ultrasonic waves
- In order for sound waves to enter the material, there should not be much difference between the acoustic impedance (z) inside the probe and the acoustic impedance in the material.
- There should be no air between the probe surface and the material surface.
- For this reason, coupling agent is used.



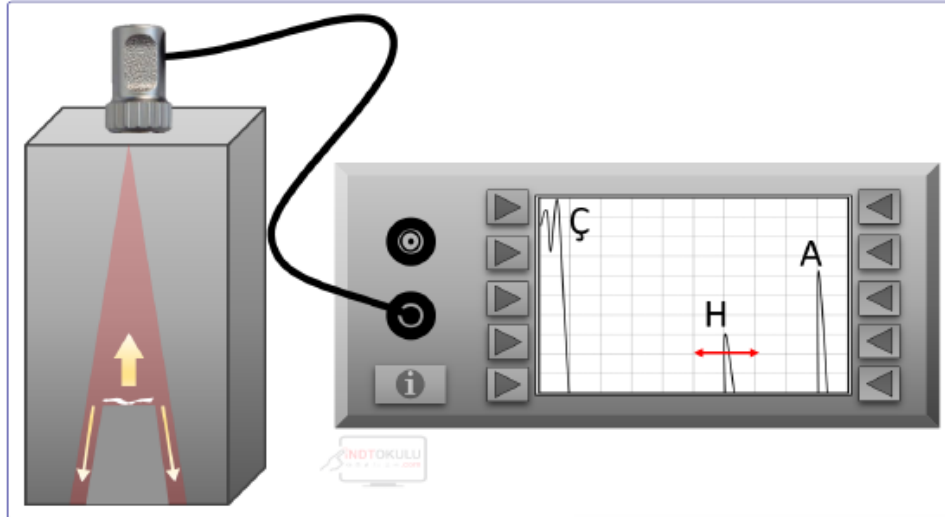
ULTRASONİK MUAYENE (UT)

- Probes in which longitudinal sound waves are sent perpendicular to the material are called **Single Beam Probe (SBP)**.
- By sending the longitudinal sound waves produced in the probe to the material with an angle, the sound waves are refracted (Snell's Law) and the mode transformation is performed. As transverse sound waves, the material enters at an angle. These probes are called **Angle Beam Probes (ABP)**.



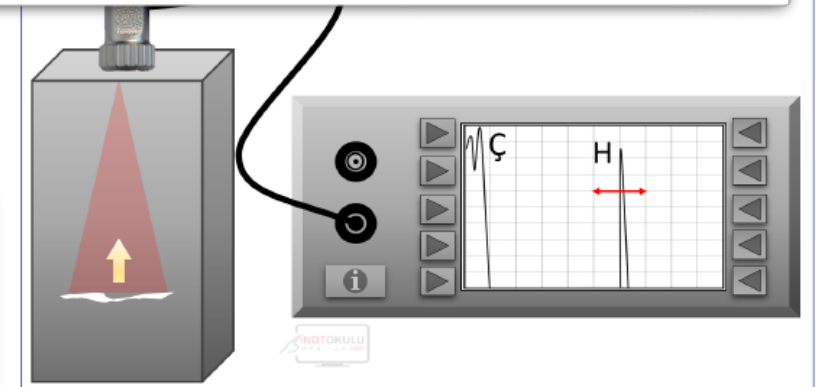
ULTRASONIC TESTING (UT)

- The UT device measures the Time of Flight (TOF) of the sound wave.
- «Distance Calibration» should be done.



If the sound beam hits an discontinuity in the position perpendicular to the direction of travel, some of the ultrasonic waves are reflected back. Thus, an indication (H) is seen between the output echo (Ç) and the backwall echo (A).

If the reflector on the sound path is perpendicular to the sound beam axis and wider than the sound beam, no backwall echo is seen.



ULTRASONIC TESTING (UT)



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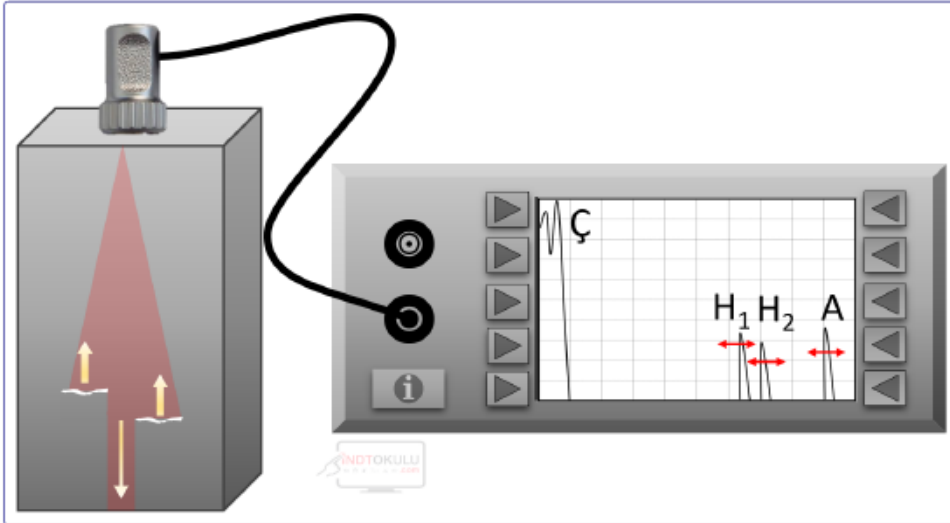


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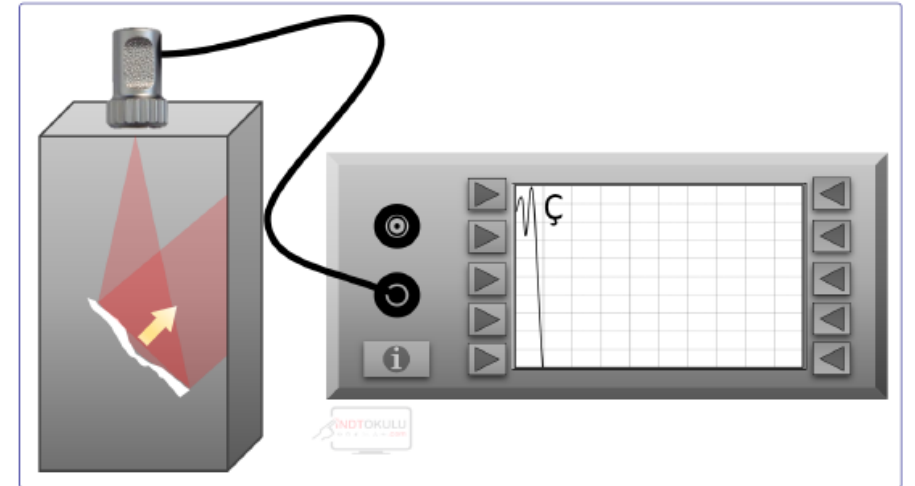


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Signals from reflectors at different distances will create different signals.

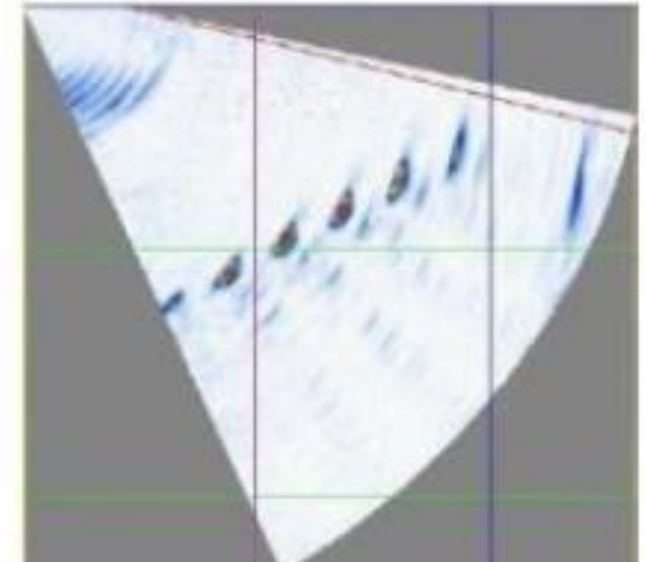
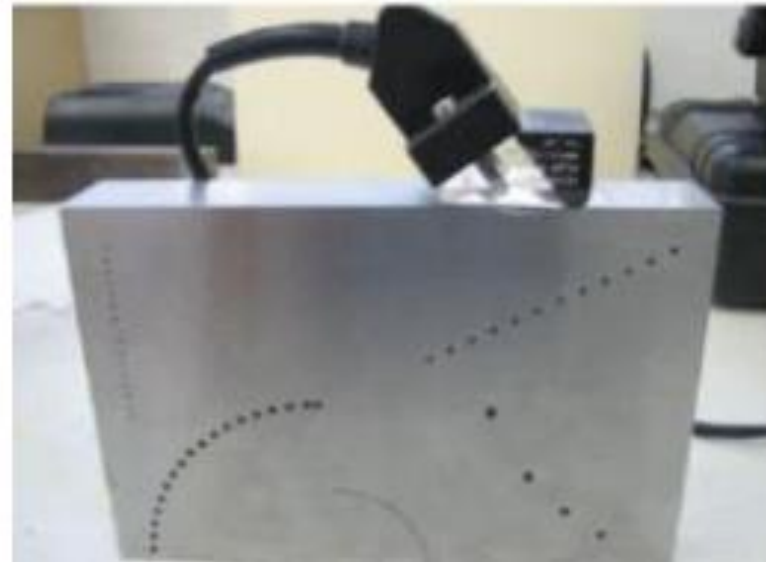
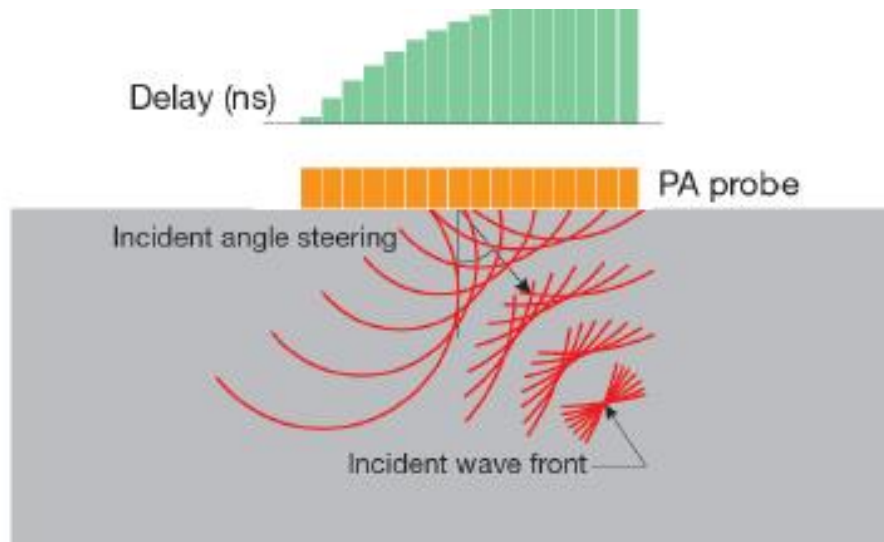


If the reflector on the sound path is not perpendicular to the sound beam axis and is larger than the sound beam, the sound pulse changes direction and the echo cannot come back to the probe. Since no sound waves reach the back wall, no back wall echo is received



PHASED ARRAY ULTRASONIC TESTING (PAUT)

PAUT devices have many small crystals (usually 16, 32, 64 or 128) inside a single probe that can be excited independently of each other. It is called "phased" because these small crystals are not fired at the same time, but with time delays of the microsecond order. Through these delays, sound waves can be directed at an angle or focused at a specific depth, creating constructive interference.



PHASED ARRAY ULTRASONIC TESTING (PAUT)



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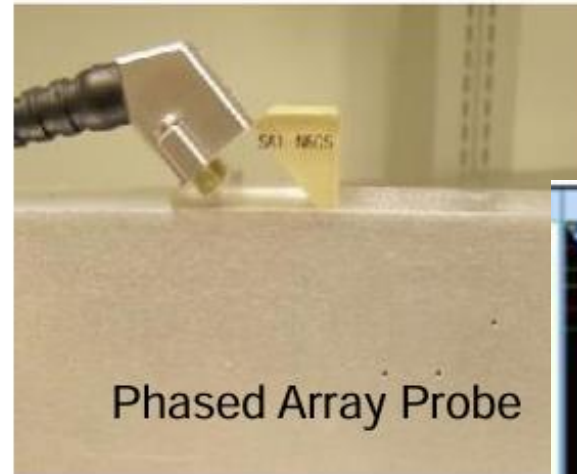
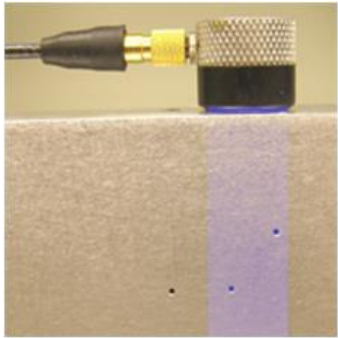


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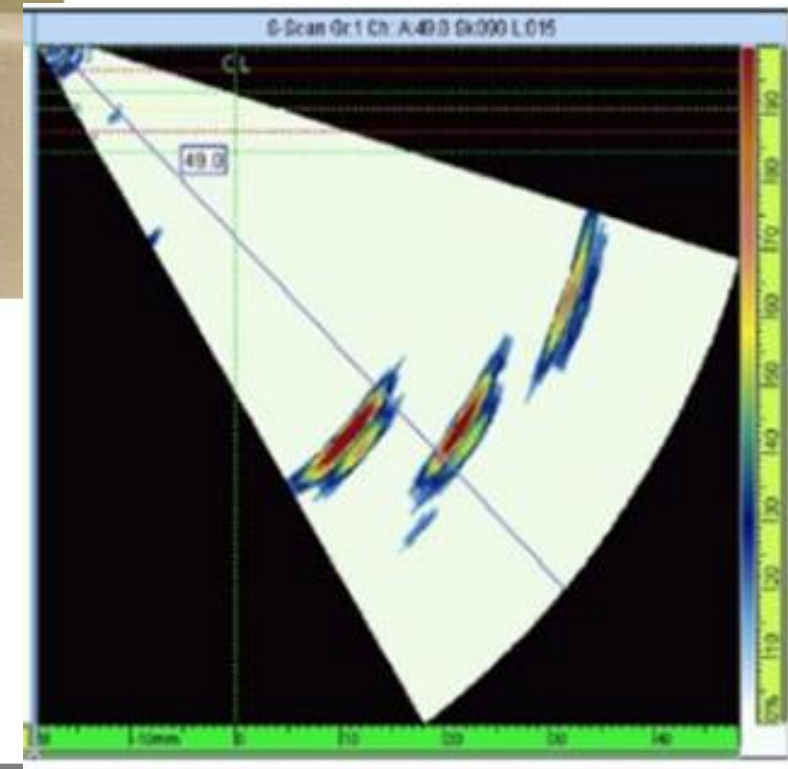
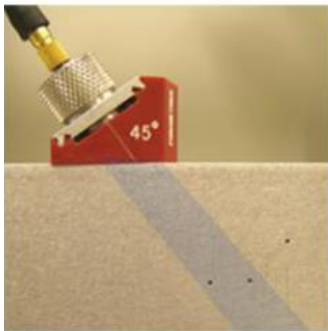
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Conventional SBP



Phased Array Probe

ABP



PHASED ARRAY ULTRASONIC TESTING (PAUT)



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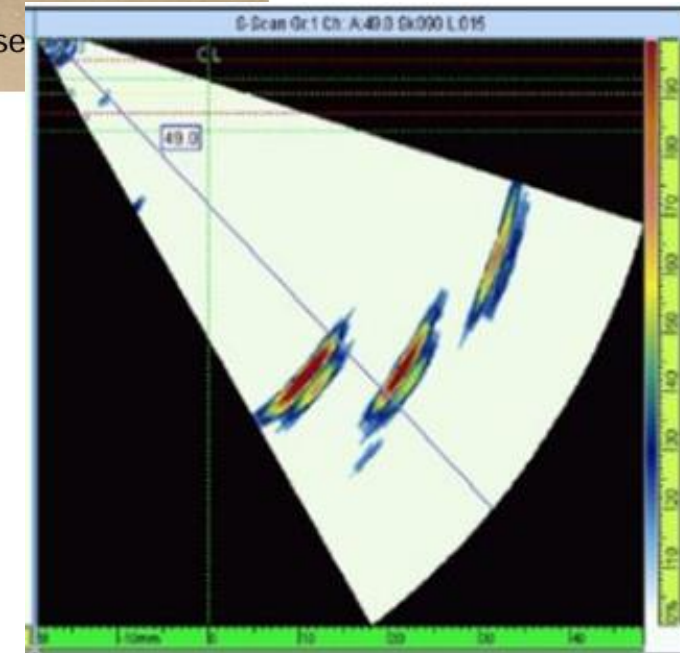
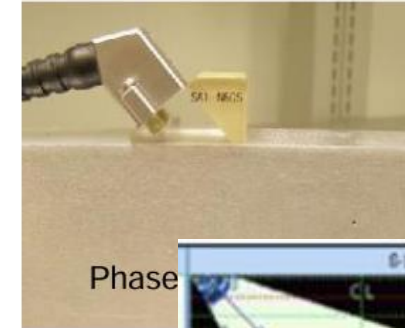
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Advantages:

- **Complex Geometries:** PAUT can "look" into hard-to-access areas because it can direct the beam electronically.
- **Defect Characterization:** It is very successful in detecting lack of fusion and microporosity, which are common in AM parts.
- **Quick Scanning:** Saves a lot of time in quality control of mass production AM parts.

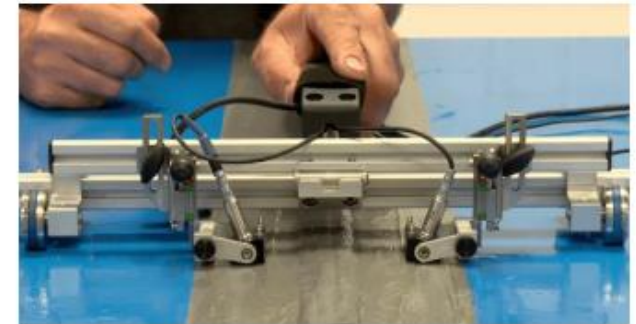
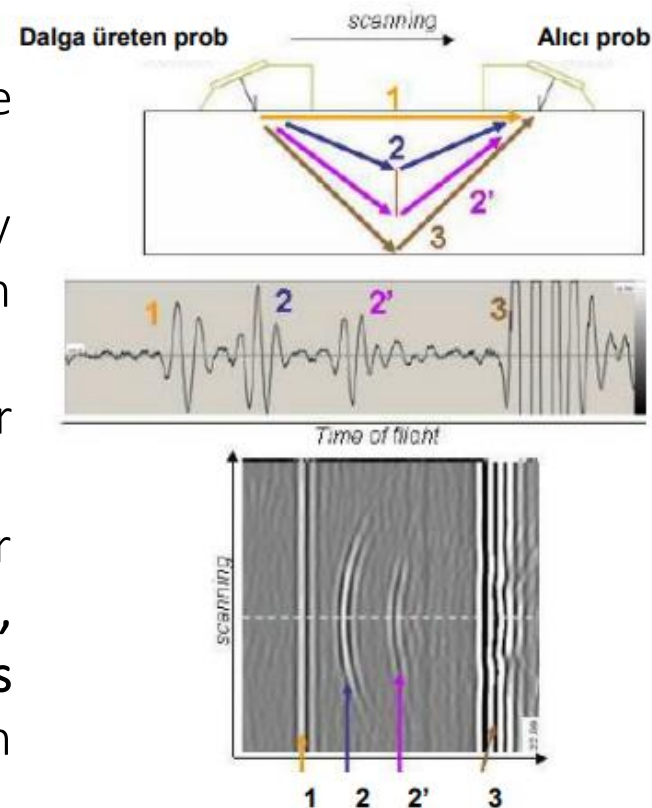
Challenges:

- **Microstructure:** Parts produced with metal 3D printers usually have a coarse-grained and oriented crystal structure. This causes the sound wave to **scatter** too much and cause noise.
- **Surface Roughness:** As-built AM part has a rough surface. It becomes difficult for the PAUT probe to make full contact (coupling) with the part. So it is usually applied after surface machining

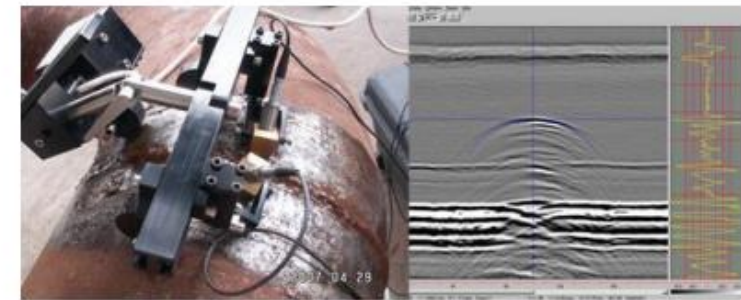


TIME OF FLIGHT DIFFRACTION TECHNIQUE (TOFD)

- TOFD is a method based on the principle of **diffraction** instead of reflection.
- Two probes, one transmitter and the other receiver, are used mutually.
- When the sound wave hits an defect, very weak diffraction waves are emitted from the endpoints of the error.
- TOFD detects the error by monitoring for these weak end waves.
- While other UT methods seek an answer to the question "**how big is the error?**", TOFD answers the question "**where does the error start and end?**" with micron precision.



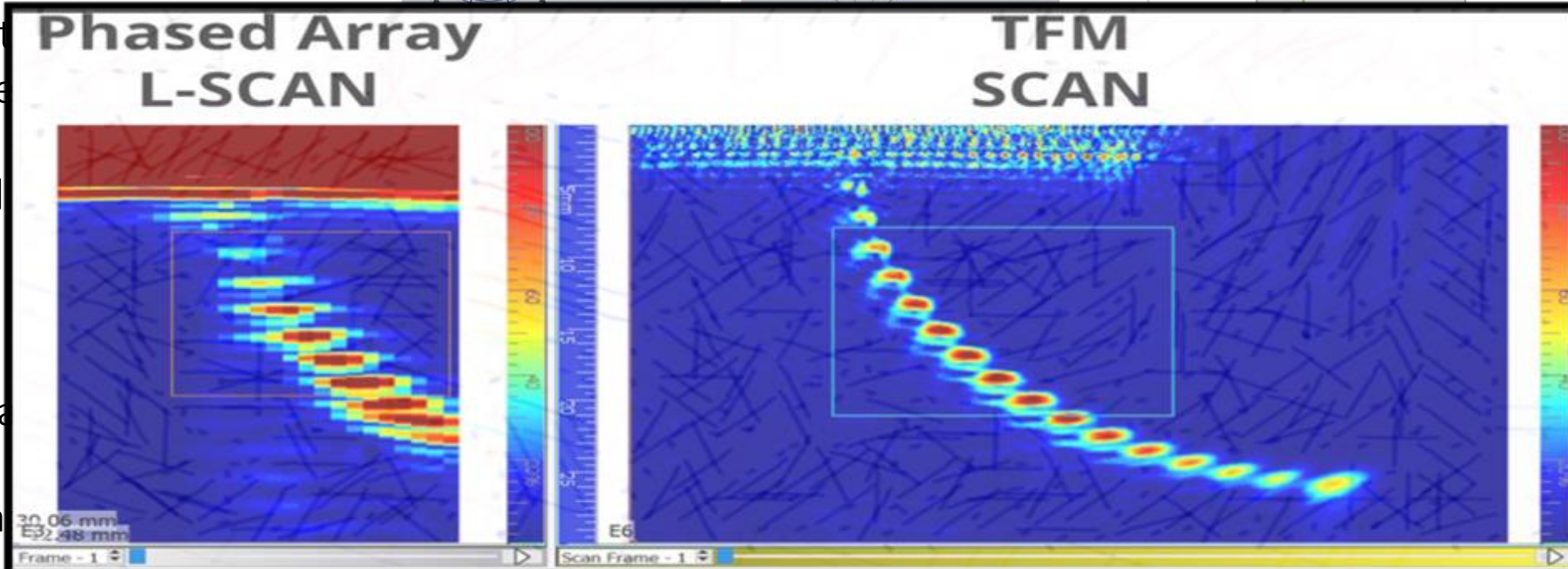
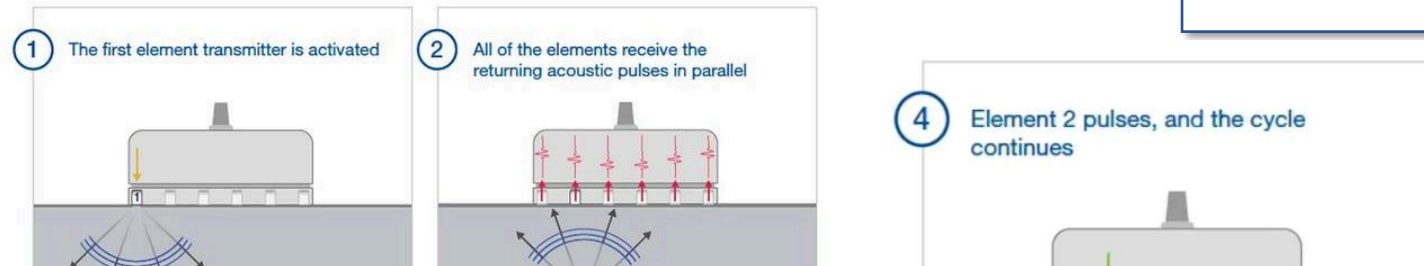
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<https://ndt-kits.com/wp-content/uploads/2022/02/tofd-ultrasonic-testing-.png>
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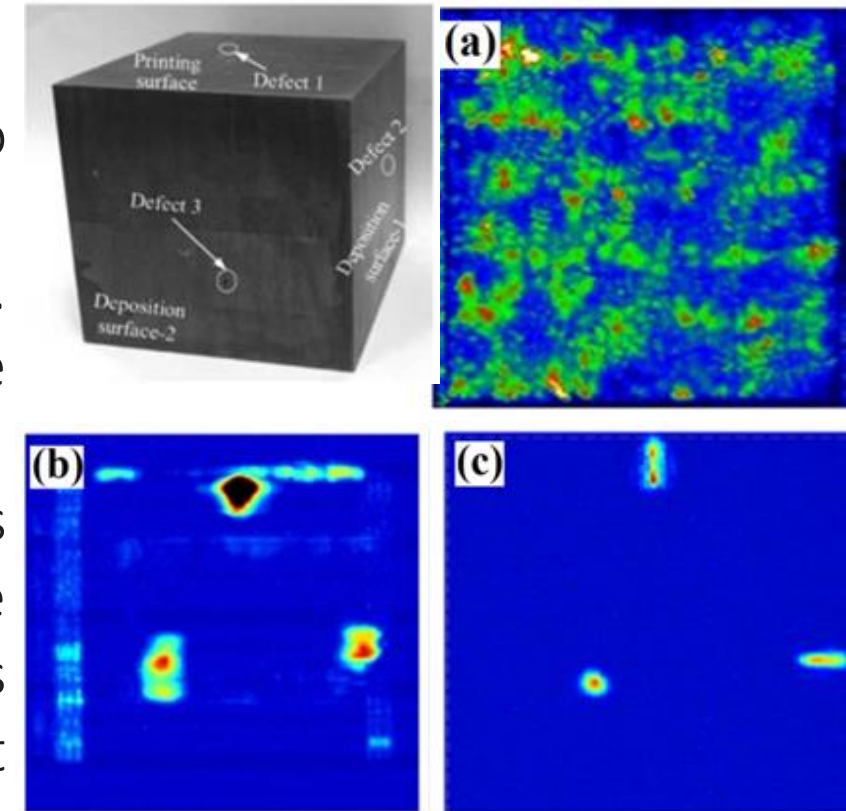
TOTAL FOCUSING METHOD (TFM)

- TFM is a software algorithm that actually uses **Phased Array** hardware, but the way it **processes data is completely different**.
- In PAUT, directed beam forms in a certain depth. But, in TFM method, the Phased Array probe sends a pulse and all crystals listen (this is called FMC - Full Matrix Capture).
- Using the huge data device "focuses" each pixel one by one.
- The classic Phased Array forms a beam at a certain depth, while TFM forms a beam at every pixel of the image.



ULTRASONIC TESTING in AM

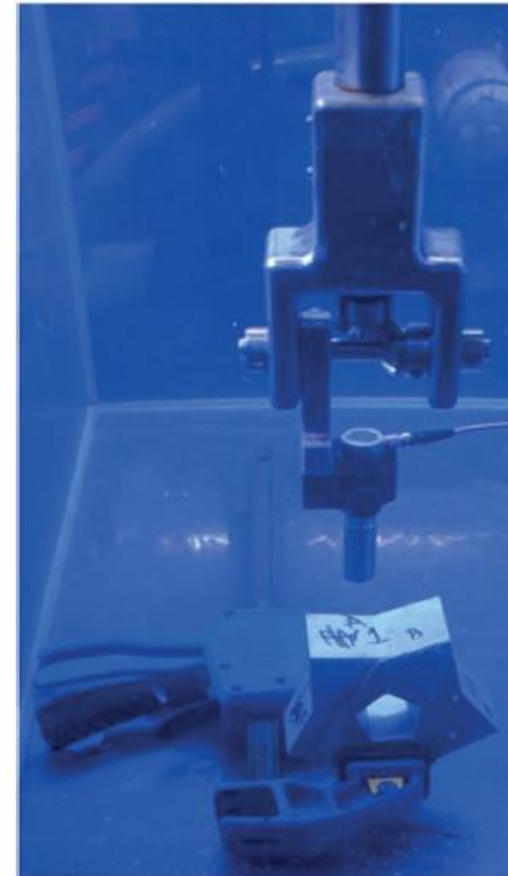
- ❖ Ultrasonic testing in additive manufacturing is highly dependent on the **process, material, and defect**
- ❖ Thicker layers in DED improve UT detectability compared to other AM methods
- ❖ **Polymers** absorb sound very quickly (attenuation). Conventional UT often fails due to the loss of sound inside the polymer.
- ❖ PAUT is more suitable contact method for AM parts. Thanks to its multi-crystal structure, the sound beam can be directed. There is a high chance of catching delaminations or lack of fusion (LOF) by looking at them from different angles.



C-scan images, a) conventional UT, b) linear array PAUT, c) annular array PAUT
[http://refhub.elsevier.com/S0041-624X\(20\)30166-9/h0525](http://refhub.elsevier.com/S0041-624X(20)30166-9/h0525)

ULTRASONIC TESTING in AM

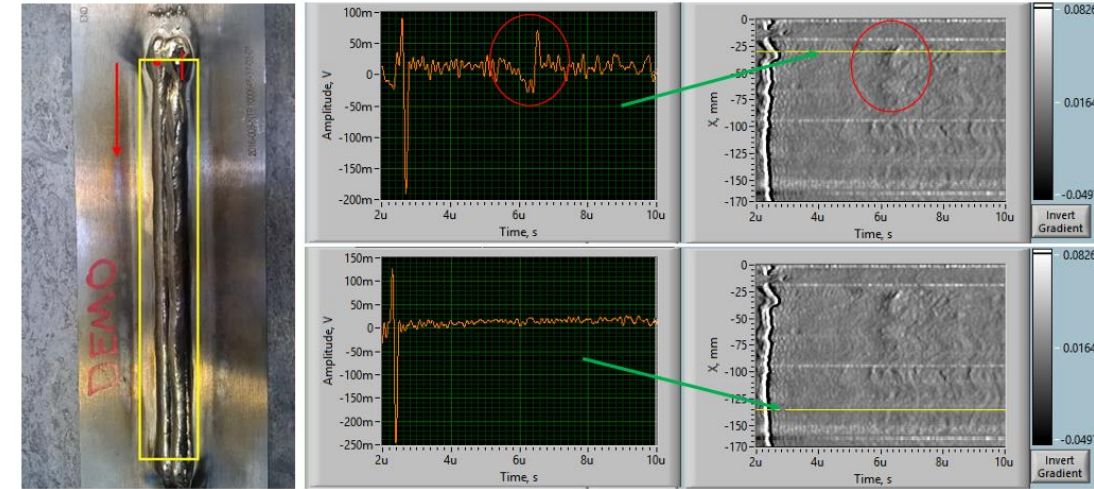
- ❖ Immersion UT for Metal AM is the inspection of the part by immersing it in water. It solves the problem of "air gaps" on rough surfaces with water. It is ideal for transmitting sound from every point of small metal parts with complex geometries (e.g. implants). But for Polymer AM, it is not recommended if the polymer is water-absorbing (open-cell structures); otherwise, it will give smooth results.
- ❖ Total Focusing Method (TFM) for Metal AM is a level up from PAUT. It focuses on every point of the region. It is an advanced algorithm that shows very fine and unoriented errors such as "lack of melting" in AM parts with the highest resolution. It has started to be recommended for critical parts in standards (such as ISO 52905).



ULTRASONIC TESTING in AM



- ❖ The Laser Ultrasound Technique (LUT) does not require contact with the part. In this way, it can be used in situ monitoring inside the 3D printer. It can catch layer defects even when the part is still hot (nearly 1000°C) and rough. It can work on both without surface preparation **for metal and polymers**, but the system is very expensive and complex to install.



DED sample with scan details (left); A-Scans (centre); and B-Scans showing an area with LOF (right) [Zhou X. et al. 3D-imaging of selective laser melting defects in a Co-Cr-Mo alloy by synchrotron radiation micro-CT," Acta Materialia]

- ❖ Air-Coupled Ultrasonic is the gold standard for polymers. Because polymers can be porous, the classic couplant can damage or trap the part. The air-contact UT detects layer separations in wafer-like polymer AM parts without using any liquids.

DRAWBACKS of UT in AM



- The following features observed in additive manufacturing parts make it difficult for ultrasonic waves to propagate:
 - Layered structure → multiple echoes
 - Anisotropy → signal interpretation
 - Surface roughness → reduce coupling quality
 - Complex geometries → create blind zones
- PAUT and TOFD can be applied for DED parts, but calibration is challenging due to anisotropy

ULTRASONIC TESTING in AM



Types of UT	Metal AM (PBF/DED)	Polimer AM (FDM/SLA)	Main Purpose of Use	Limitations
Conventional UT	Low (Surface treated)	Very Low	Thickness measurement, large voids.	Detectability of micron size defects, Coupling problems due to rough surfaces, Poor performance in complex geometries
PAUT	High	Medium	Delamination, Lack of Fusion	Beam steering errors in anisotropic AM microstructures, Complex calibration, High operator dependency, Reduced reliability in fine microstructures
Laser UT (LUT)	High (In-situ)	Medium	Contactless , fast scanning, in-situ monitoring	Very high system cost, Sensitive to surface condition, Limited industrial deployment, Complex data interpretation
Air Coupled UT	Low	High	Polymers that should not be contacted by liquid.	Very low signal-to-noise ratio, Limited penetration depth , Not suitable for metals, Only detects large defects
TFM	Highest	Low	Critical defect characterization	Extremely sensitive to anisotropy , High computational cost, Requires high-quality FMC data, Limited industrial robustness

RADYOGRAFİK TESTING (RT)

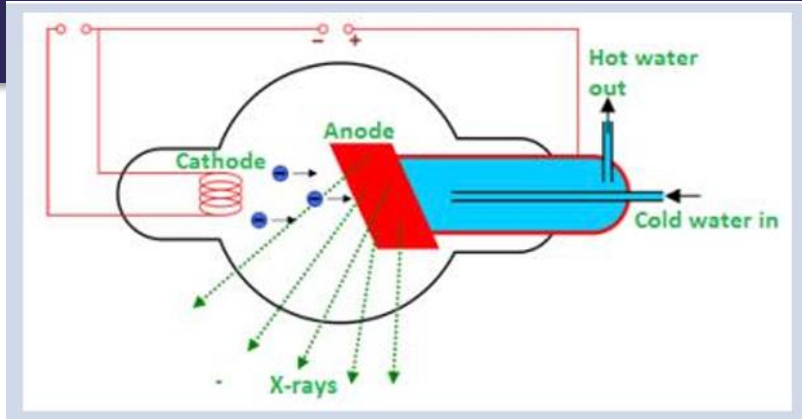
- X and gamma rays are electromagnetic waves and show both particle and wave properties.
- X and Gamma rays have high energy (low wavelength).
- They can penetrate materials.
- It has ionizing effects.
- They progress linearly.
- They can be defined as soft or hard.

Hard beam : High penetration
Soft : Low penetration

ELEKTROMANYETİK RADIASYON

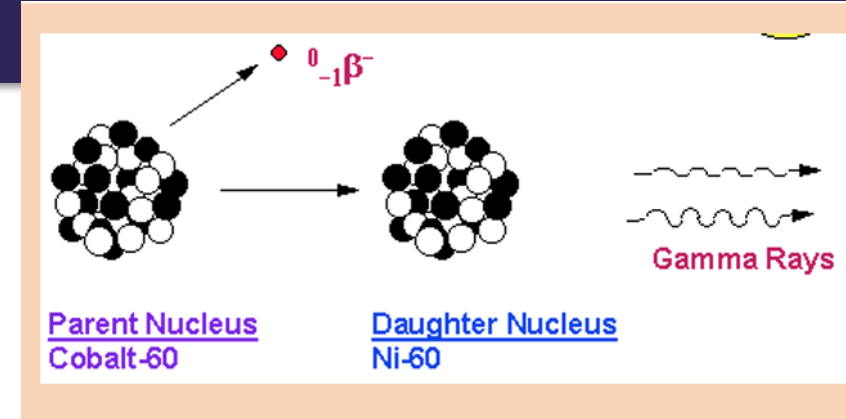


X-RAYs



- When electrons accelerated by a voltage difference hit an obstacle in their path, some of their kinetic energy is converted into X-rays.
- Three stages must occur for this event to occur:
 - 1- Electrons should be produced,
 - 2- It should be accelerated,
 - 3- A suitable obstacle should be placed in front of them to stop (brake).

GAMMA RAYS



- A continuous decay event occurs in a radioactive substance, in which excess energy is released as radiation, causing atomic instability.
- Alpha, Beta or Gamma rays or their mixtures are observed.
- Gamma rays are often used for radiographic examination.
- In the decay process, the intensity of radiation decreases. However, since the character of the decay does not change, the radiation energy remains the same.



RADYOGRAFIC TESTING (RT)



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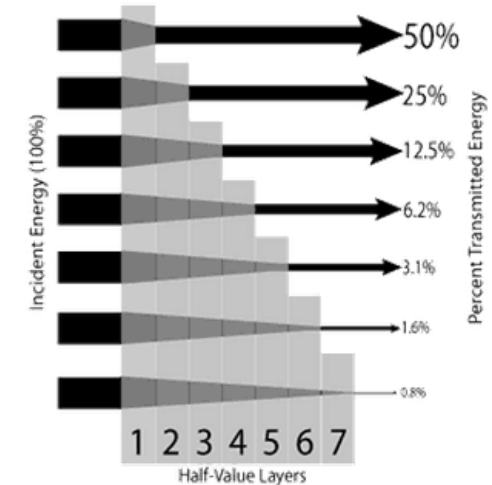
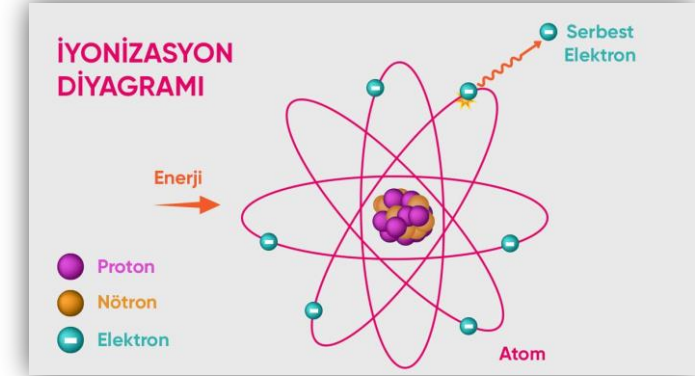
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Attenuation of Radiation:

- The intensity of radiation decreases (weakens) by the difference between the intensity of the radiation entering the material and the radiation exiting.
- The attenuation of radiation depends on absorption and scattering. The absorbed rays do not appear again.
- The energy of the scattered radiation is lower than the energy of the primary radiation due to losses and adversely affects the radiographic examination as it is in random directions.
- When X- or gamma rays hit the outer orbital of an atom, it knocks off an electron. The separation of one or more electrons from the atom turns the atom into an ion with a positive electric charge (ionization)



RADYOGRAFIC TESTING (RT)



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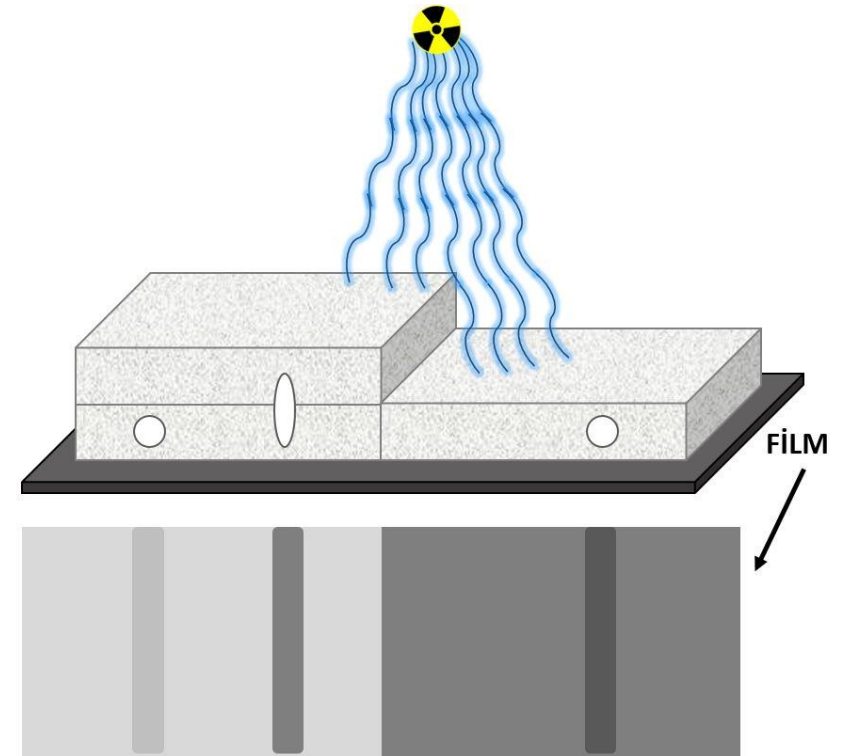
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Image Quality - Intensity and Contrast

- With radiography, thickness differences in an object, residues and voids in the internal structure, and other discontinuities are made visible on a film.
- In this method, X- or gamma rays passing through the material create different darkening amounts on films sensitive to these rays due to thickness differences in the material.
- The difference in intensity created by different amounts of darkening is called radiographic contrast. As the radiographic contrast increases in the image, the details of the discontinuities are more easily perceived.



RADYOGRAFIC TESTING (RT)



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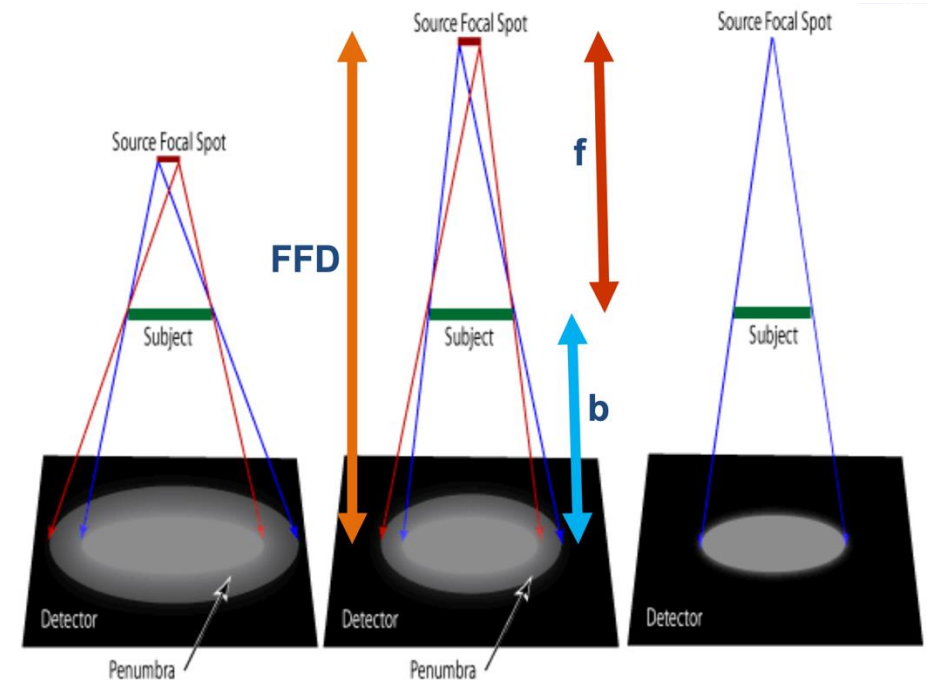
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Image Quality - Unsharpness

- It is the penumbra that distorts the sharpness in the image. The smaller the unsharpness, the better the image quality.
- The unsharpness has two components, the inevitable (U_i) and the geometric unsharpness (U_g).
- The decrease in sharpness due to irradiation geometry is called geometric penumbra, and the one formed by the effect of electrons breaking off from the film, screen or atoms in the material itself is called inevitable penumbra.



RADYOGRAFIC TESTING (RT)



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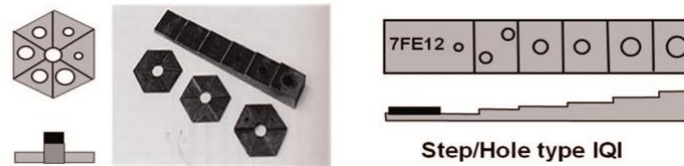
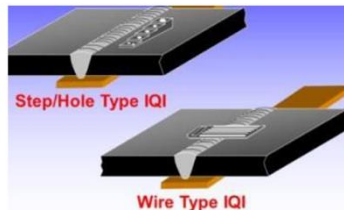
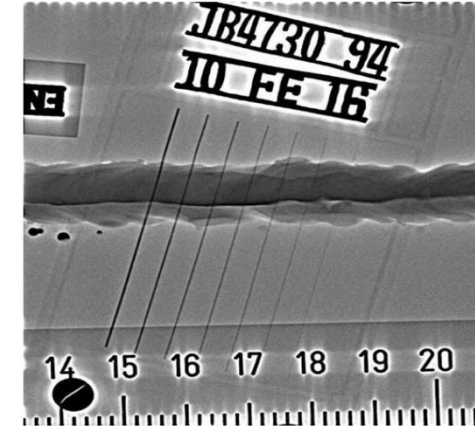
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Image Quality - Indicators

- Image Quality Indicators (IQI) have been developed to determine whether the film has a level of image quality that can show errors and to evaluate it impartially.
- In **EN ISO 19232** standards, 3 separate image quality indicators are defined:
 1. Wired image quality markers (**EN ISO 19232-1**)
 2. Graded/Hole-type image quality markers (**EN ISO 19232-2**)
 3. Double-wire image quality markers (**EN ISO 19232-5**)



Step/Hole type IQI



Wire type IQI

RADYOGRAFIC TESTING (RT)

EN ISO 5579 : General rules for radiographic testing

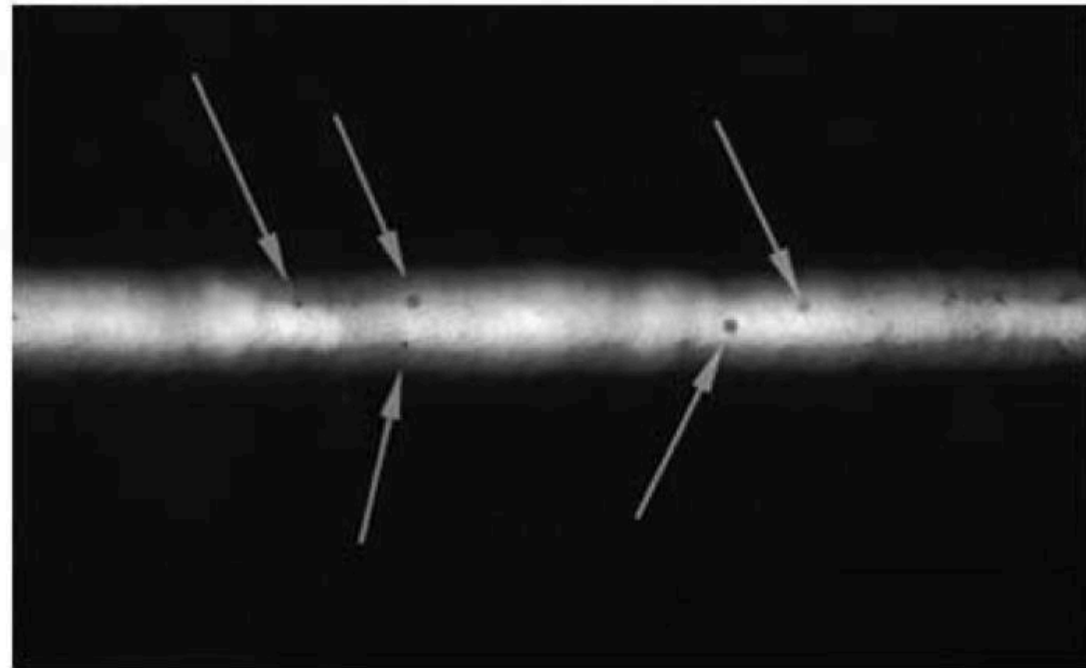
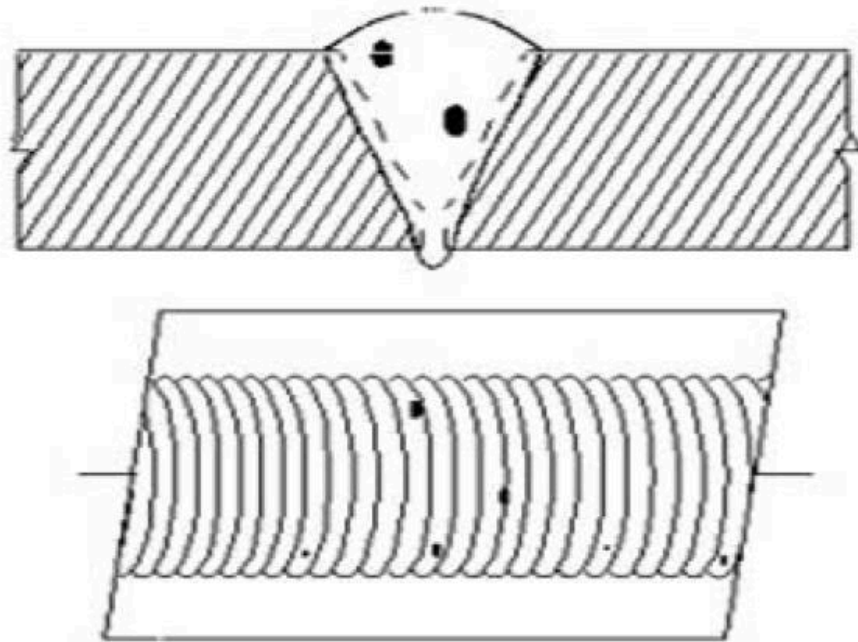
- The Energy (kV) to be used in the inspection is selected depending on the thickness and type of the material
- Select the Film class to be used
- Shooting arrangement is determined
- The appropriate penetrometer is selected
- The appropriate density is determined
- Exposure time is calculated
- Film exposure is performed
- Film development processes are completed
- Film review



RADYOGRAFIC TESTING (RT)

The EN ISO 6520 standard defines defects that occur after the welding process

- Porosity



RADYOGRAFIC TESTING (RT)



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The EN ISO 6520 standard defines defects that occur after the welding process

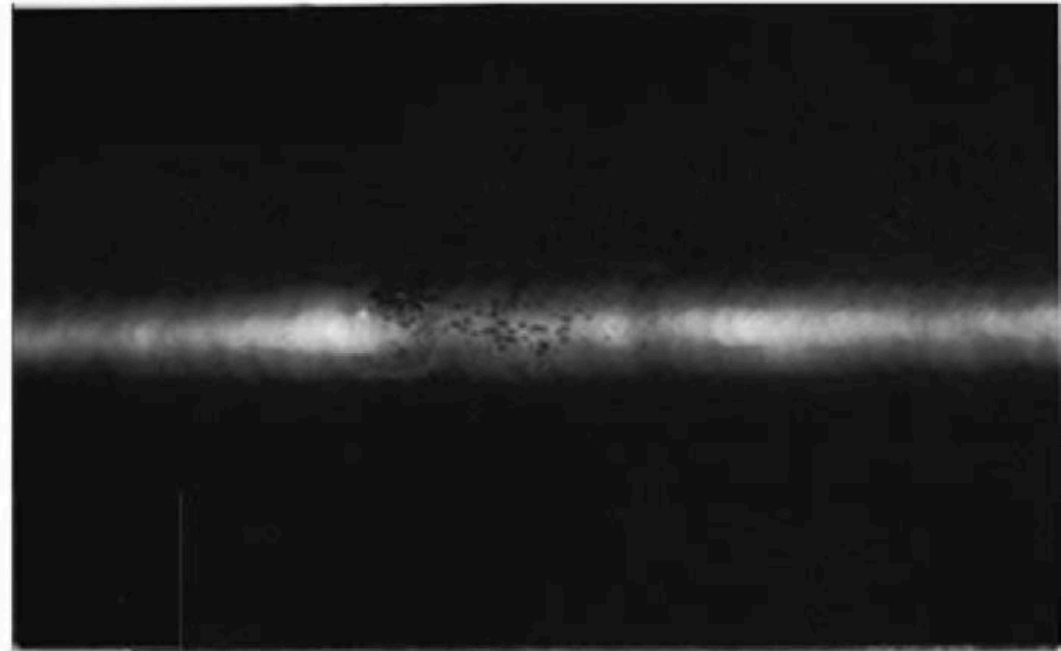
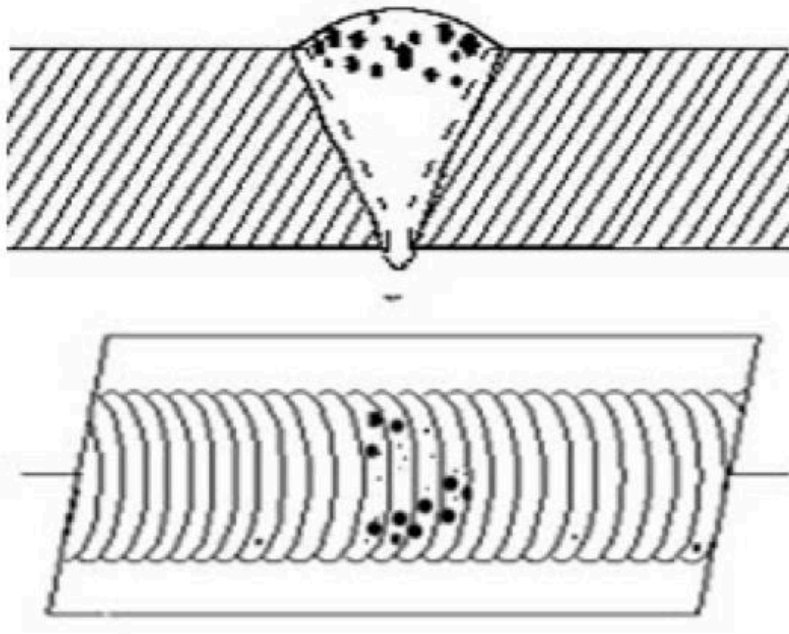
- Clustered Porosity



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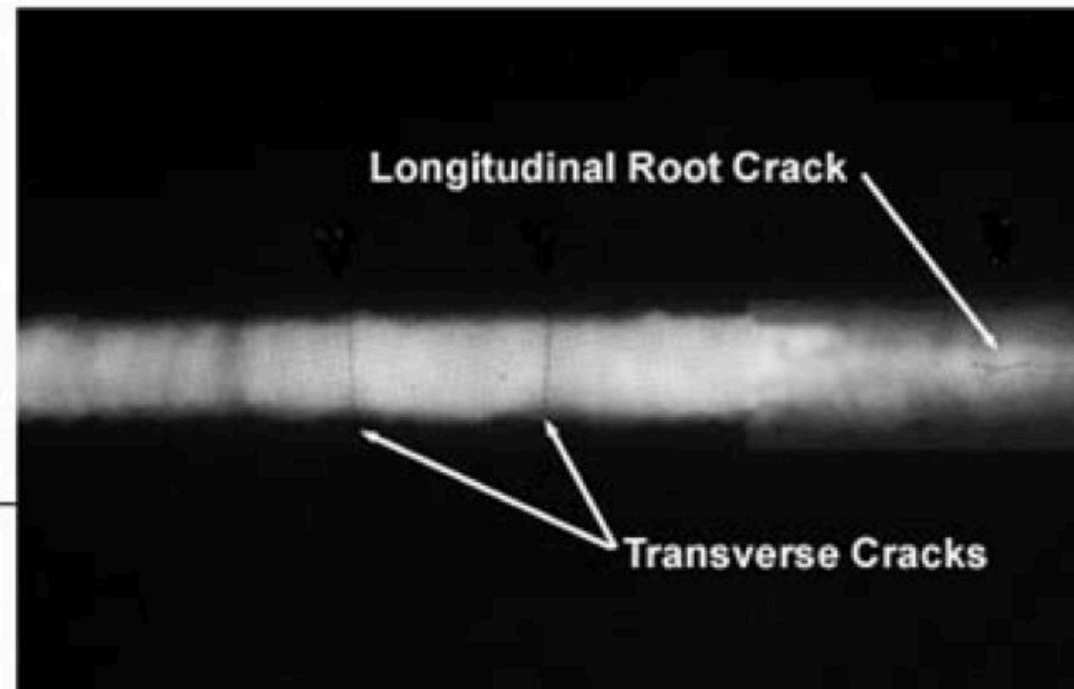
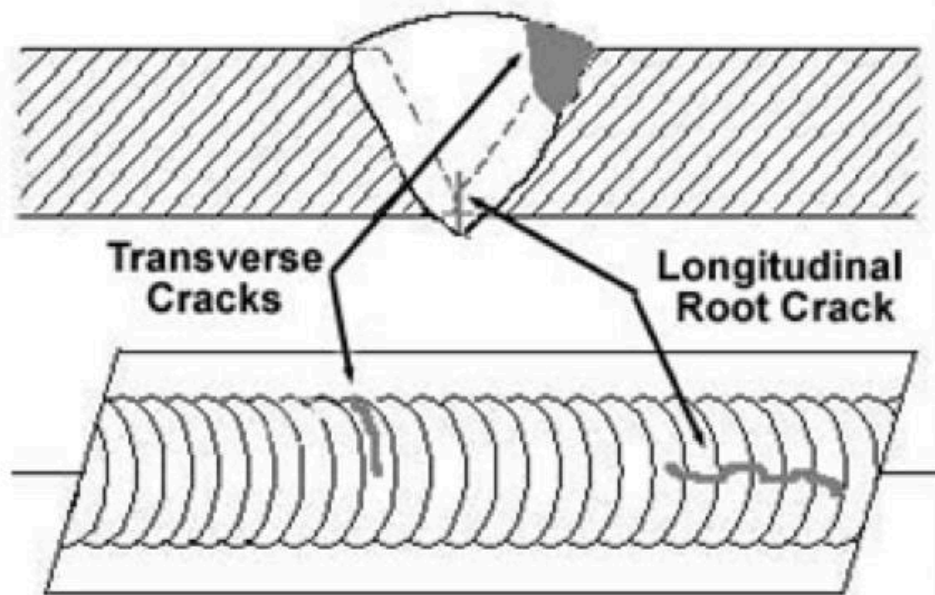
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RADYOGRAFIC TESTING (RT)

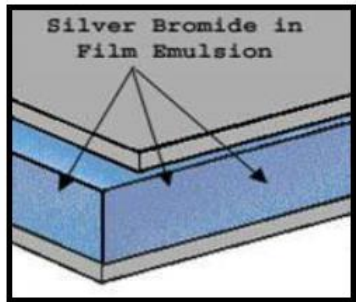
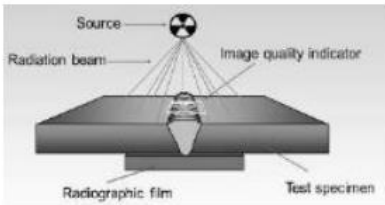
The EN ISO 6520 standard defines defects that occur after the welding process

- Crack

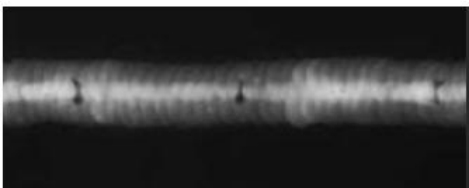


DIGITAL RADYOGRAFIC TESTING (DRT) and COMPUTED TOMOGRAPHY (CT)

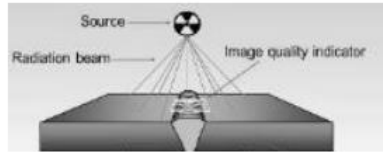
Film Radiography (RT)



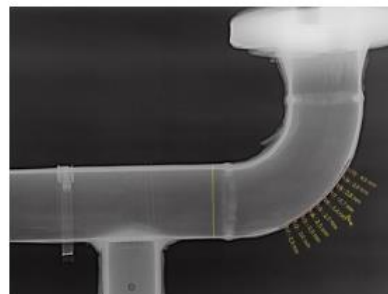
Radiation
→ ionization of AgBr particles
(hidden image)
Chemical processing in a dark room
→ Grayscale image on a film



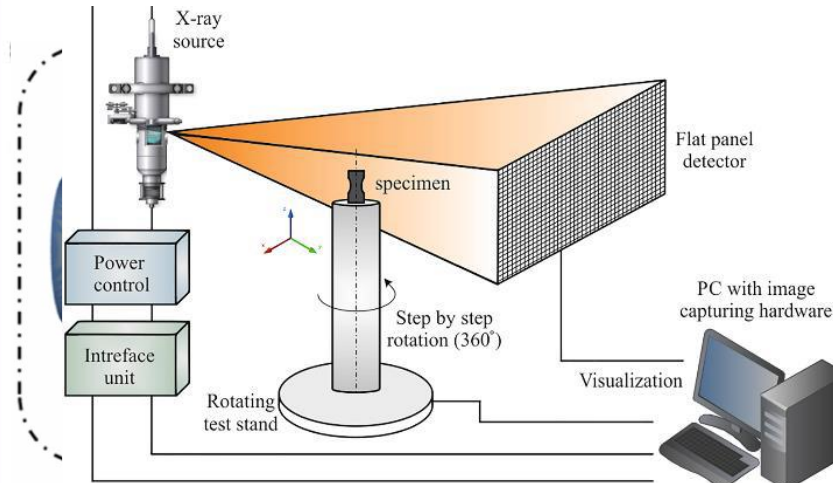
Digital Radiografi (DR)



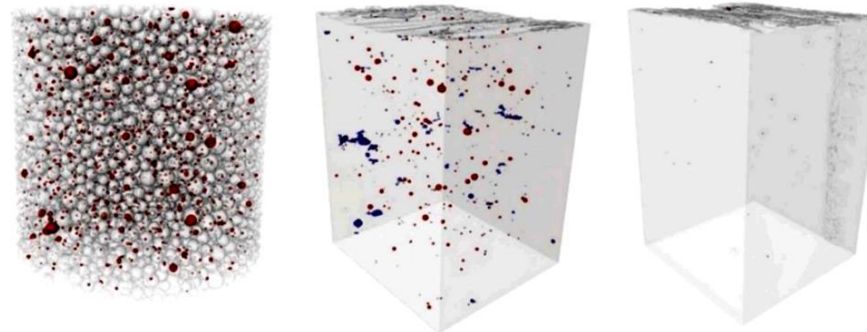
Film → Panel
containing micro-capacitors that
convert radiation into electrical
signals and image pixels
→ Digital image on the computer



Computed Tomography (XCT)



Khosravani, M.R., Reinicke, T. On the Use of X-ray Computed Tomography in Assessment of 3D-Printed Components. J NondestructEva139, 75 (2020)



Drawbacks

- Detection limit = minimum voxel size
- No international standard
- Difficult processes
- Lack of 3D-printed artifacts for calibration
- High Cost
- Lack of well-trained personnel

Images

Projection images

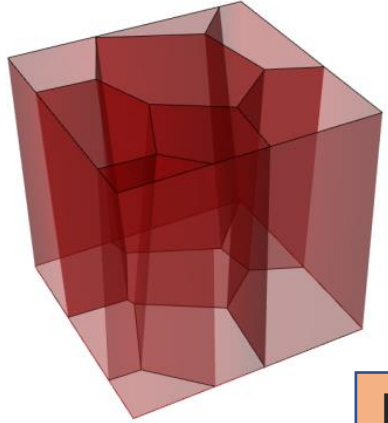
DIGITAL RADYOGRAFIC TESTING (DRT)



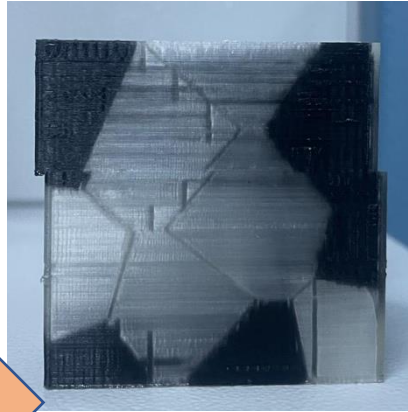
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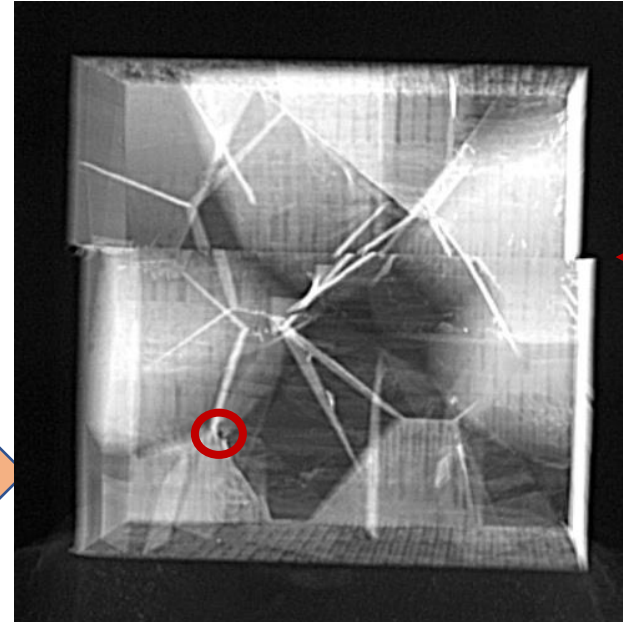
ULAŞ YAMAN RESEARCH GROUP STUDIES



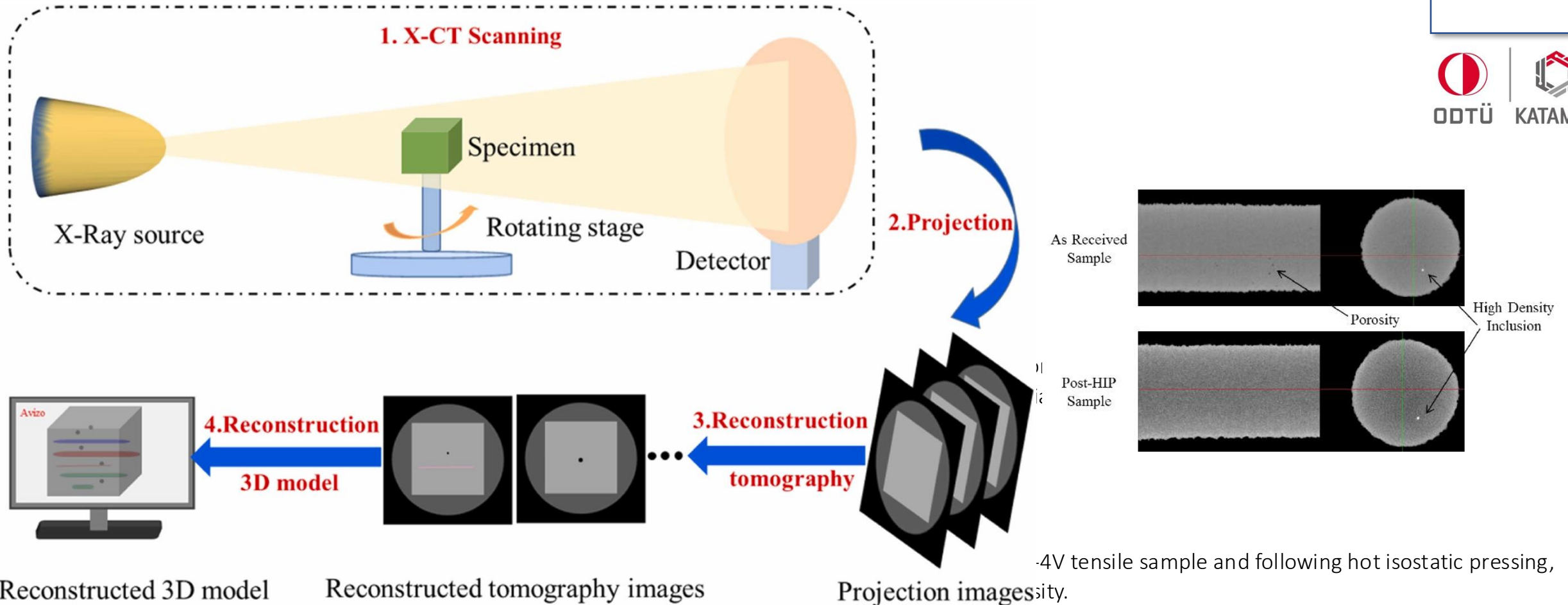
FLA via FFM



DDA

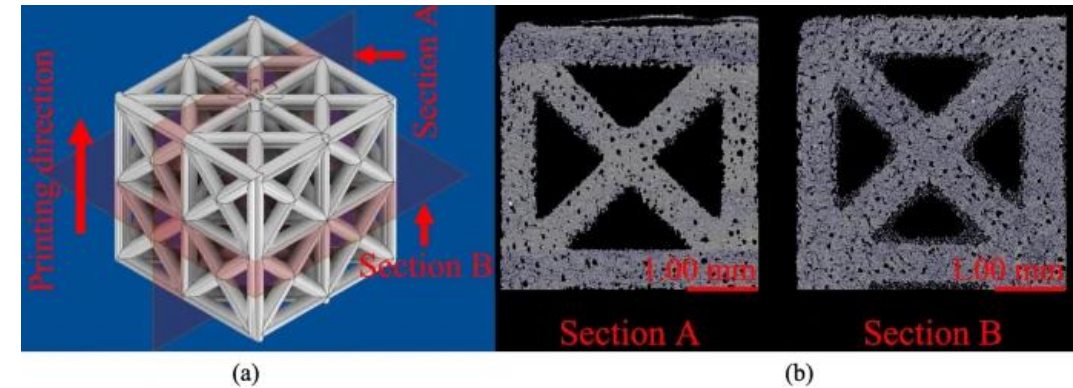
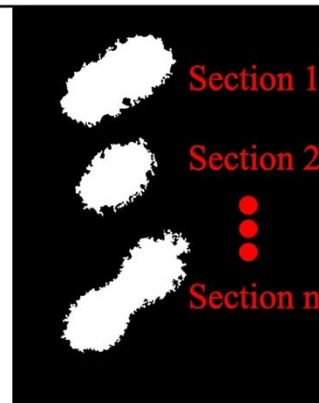
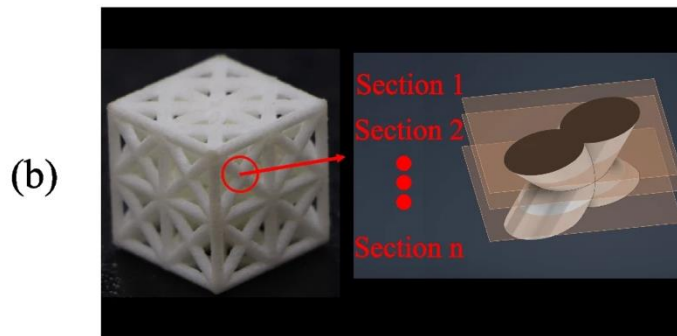
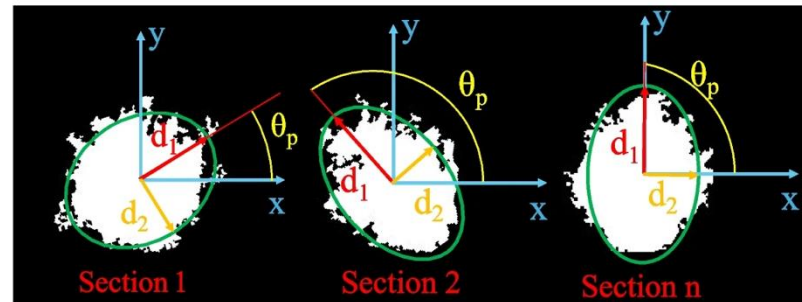
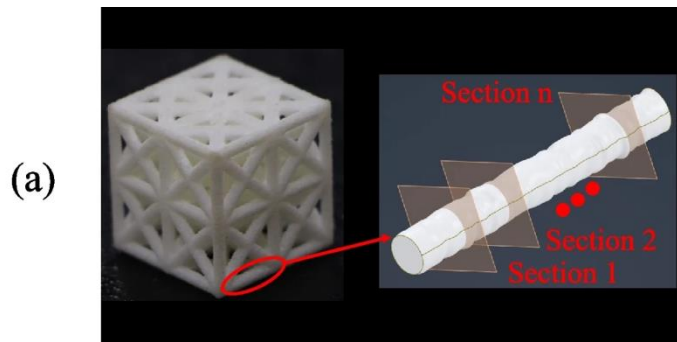


COMPUTED TOMOGRAPHY (CT)



COMPUTED TOMOGRAPHY (CT)

CT for Polymer AM



The procedure for geometric defect characterisation in a single strut (a), including sectioning the strut along its length at various layers (the left-side image) and fitting an ellipse to the strut cross-section at the corresponding layer (the right-side image), and (b) a single node, including sectioning the structural node along its length at various layers (the left-side image), and the calculation of node cross-sectional area for the corresponding section (the right-side image)

DIGITAL RADYOGRAFIC TESTING (DRT) and COMPUTED TOMOGRAPHY (CT)



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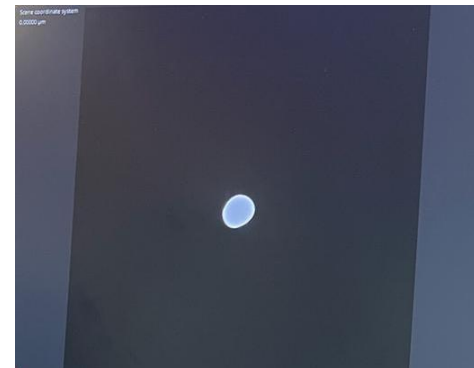
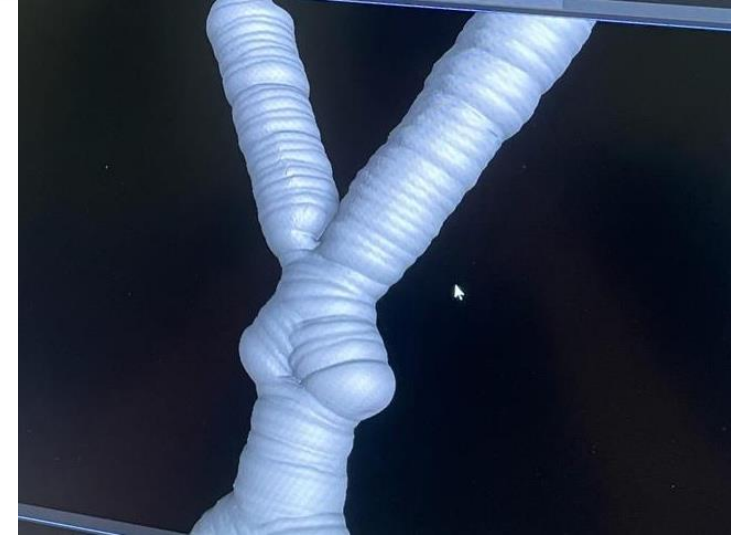
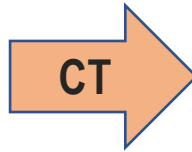


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RT, DRT and CT in AM



Feature	Film Radiography	Digital (DDA/CR)	Computed Tomography (CT)
Image Size	2D	2D	3D (Volumetric)
Speed	Slow (Film Processing available)	Fast	Medium/Slow (Processing time)
Internal Channel Analysis	Weak	Medium	Excellent
Precision	High	Very High	Highest (Submicron)

RT, DRT and CT in AM

Table 5 — Review of NDT technique potential for AM parts **Post built NDE method potential for a complex lattice structure with as built surface finish (capability levels are H – High, M – Medium, L – Low and Empty – None)**

Class	Type	Sub-type	Including...	Surface breaking cracks / lack-of-fusion	Surface breaking voids	Internal cracks / lack-of-fusion / layer defects	Isolated / clustered porosity	Internal voids, incl. cross-layer defects	Inclusions	Trapped powder (Powder Bed Fusion only)	Near surface micro-structure variation	Sub-surface micro-structure variation	Near surface residual stress	Sub-surface residual stress
Mechanical	Ultrasonic	Contact or near-contact (air-coupled)	Single / twin / array probe, Time of Flight Diffraction											
		Immersion												
	Vibration analysis	Resonance testing	Acoustic pattern recognition	M	M	L	L	M		M				
Optical / visible light	Simple		Aids such as lighting / borescope etc.		M					M				
	Dye-penetrant		Fluorescent / visible											
Radiographic	X-ray	Conventional, 2D	Film / Computed / Real-time / Digital		M		M	M	M	M				
		Computed Tomography	2D (fan beam) / 3D (cone beam) CT / Laminography	L	H	L	H	H	H	H				
		Diffraction												

METALS and POLYMERS in AM INSPECTION



Metal AM Parts

Surface Condition: The surface is generally rough. This roughness makes the liquid penetrant difficult to clean and leads to "pseudocrack" signals.

Internal Defect Detection: It is resistant to X-ray due to its high-density atomic structure. Requires very high energy (150kV+, depend on thickness) X-ray or Micro-CT systems for thick parts.

Polimer AM Parts

Surface Condition: Layer lines (especially in FDM) create micro-channels that draw the liquid into it. Liquid (in PT or UT) can permanently contaminate or degrade the part.

Internal Defect Detection: Thanks to its low-Z structure, it is transparent to X-rays. Even with very low energy (40-100kV), high-resolution internal structure images can be obtained.

LIMITATIONS of TECHNIQUES



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Metal AM Parts

Sound Conductivity: The metallic crystal structure and grain orientation at the layer boundaries refract and attenuate the ultrasonic sound waves. Forward focusing, such as **PAUT** or **TFM**, is required for precise measurement.

Physical Properties: It has electrical conductivity and (in some materials) magnetic properties. In this way, subsurface microscopic cracks can be scanned with **ET** and **MT**.

Polimer AM Parts

Sound Conductivity: Polymers inherently absorb sound very quickly (attenuation). Traditional ultrasonic probes often remain "blind"; In general, **non-contact laser ultrasonic** methods are investigated.

Physical Properties: It is electrically insulating. Magnetic or electrical NDT methods (**MT, ET**) **cannot be used** on these parts.

LIMITATIONS of TECHNIQUES



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Metal AM Parts

Discontinuities Types: Lack of Fusion between layers, gas pores and microcracks due to high thermal stress are the most critical defects.

Aviation Admission: In accordance with *ISO/ASTM 52905*, 100% volumetric (CT) and surface inspection is generally required. Part criticality is very high.

Polimer AM Parts

Discontinuities Types: Delamination, internal voids, warping, and retention of support structures in internal channels are critical.

Aviation Admission: It is generally used in non-structural parts (cabin interior, etc.). Dimensional accuracy and visual quality are paramount over internal structural defects.



THANKS



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References



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- NASA-STD-5009: Nondestructive evaluation requirements for fracture-critical metallic components.
- EN 16602-70-15:2021 - Space product assurance - Non-destructive testing.
- ISO/ASTM 52905:2023 - Additive manufacturing of metals — Non-destructive testing and evaluation — Defect detection in parts.
- ISO/ASTM 52906:2022 - Additive manufacturing — Non-destructive testing — Intentionally seeding flaws in metallic parts
- ASTM 3166: Standard Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build.
- ISO/ASTM DIS 52948 Additive manufacturing for metals — Non-destructive testing and evaluation — Imperfections classification in PBF parts
- ISO/ASTM DIS 52969 Additive manufacturing of metals — Non-destructive testing and evaluation — Classification of imperfections in DED parts
- Khosravani, M.R., Reinicke, T. On the Use of X-ray Computed Tomography in Assessment of 3D-Printed Components. J NondestructEval39, 75 (2020)
- <https://www.sciencedirect.com/journal/current-opinion-in-solid-state-and-materials-science>
- [http://refhub.elsevier.com/S0041-624X\(20\)30166-9/h0525](http://refhub.elsevier.com/S0041-624X(20)30166-9/h0525)
- ASTM 3166: Standard Guide for Nondestructive Examination of Metal Additively Manufactured Aerospace Parts After Build
- ISO/ASTM JG59 DTR 52905, 'Additive Manufacturing — Non-Destructive Testing and Evaluation — Standard Guideline for Defect Detection in Metallic Parts
- Amirian, A., Battley, M., Diegel, O. et al. Additive manufacturing defects in polymeric lattice structures: a comprehensive analysis of morphology, distribution, and printing orientation influence. Int J Adv Manuf Technol 140, 5361–5384 (2025).
- Du W, Bai Q, Wang Y B and Zhang B 2018 Eddy current detection of subsurface defects for additive/subtractive hybrid manufacturing Int. J. Adv. Manuf. Technol. 95 3185–95



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ECSS-Q-ST-70-80C-Processing and quality assurance requirements for metallic powder bed fusion technologies for space applications

Table 8-2: Overview of non-destructive tests for AM hardware

Test definition	Safety Class 1.1	Safety Class 1.2	Safety Class 2	Safety Class 3
X-Ray CT	100 %	100 %	-	-
Visual inspection	100 %, or as far	100 %, or as far	100 %, or as	100 %, or as far

PMP.MPS.000102845-Procurement specification: manufacturing of Ti-6Al-4V ELI parts made by Laser Beam Additive Manufacturing

	HIP	No HIP
Class A (*)	No gas porosities > 0.1 mm. No inclusions > 0.1 mm	No gas porosities > 0.2 mm. No inclusions > 0.2 mm
Class B (**)	No gas porosities > 0.1 mm. No inclusions > 0.1 mm	No gas porosities > 0.2 mm. No inclusions > 0.2 mm

AIMS03-22-000-Additive Manufacturing Metallic Powder Bed Fusion Technology. Titanium Alloys Blank Product

Table 4: Internal defects for qualification and cut-up validation

Description of material discontinuity	Acceptance Criteria		
	Acceptance level		
	QL1	QL2	QL3
Cracks ⁽¹⁾	<200x200x200 µm		
Lack of Fusion ⁽¹⁾			
Recoating defect/delamination ⁽¹⁾			
	<200x200x200 µm	<500x500x500µm	
Gas porosities and less dense inclusion ⁽¹⁾	No line porosity is acceptable Where the distance (d) between two individual porosities is ≤ d1 (where d1 is the size of larger pore) they shall be considered as a single pore		
			
		<200x200x200µm accepted; ≥200 x200x200 µm and <400x400x400 µm accepted if distance between two or more defects of this range of size is > 25mm; ≥400x400x400 µm are rejected	<500x500x500µm accepted; ≥500x500x500µm and <800x800x800µm accepted if distance between two or more defects of this range of size is > 25mm; ≥800x800x800µm are rejected
Solid inclusion ⁽²⁾			

⁽¹⁾: CT devices and inspection procedures shall show capability to detect the minimum dimension of the acceptable material discontinuity.

⁽²⁾: CT inspection process might lead to oversizing of the actual inclusion size. In case of non-compliance of the criteria, a proper demonstration of the real defect size (re-scan at a higher resolution or metallurgical cut-up) shall be provided.

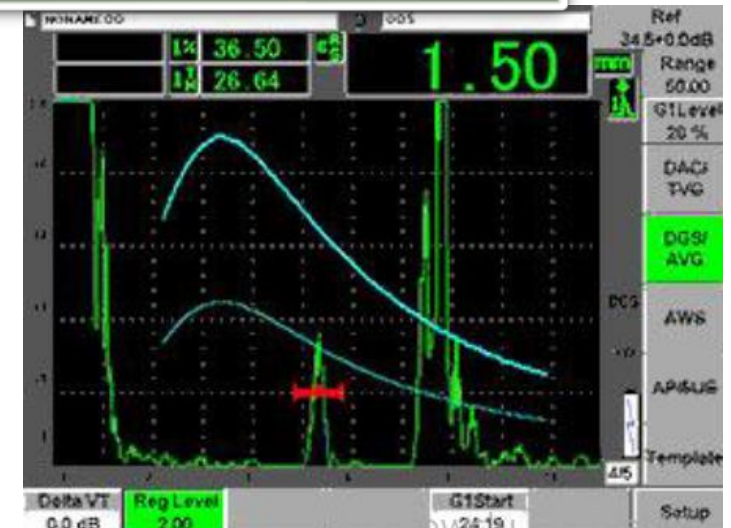
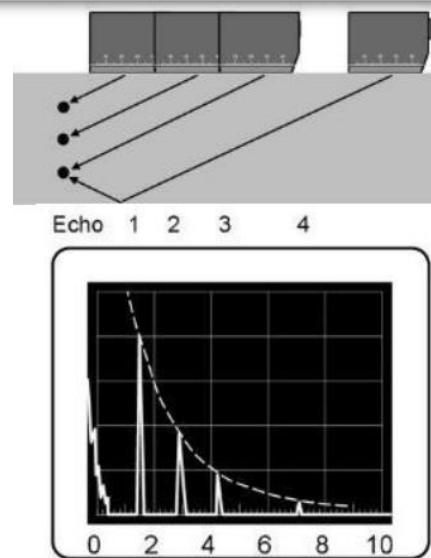
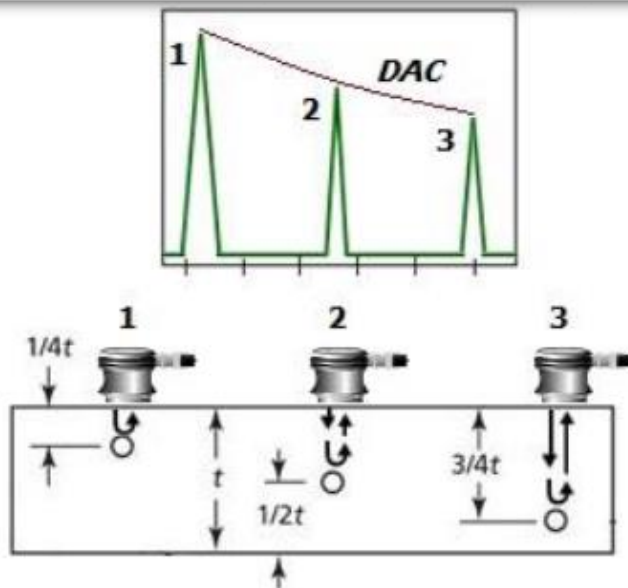
ULTRASONIC TESTING (UT)



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- Ultrasonic inspection with SBP is highly effective in thick materials, especially in lamination inspection. If the defect length is greater than the diameter of the sound beam, the size can be found with the **Half value method**.
- If the defect size is less than the sound beam diameter, an approximate error size can be found by drawing comparison curves (DAC or DGS curve)



RADYOGRAFIC TESTING (RT)



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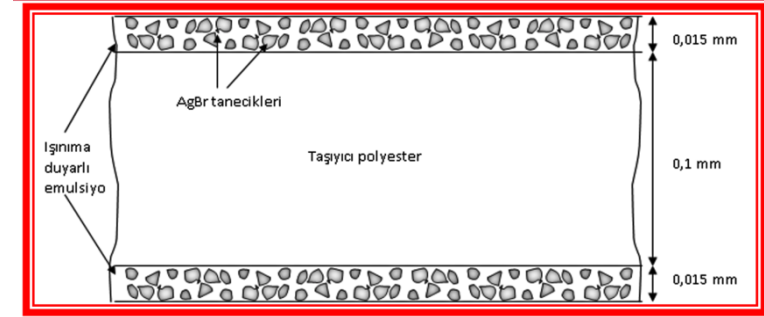
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Radiographic Film

- The carrier layer in a radiographic film is made of polyester material, which is rigid but flexible and transparent.
- This layer is coated on both sides with a layer of AgBr emulsion that is sensitive to radiation with a thickness of approximately 0.015 mm.
- The exposure time required for high-sensitivity films (fast films) is short; Because the grain size of the films is larger.
- Low-sensitivity films, on the other hand, are fine-grained and require longer exposure times to achieve a certain density compared to coarse-grained films.

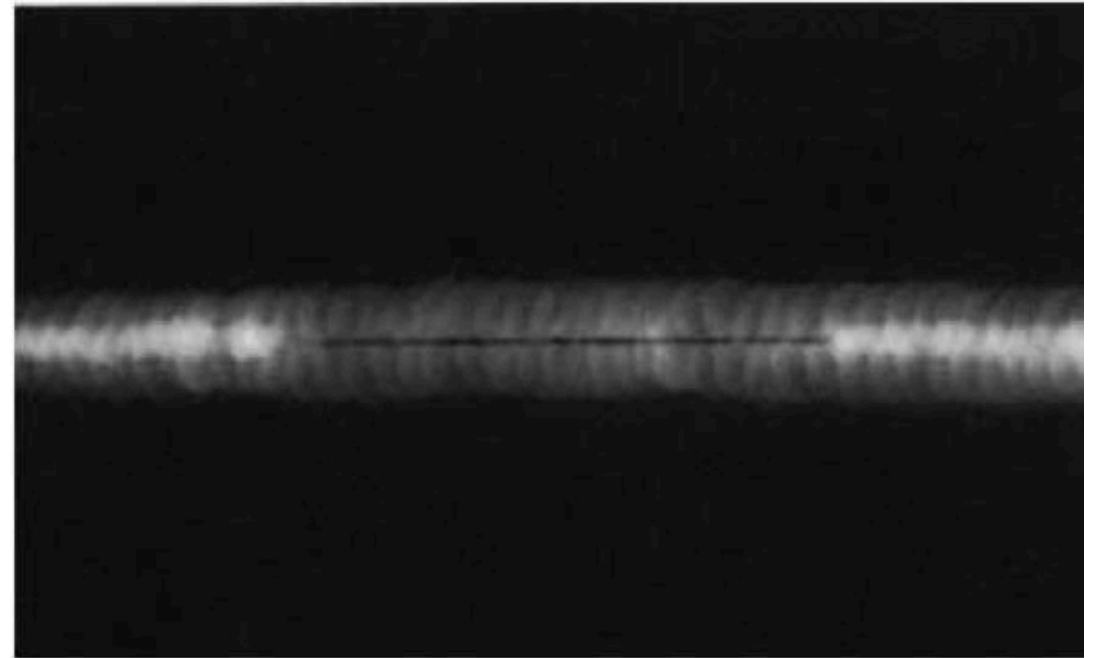
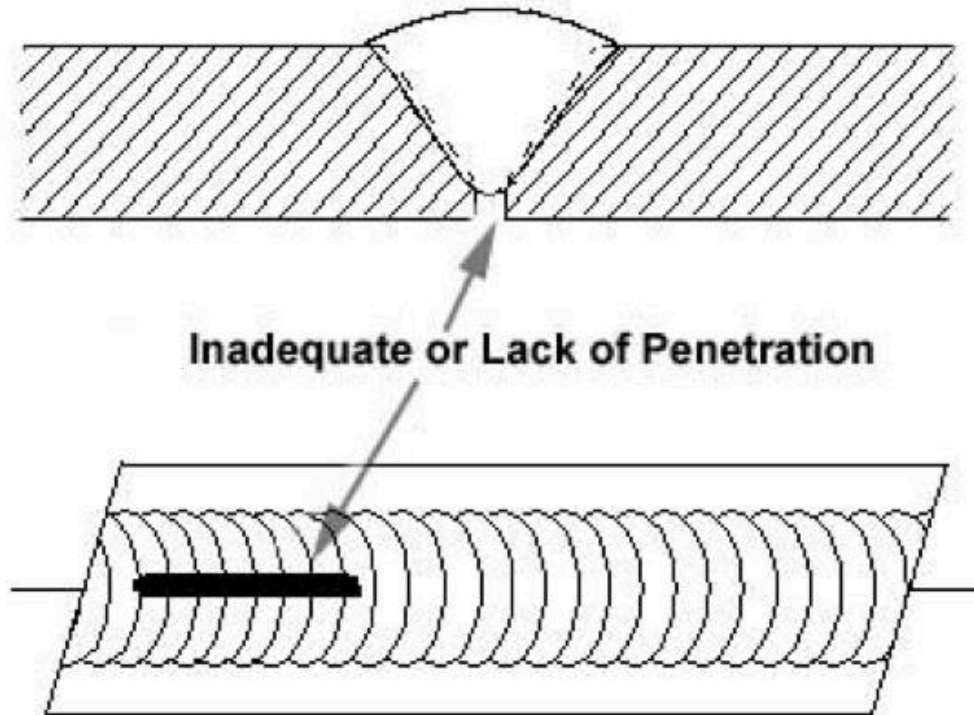


Film sınıfı	Tanesellik	Duyarlılık	Film hızı	Küçük süreksizliklerin belirlenmesi
C1	Çok küçük	Çok düşük	Çok yavaş	Çok iyi
C2	Küçük	Düşük	Yavaş	İyi
C3	Orta	Orta	Orta	Orta
C4	Orta	Orta	Orta	Orta
C5	İri	Yüksek	Hızlı	Zor
C6	Daha iri	Daha yüksek	Daha hızlı	Daha zor

RADYOGRAFİK MUAYENE (RT)

The EN ISO 6520 standard defines defects that occur after the welding process

- Insufficient Penetration



RADYOGRAFIC TESTING (RT)



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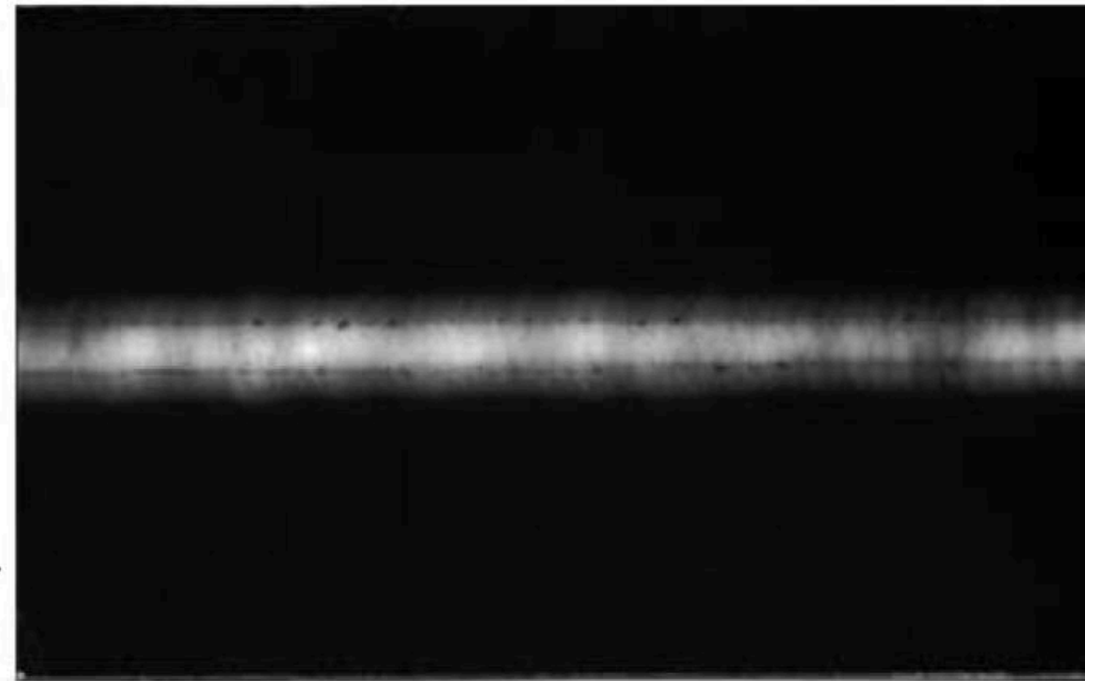
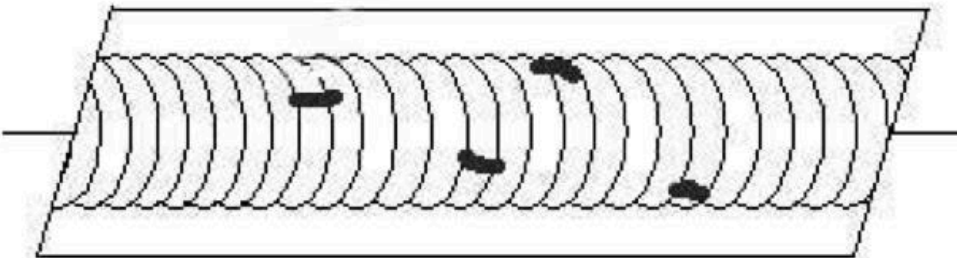
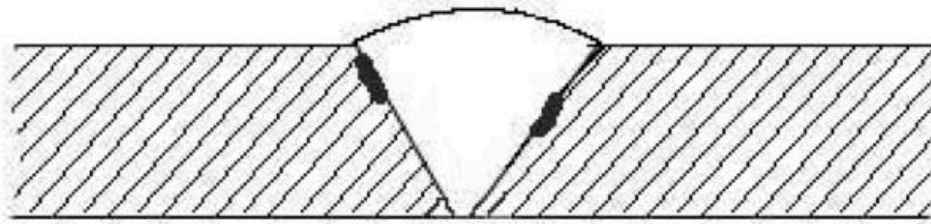
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The EN ISO 6520 standard defines defects that occur after the welding process

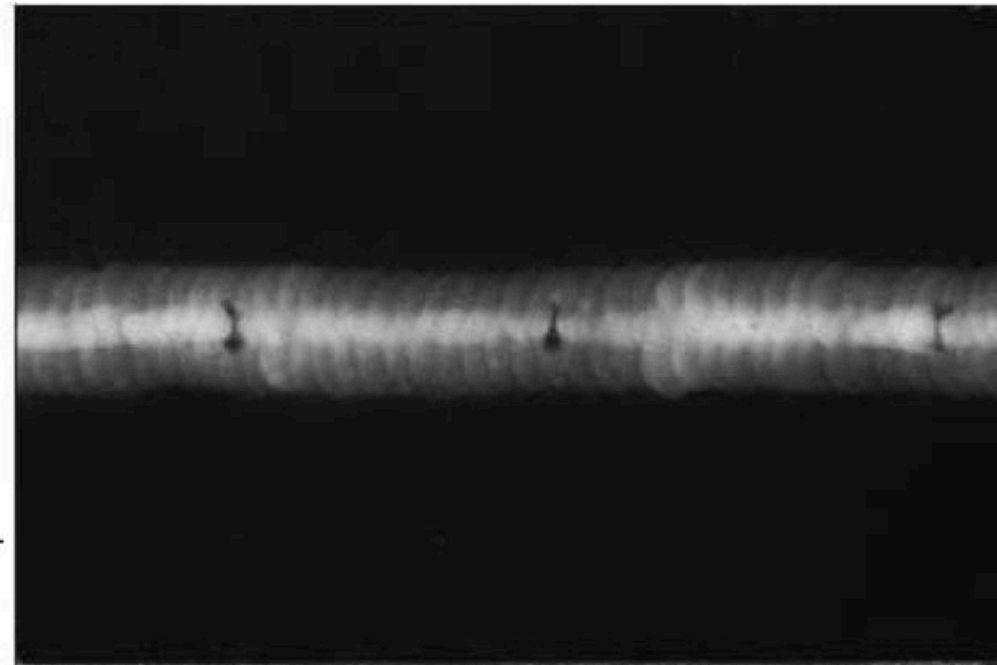
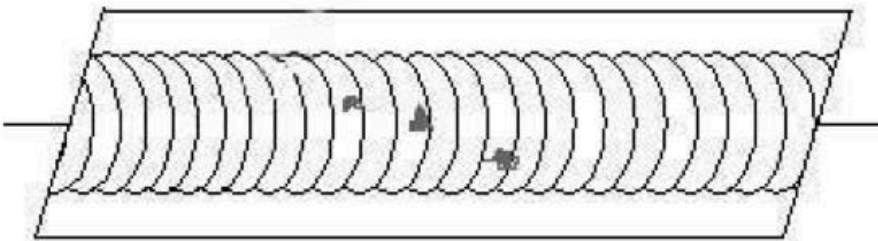
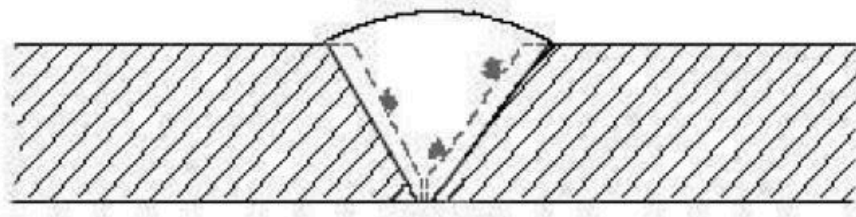
- Insufficient melting on the side wall



RADYOGRAFIC TESTING (RT)

The EN ISO 6520 standard defines defects that occur after the welding process

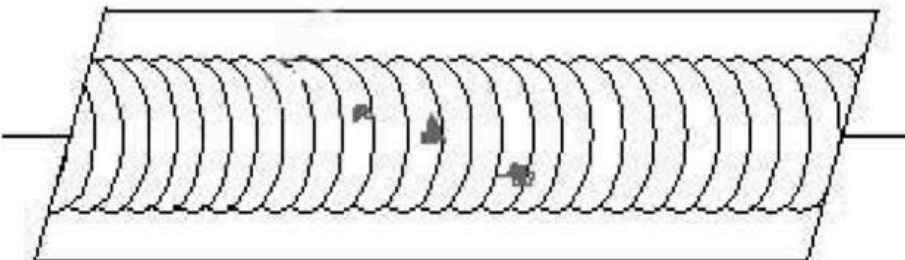
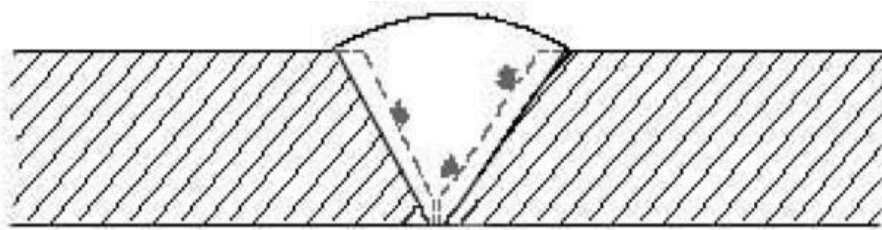
- Slag Inclusions



RADYOGRAFIC TESTING (RT)

The EN ISO 6520 standard defines defects that occur after the welding process

- Tungsten Inclusion



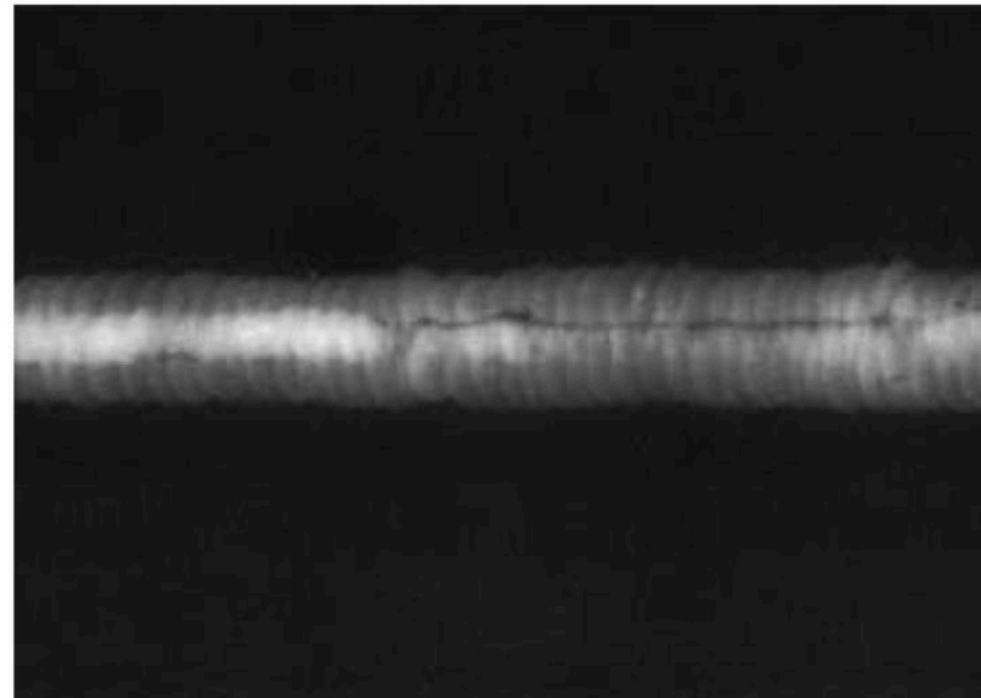
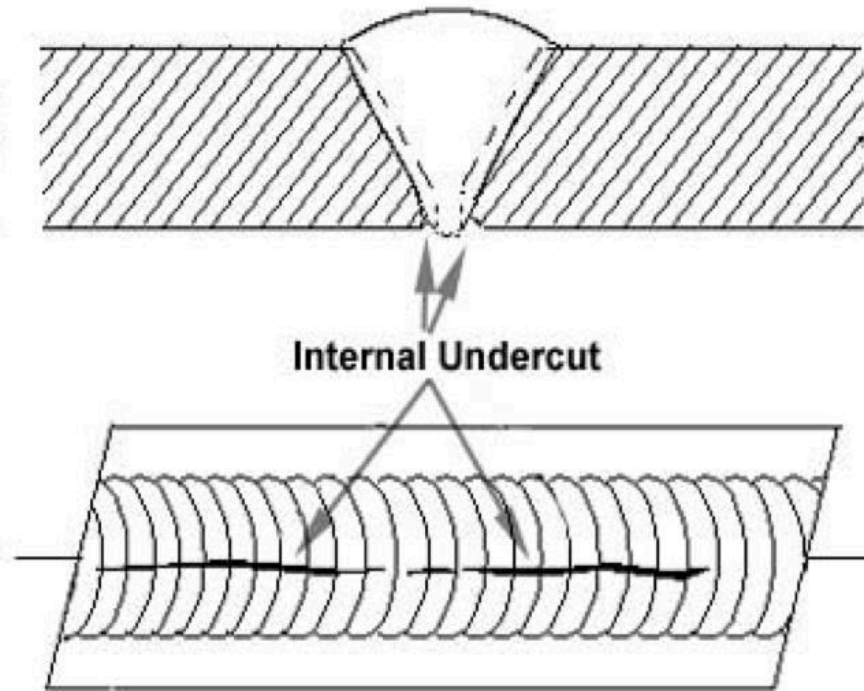
RADYOGRAFIC TESTING (RT)



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The EN ISO 6520 standard defines defects that occur after the welding process

- Internal Undercut



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RADYOGRAFIC TESTING (RT)



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The EN ISO 6520 standard defines defects that occur after the welding process

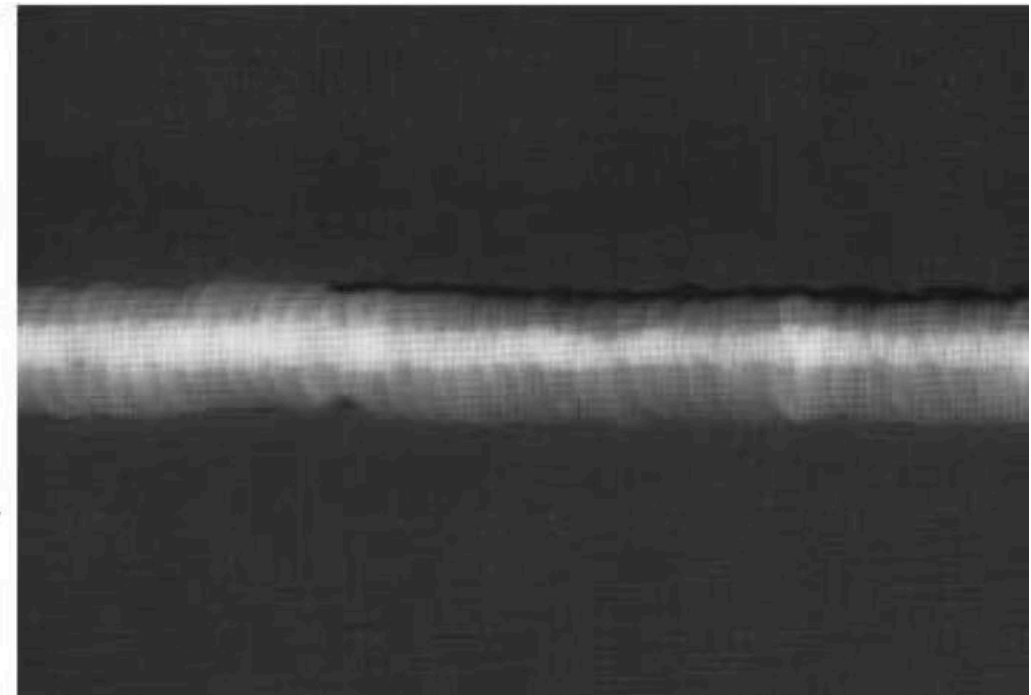
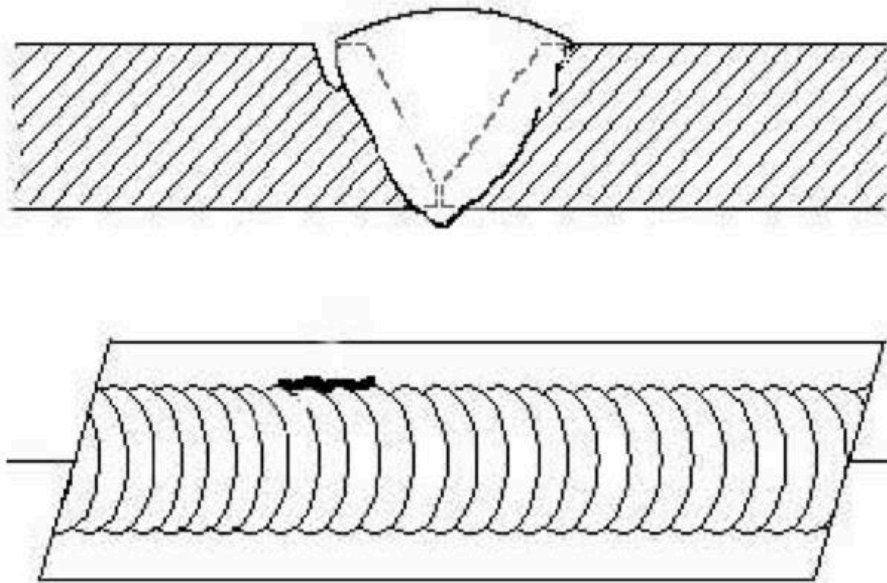
- Undercut in the cap



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ULTRASONIC TESTING (UT)



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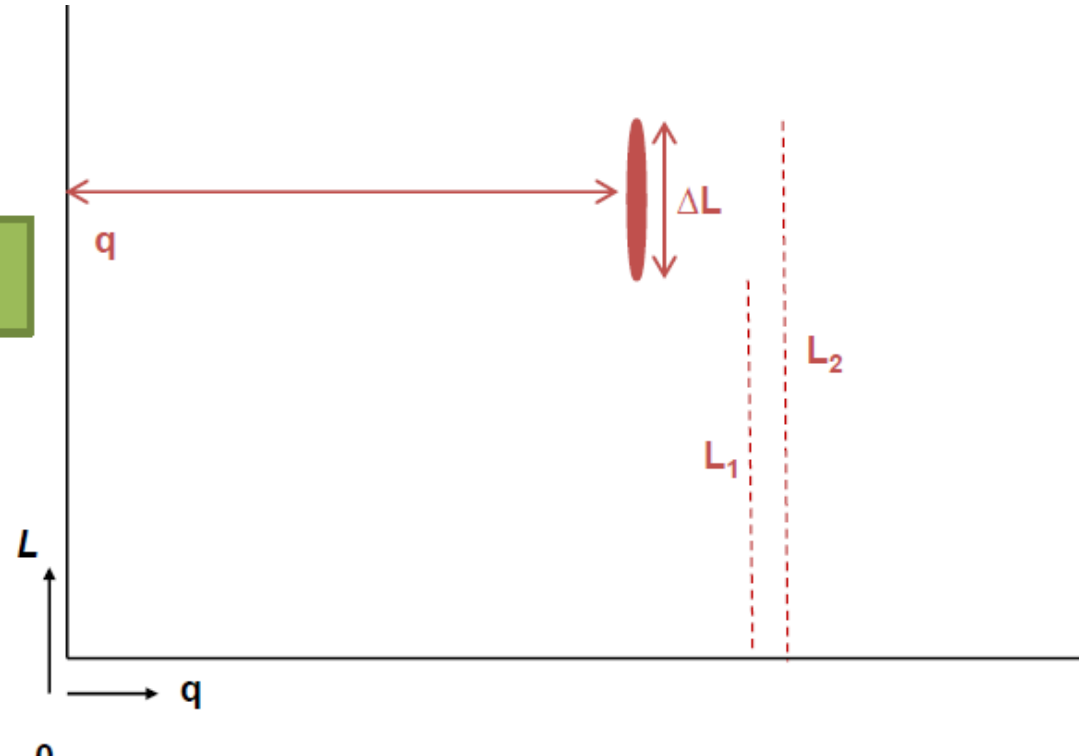
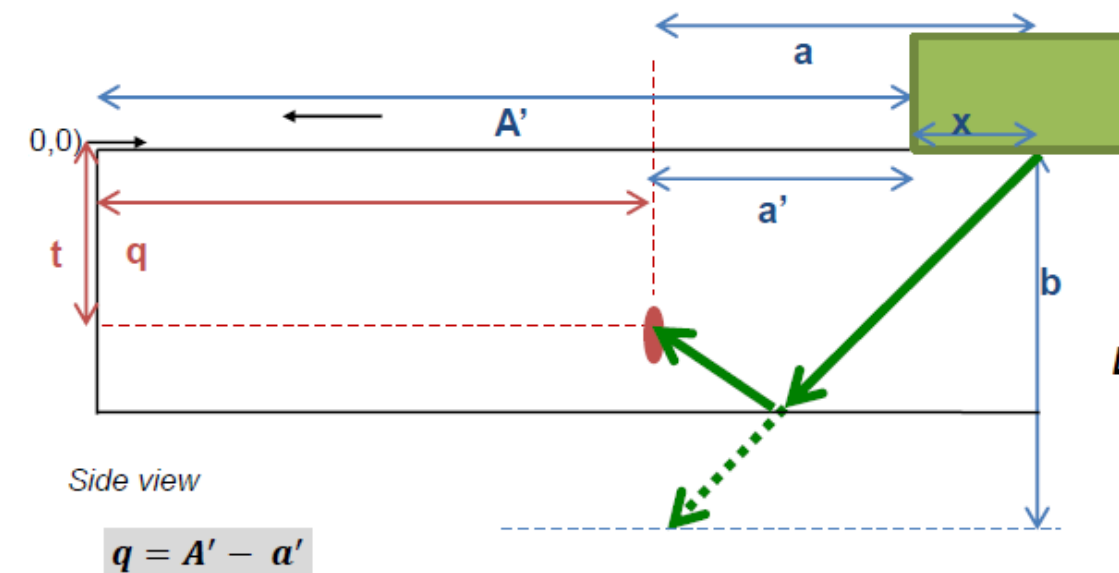
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$$a = S \sin \alpha$$

$$S \leq S_{p/2} \Rightarrow t = S \cos \alpha$$

$$a' = a - x$$

$$S_{p/2} < S \leq S_p \Rightarrow t = 2w - S \cos \alpha$$





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Case Studies Review

Başak Güneş

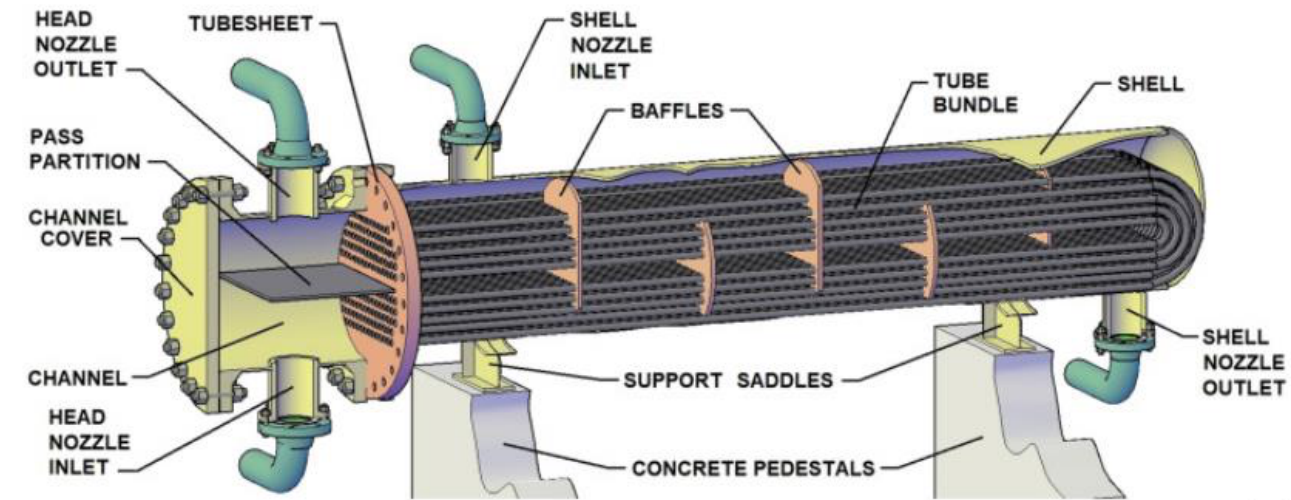
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Welding Technology and NDT Center



Case Study 1

The ultimate goal of this study is to determine the optimal manufacturing parameters that can be used in the production of a heat exchanger, by taking advantage of the high thermal conductivity of pure copper.



Copper and Its Properties



- **Electrical and Thermal Conductivity**

After silver, copper is known to be the best electrical and thermal conductor.

- **High Recyclability:**

Copper is a fully recyclable metal.

- **Areas of Application:**

Electronics, construction and plumbing, marine applications, etc.

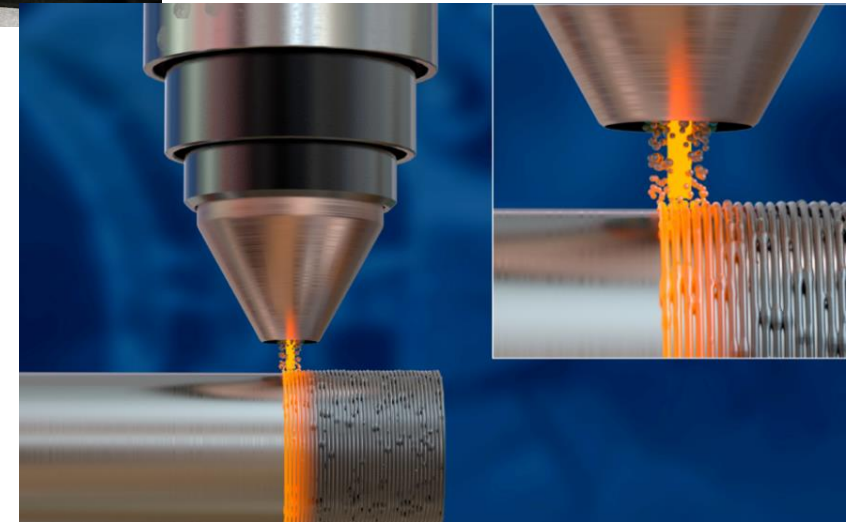
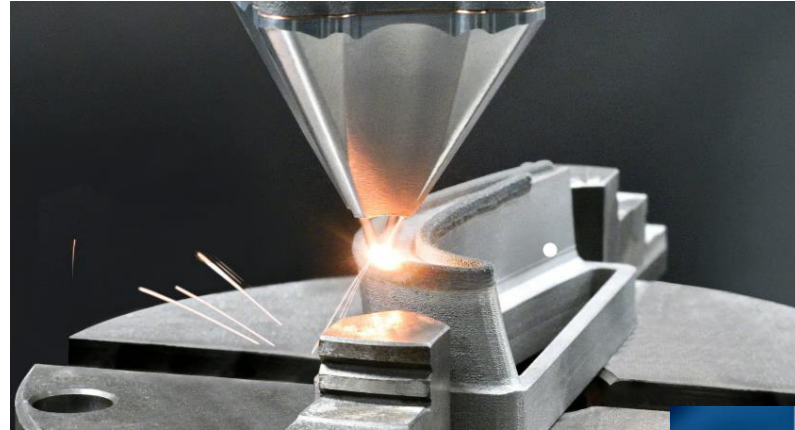
Challenges of Additive Manufacturing with Copper



DED (Directed Energy Deposition)

Metal is melted and deposited directly during the process

- Feedstock:
 - Powder or wire
- Energy source:
 - Laser or electron beam (or arc)
- Commonly used for:
 - Large metal parts
 - Repair and surface coating
 - Functionally graded materials
- Typical materials:
 - Steel
 - Titanium alloys
 - Nickel-based superalloys



PBF (Powder Bed Fusion)

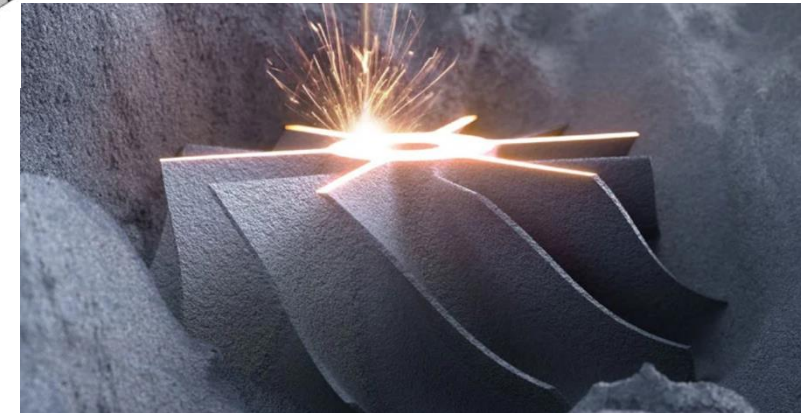
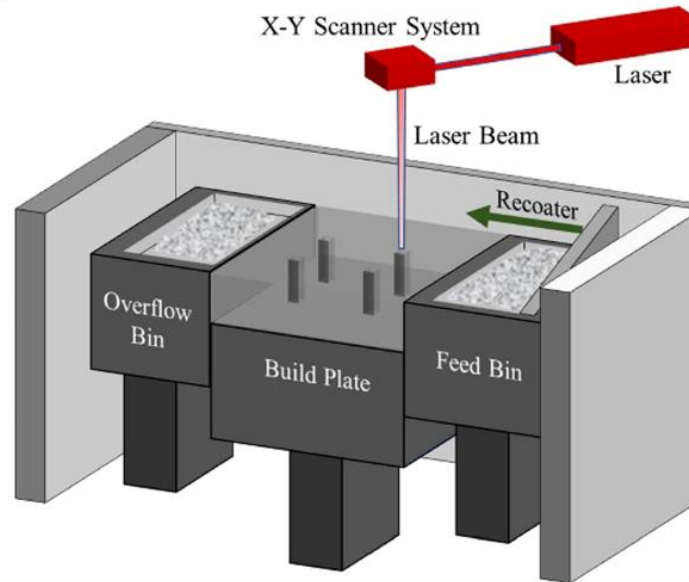


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Thin layers of metal powder are spread on a powder bed

- Powder is melted layer by layer using:
 - Laser (LPBF)
 - Electron beam (EB-PBF)
- High dimensional accuracy
- Commonly used for:
 - Small to medium-sized complex parts
- Typical materials:
 - Stainless steel
 - Titanium alloys
 - Aluminum alloys
 - Nickel-based superalloys



Challenges of DED & PBF for Copper



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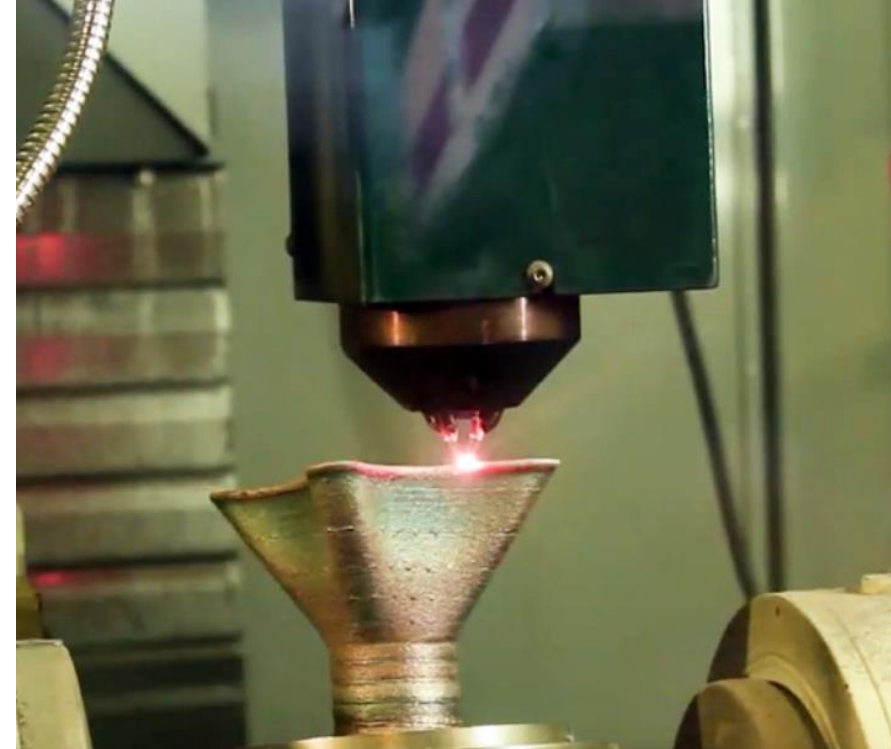


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- Copper has very high thermal conductivity
- Copper has high laser reflectivity
- In laser-based systems:
 - Low energy absorption
 - Insufficient melting
 - Porosity and lack-of-fusion defects
- Difficult to achieve near 100% density
- Especially in powder-based methods, pores and defects occur due to insufficient melting of the material



WAAM - Wire Arc Additive Manufacturing



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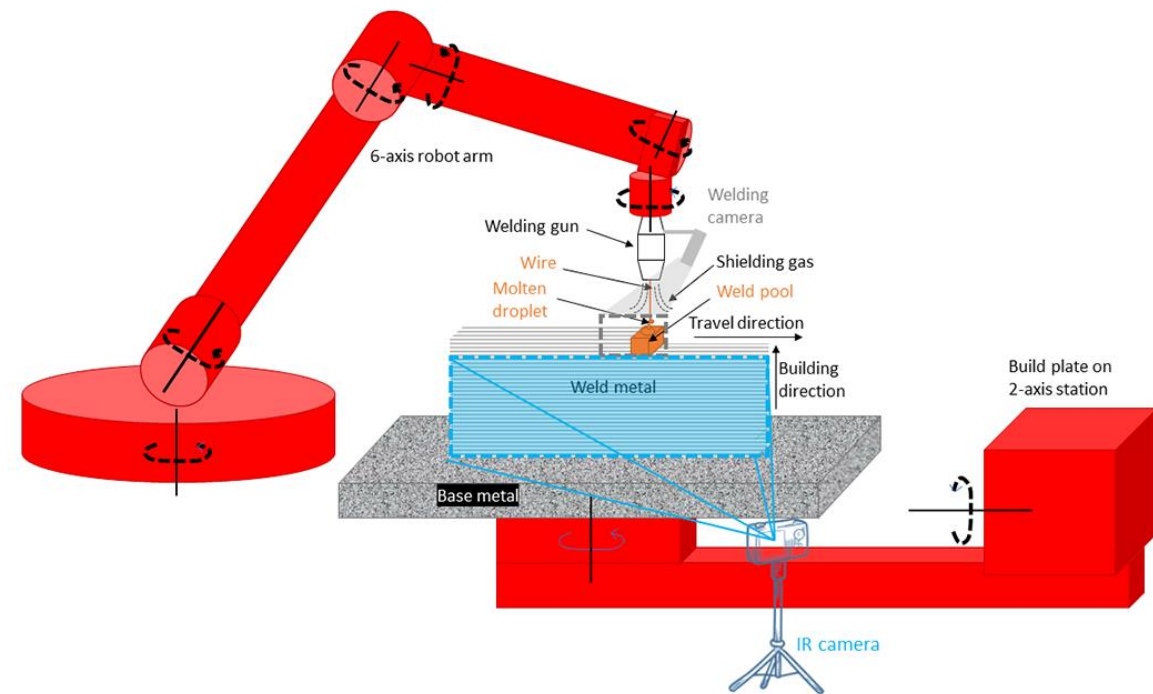


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- Wire-based additive manufacturing
- Uses electric arc as the energy source
- Provides very high heat input
- No laser → no reflectivity problem
- Enables:
 - Stable melting
 - Dense and pore-free copper structures
- Suitable for:
 - Heat exchangers
 - Large-scale copper components



Experimental Setup



- ABB IRB 1600 robotic arm with a 6-10kg/1.45m payload capacity
- MIG welding torch mounted on the robotic arm
- Fronius welding machine
- 10 mm thick pure copper plate

Welding wires:

- Cu-wt. %1 Sn
- Cu-wt. %30 Ni
- 60 wt. % Ni - (Fe, Cr, Mo)
- Fe-wt. %18 Cr-wt. %10 Ni
- Fe-wt. %18 Cr-wt. %10 Ni-Mn
- Fe-Mn-Si

Experiment



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A gas mixture of 50% Argon and 50% Helium was used.

After the toolpath was programmed using RobotStudio and Grasshopper, the program was transferred to the robot's control panel to initiate the experiment.

A Cu-1% Sn welding wire was utilized, and the parameters listed in Table were followed. The primary focus was to perform welding on pure copper lines for process optimization.

Weld	Voltage (V)	Wire Feed Speed (WFS) (mm/s)	Scan Speed (mm/min)	Stand-off Distance (mm)	Welding Type
Determined Parameters	15.5	83.3	8.5	15	MIG
3	15.5	100	8.5	15	MIG
4	15.5	150	8.5	15	MIG
5	20	150	8.5	15	MIG
6	25	175	8.5	15	MIG
7	25	175	8.5	15	MIG
8	25	175	7	15	MIG
9	25	250	7	15	MIG
10	25	250	5	15	MIG

Deshmukh et al. (2022)

Results

During the experiment series, it was observed that voltage adjustments could not be made through the robot control panel or the welding machine. Due to this limitation, sufficient flexibility for parameter optimization was not achieved

- Irregular welding beads
- High thermal conductivity
- Need for preheating
- Low welding speed

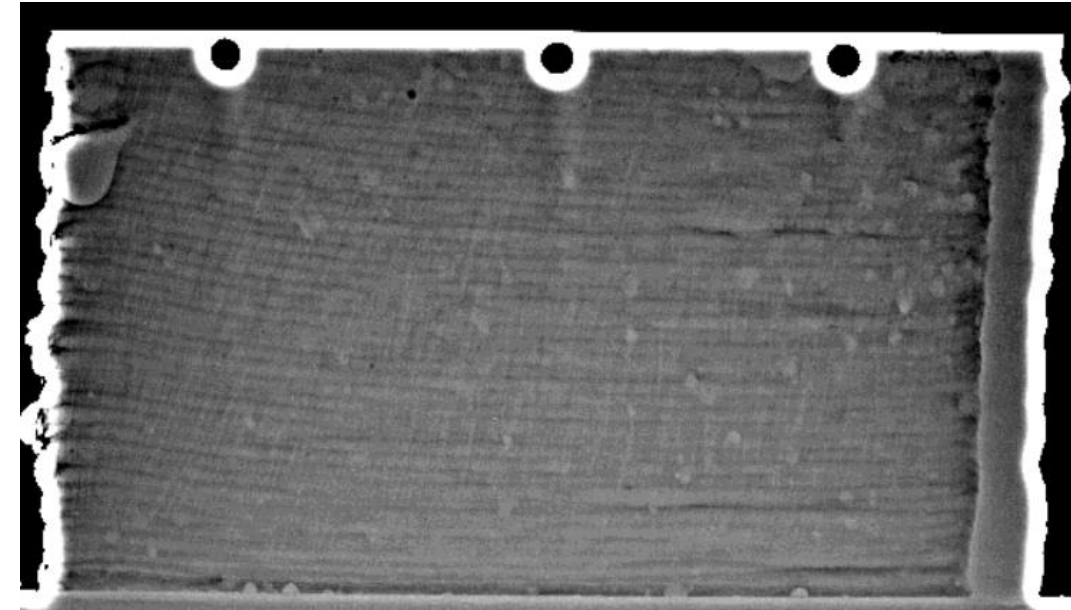


Results



Applicable NDT Methods

- Eddy Current Testing (ET)
- Penetrant Testing (PT)
- Radiographic Testing (RT)



Case Study 2



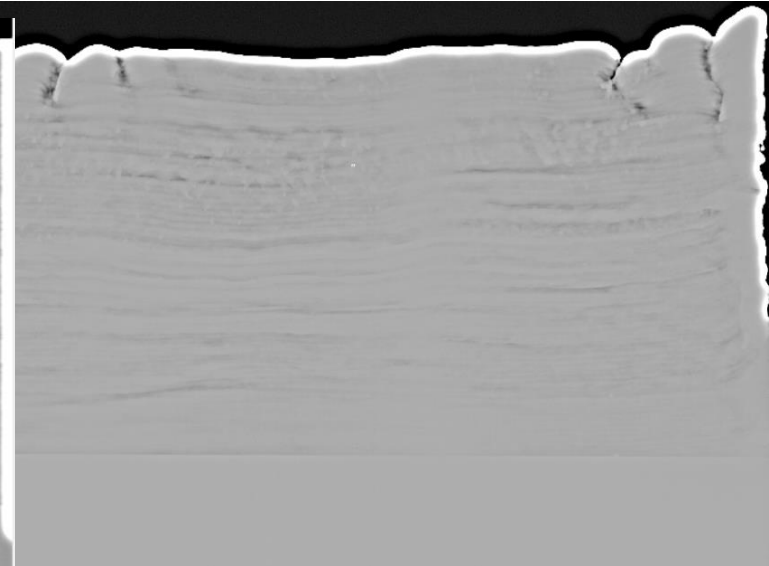
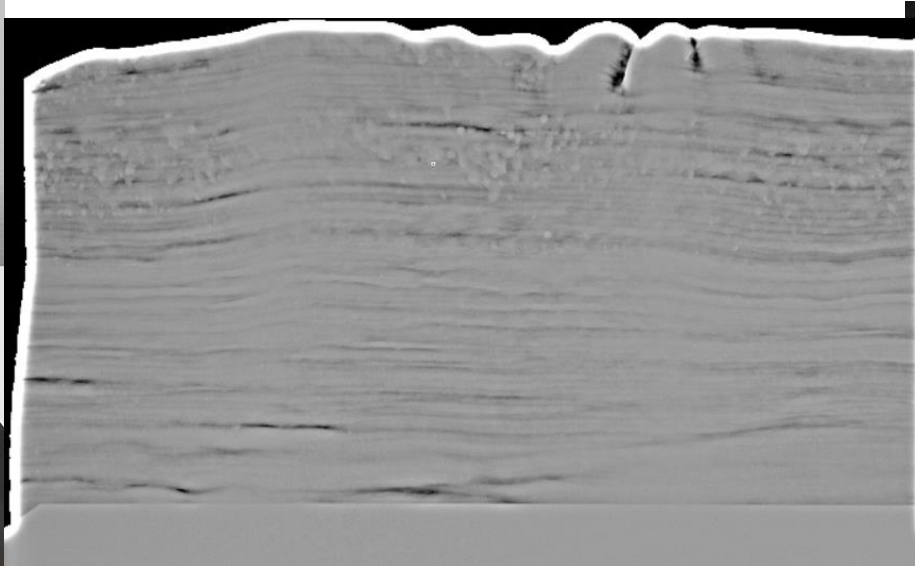
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Case Study 3



This project studies materials produced by additive manufacturing (SLS) with copper and ceramic particles using non-destructive testing.

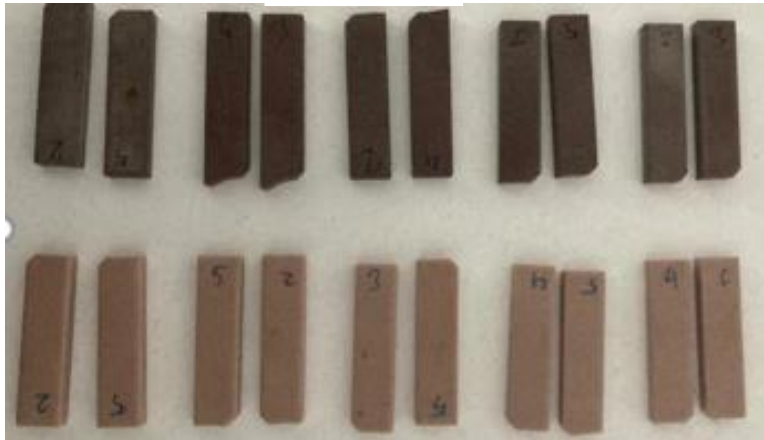
Objectives:

- To estimate the amount and distribution of copper and ceramic content in PA12
- To detect defects caused by inhomogeneous mixing or insufficient melting
- To calculate the elastic modulus

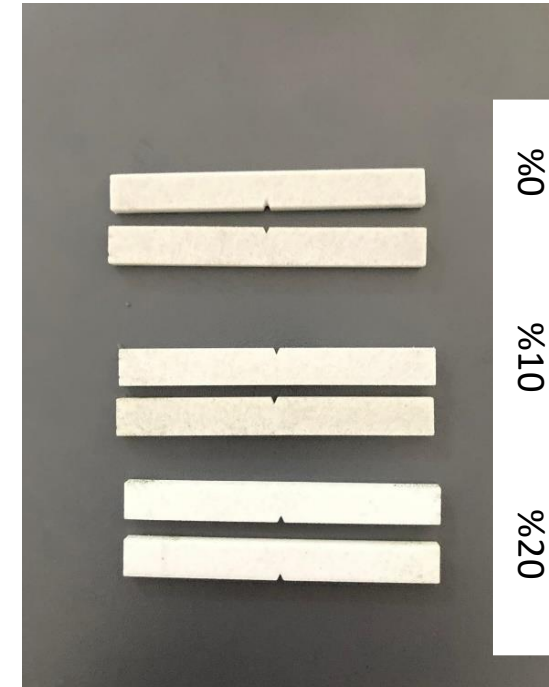
Performed Studies

Test Specimens

Dendritic



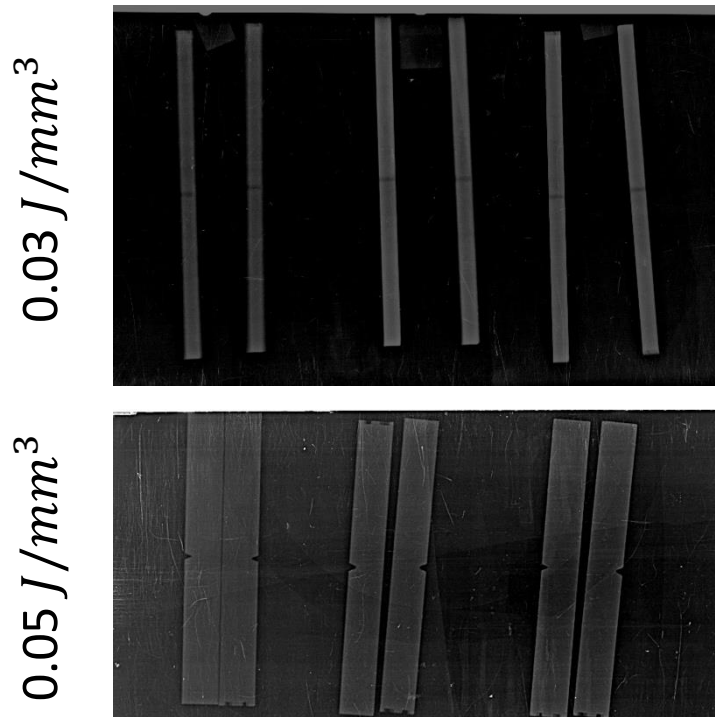
Spherical



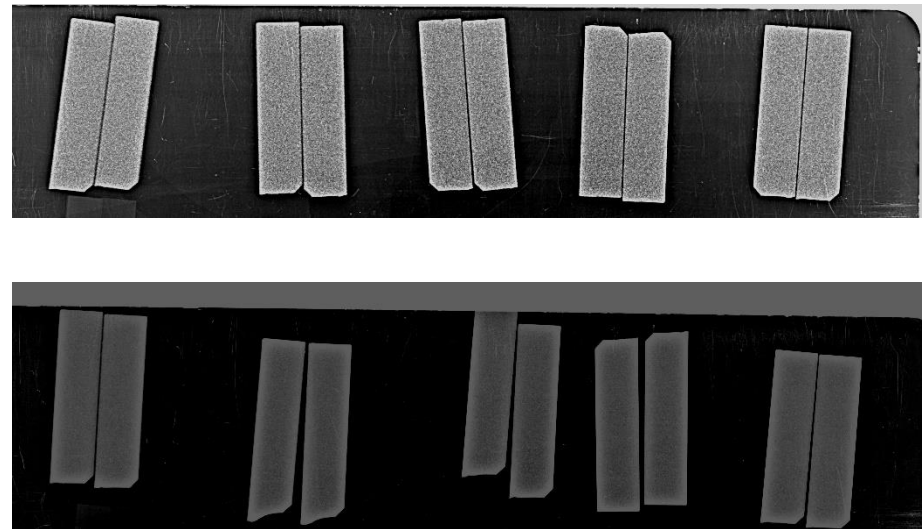
Performed Studies

Specimen Suitability Check for Testing

Ceramic Added PA12



15% Copper Added PA12

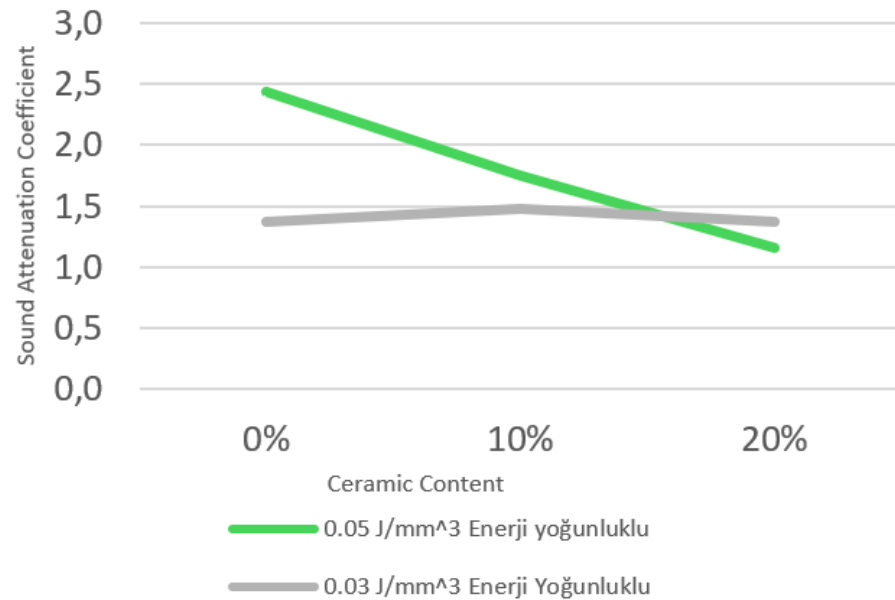


0.47 0.46 0.44 0.43 0.42
Enerji yoğunluğu J/mm^3

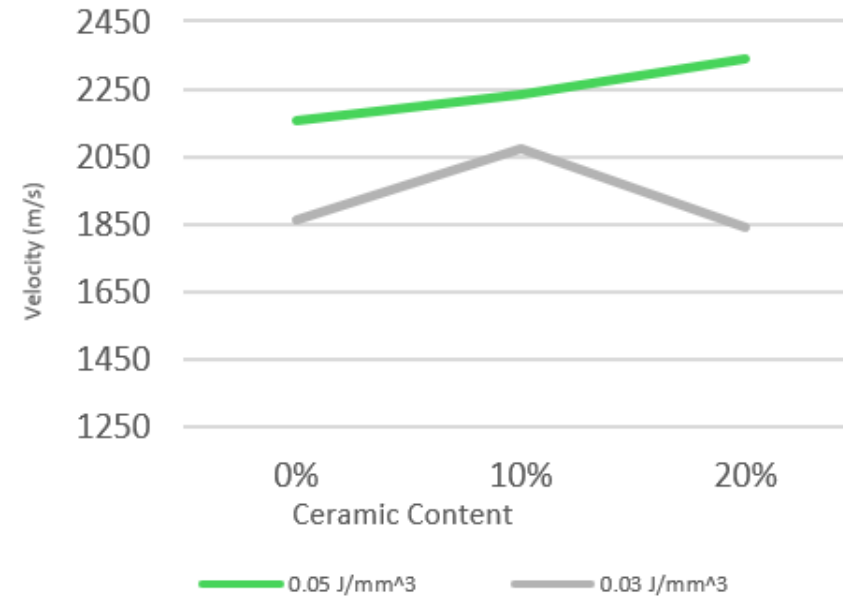
Results

Ceramic Added Specimens

Sound Attenuation Coefficient vs. Ceramic Content (PA12)



Velocity vs. Ceramic Content (PA12)



Results



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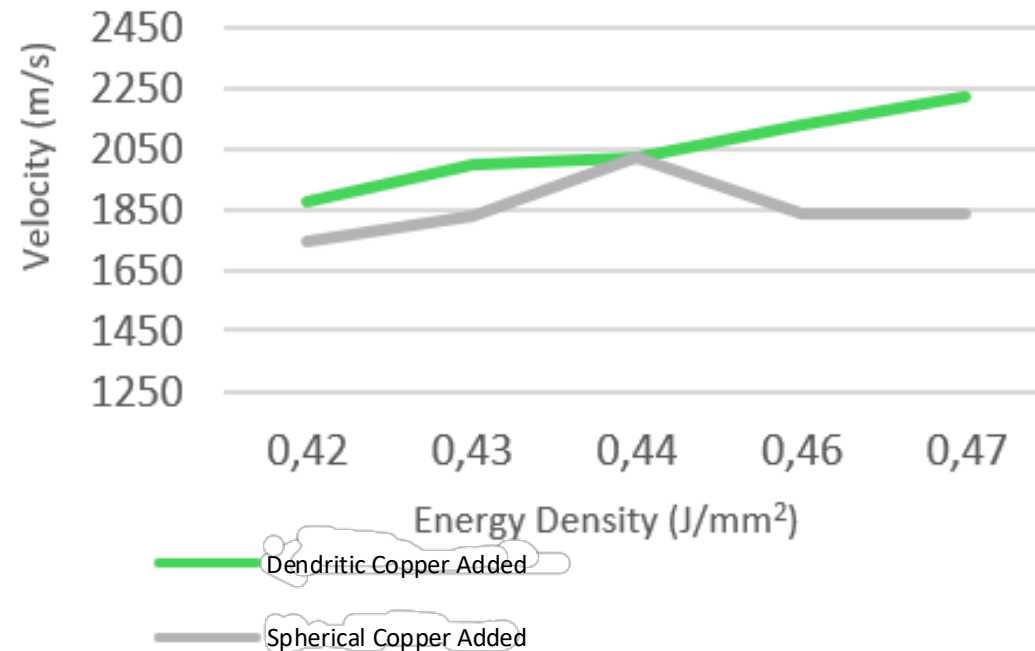
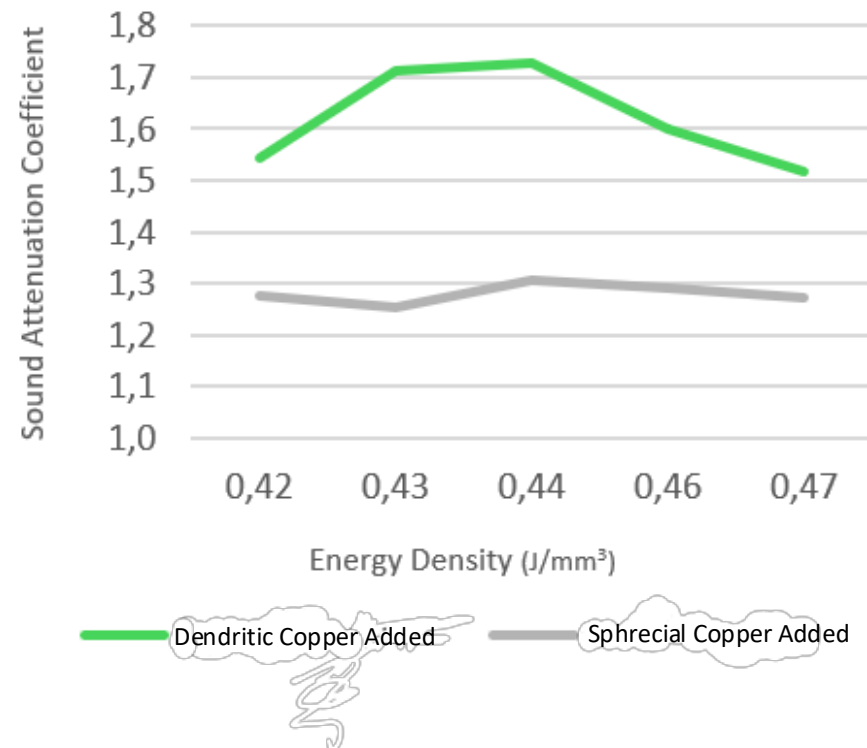


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Copper Filled Specimens



Results



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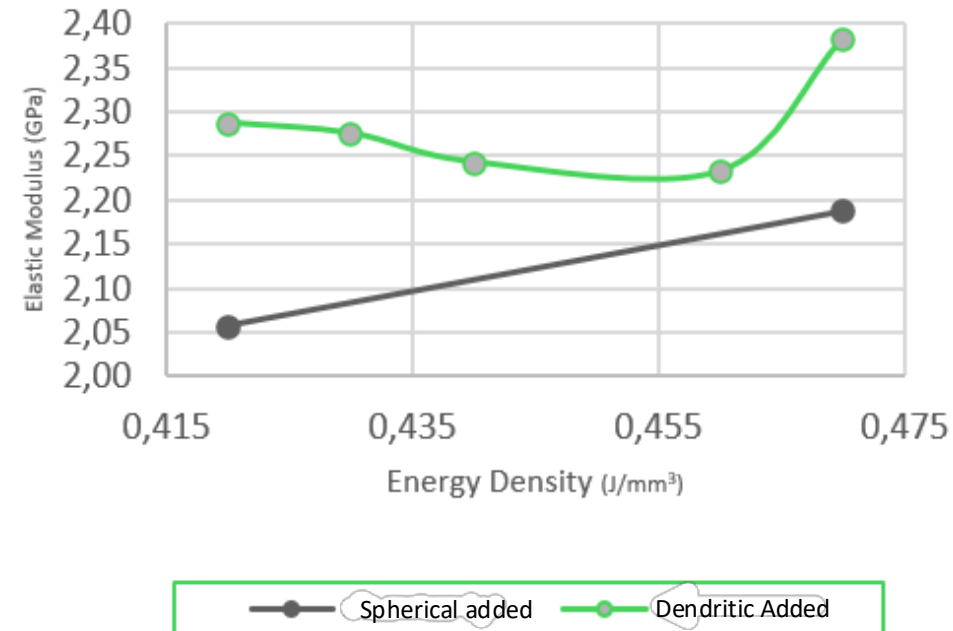


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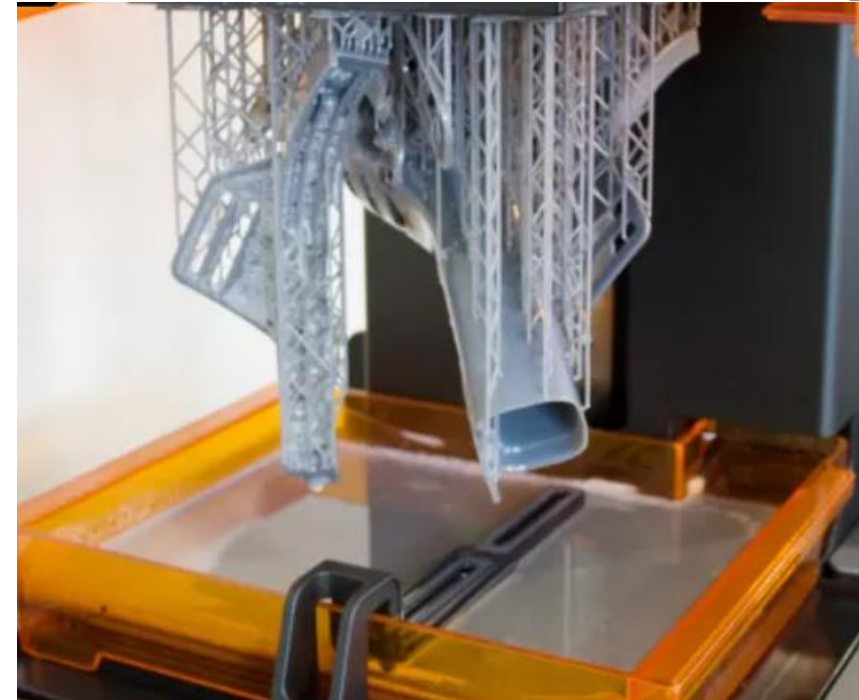
Copper Added Specimens



Case Study 4



SLA (Stereolithography) is an additive manufacturing process in which a liquid photopolymer resin is selectively cured by a UV laser, solidifying layer by layer





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1.3 - Strategies for inspection in Additive Manufacturing

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• Course Overview

- Importance of NDT in Additive Manufacturing
- Defect Formation Mechanisms
- Post-Build Inspection (Traditional NDT)
- In-Situ Process Monitoring (Real-time)
- Case Studies : NASA



The Context: Why is NDT Critical for AM?



- **The Technology:** Focus on Laser Powder Bed Fusion (L-PBF) and Directed Energy Deposition (DED).
- **The Paradigm Shift:**
 - **Subtractive:** Material removed → Internal quality usually consistent from billet.
 - **Additive:** Material built layer-by-layer → Defects can be encapsulated anywhere.
- **Aerospace Challenge:** High-value, complex geometries (e.g., lattice structures, internal cooling channels) make traditional inspection impossible.
- **Criticality:** "Class A" parts (fracture-critical) require quantitative NDT coverage.



Defect Taxonomy in Metal AM



- **Defects are Process Signatures:** Understanding the type helps select the sensor.

- **1. Porosity:**

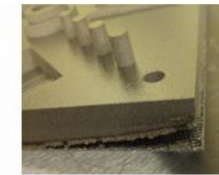
- Gas Porosity: Spherical, trapped gas (argon/moisture). Small ($<100\text{ }\mu\text{m}$).
 - Keyhole Porosity: Deep, narrow voids. Caused by excessive energy density (vaporization).

- **3. Lack of Fusion (LoF):** Irregular voids with sharp edge. Caused by insufficient energy/overlap.

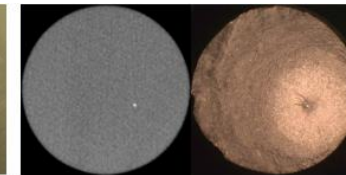
- **4. Cracking:**

- Solidification cracking & Delamination due to high residual thermal stresses.

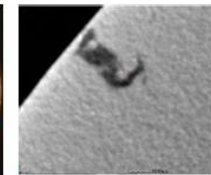
- **5. Surface Defects:** Balling, spatter, surface roughness.



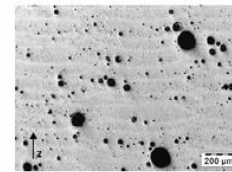
dimensions/warping



inclusions



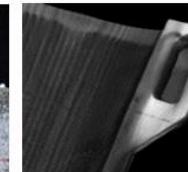
PBF process void



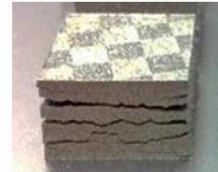
PBF gas porosity



DED gas porosity



PBF crack

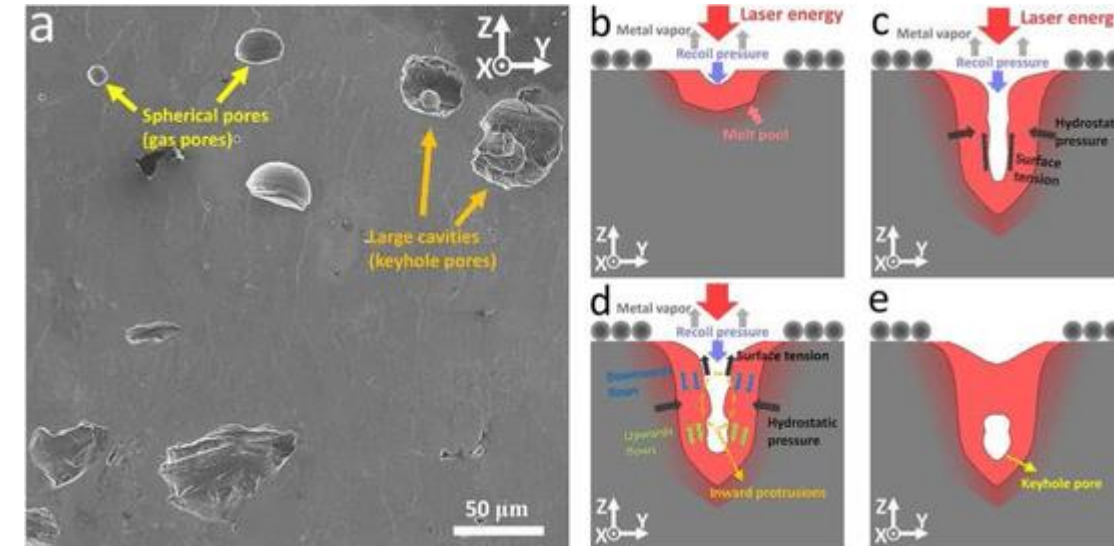


PBF delamination

Process Mechanics & Defect Formation



- **Visualization:** Diagram of Laser-Material Interaction.
- **Keyhole Mechanism:**
 - High Power / Low Speed → Deep melt pool → Vapor recoil pressure traps bubbles.
- **Lack of Fusion (LoF) Mechanism:**
 - Low Power / High Speed → Shallow melt pool → Unmelted powder between layers.
- **Spatter (Sıçranti):**
 - Ejected molten particles landing on the powder bed can create inclusions in the next layer.



The "Post-Mortem" vs. "In-Situ" Dilemma

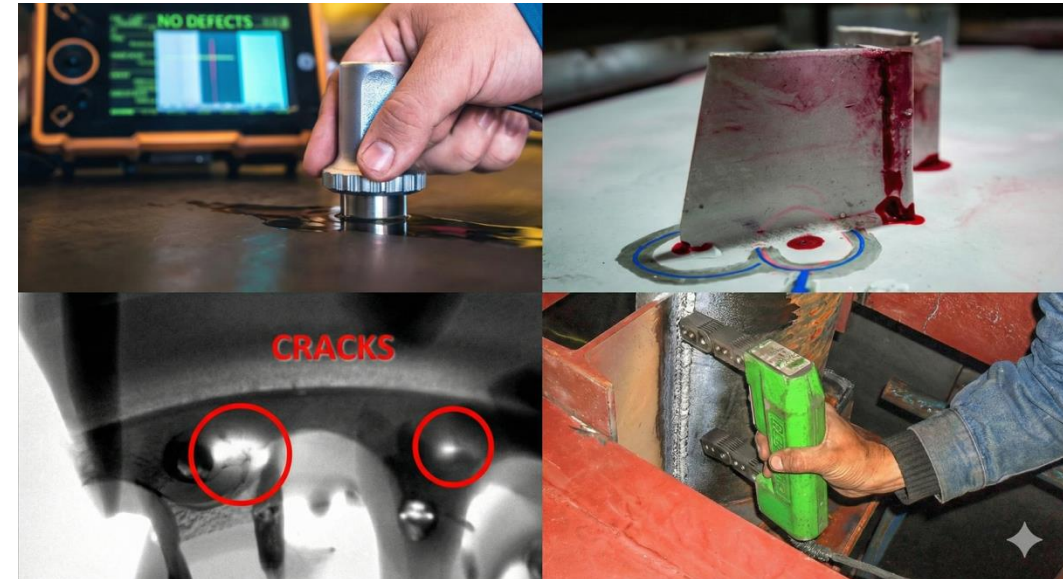


- **Traditional NDT (Post-Process):**

- **Methods:** UT, CT, PT, Eddy Current.
- **Limitation:** Conducted after the part is finished. High cost of scrap if defect is found.

- **In-Situ Monitoring (Real-Time):**

- **Concept:** Layer-by-layer inspection during the build.
- **Goal:** Detect drifts before they become defects.



Post-Build Inspection Strategies



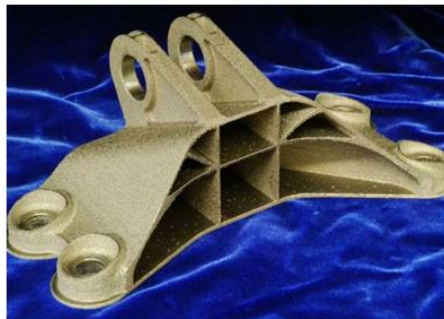
The "Inspectability" Challenge: Geometric Complexity

- **Context:** Unlike casting or forging, AM allows "Complexity for Free". But inspection is not free.
- NASA MSFC Classification (NASA-STD Framework):
 - **Group 1 & 2 (Simple Shapes):** Plates, cylinders. Accessible for UT/ET.
 - **Group 3 (Embedded Features):** Internal channels (cooling). Visual line-of-sight lost.
 - **Group 4 (Topology Optimized):** Organic shapes, varying thickness.
 - **Group 5 (Lattice Structures):** The most difficult. Thousands of struts.
- **The Rule:** As complexity increases, standard NDT (PT, conventional UT) becomes viable only for limited surfaces.

1



2



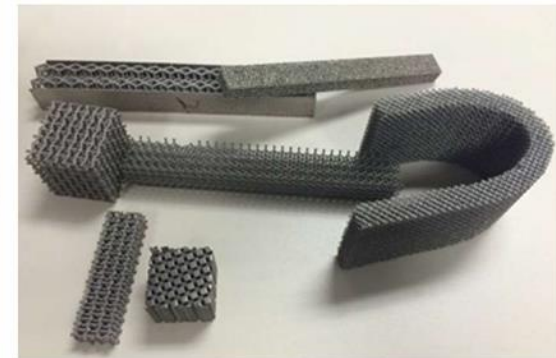
3



4



5



[§] Kerbrat, O., Mognol, P., Hascoet, J. Y., *Manufacturing Complexity Evaluation for Additive and Subtractive Processes: Application to Hybrid Modular Tooling*, IRCCyN, Nantes, France, pp. 519-530, September 10, 2008.

[§] Kerbrat, O., Mognol, P., Hascoet, J. Y., *Manufacturing Complexity Evaluation for Additive and Subtractive Processes: Application to Hybrid Modular Tooling*, IRCCyN, Nantes, France, pp. 519-530, September 10, 2008.

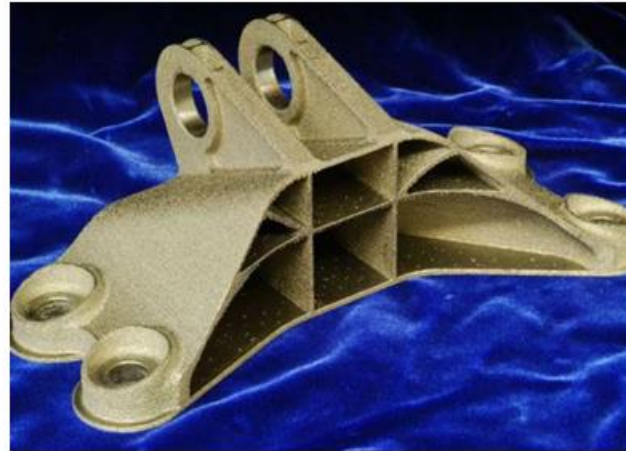
Post-Build Inspection Strategies

- Most NDE techniques can be used for Complexity Group[§] 1 (Simple Tools and Components), Group 2 (Optimized Standard Parts) and Group 3 (Embedded Features):

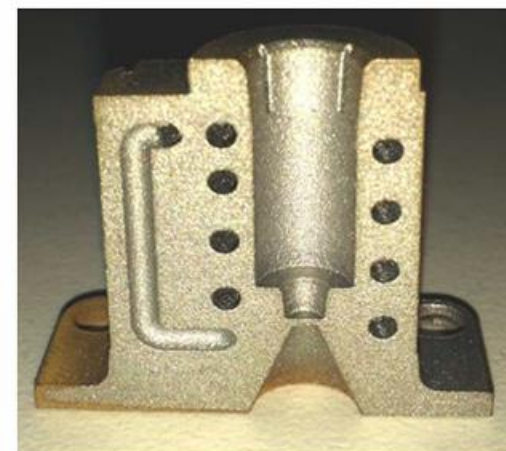
1



2



3



[§] Kerbrat, O., Mognol, P., Hascoet, J. Y., *Manufacturing Complexity Evaluation for Additive and Subtractive Processes: Application to Hybrid Modular Tooling*, IRCCyN, Nantes, France, pp. 519-530, September 10, 2008.

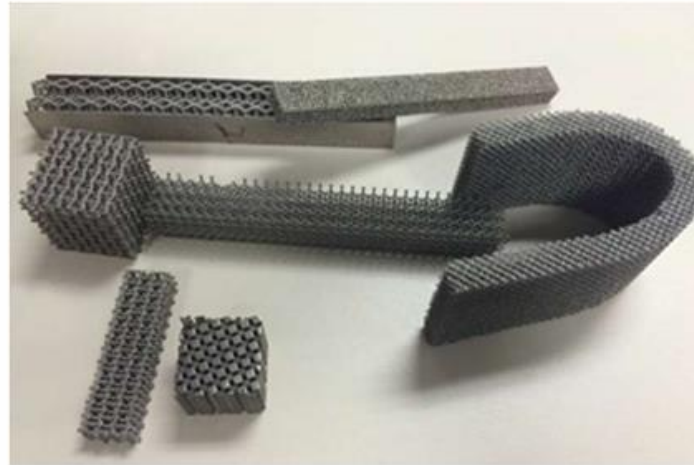
Post-Build Inspection Strategies

- Only Principle Component Resonance Testing (PCRT), Computed Tomography (CT), and Leak Testing (LT) can be used for Complexity Group[§] 4 (Design-to-Constraint or Topology Optimized Parts) and Group 5 (Lattice Structures):

4



5



[§] Kerbrat, O., Mognol, P., Hascoet, J. Y., *Manufacturing Complexity Evaluation for Additive and Subtractive Processes: Application to Hybrid Modular Tooling*, IRCCyN, Nantes, France, pp. 519-530, September 10, 2008.

Surface Inspection



Visual Testing (VT) & Optical Metrology

- **Definition:** Inspection of surface features using the naked eye, microscopes, or automated optical systems.

- **What it Detects in AM:**

- **Macroscopic Pores:** Surface-opening pores (300–400 μm diameter) often distributed along track edges.
- **Balling:** Solidified droplets caused by poor wetting, visible as rough irregularities.
- **Surface Texture:** High roughness (R_a) indicates unstable process parameters.

- **Advanced VT Tools:**

- **Optical Profilometers & Confocal Microscopes:** Essential for measuring surface roughness and 3D topography, as naked eye inspection is insufficient for micro-cracks.
- **Borescopes:** Used for inspecting internal lattice structures or cooling channels, though limited by line-of-sight.



Surface Inspection

Liquid Penetrant Testing (PT)

- **Method:** Capillary action draws dye into surface-breaking cracks.
- **Application:** Standard check for large cracks, porosity connected to surface.
- **Limitation in AM:**
 - **Surface Roughness:** As-built AM surfaces ($R_a > 10 \mu\text{m}$) can trap penetrant, creating high "background noise" (false positives).
 - **Partially Sintered Particles:** Powder sticking to the surface can be mistaken for cracks.
- **Requirement:** Surfaces often need machining/polishing before PT inspection.



Surface Inspection



Eddy Current Testing (ECT)

- **Principle:** Electromagnetic induction creates circular currents (eddy currents) in conductive materials. Defects disrupt this flow.

- **Why use it in Aerospace?**

- Sub-surface Detection: Unlike PT, it detects defects below the surface or under coatings.

- NASA Application: Specifically developed for crack detection and characterization on the International Space Station (ISS) air leak incidents.

- **The AM Challenge:**

- "Lift-off" Noise: As-built AM surface roughness (Ra) creates variable lift-off signals, masking defects.

- Solution: Requires surface machining (CNC milling) before inspection. Ideal for Hybrid Manufacturing (Add + Subtract) setups where layers are smoothed periodically.

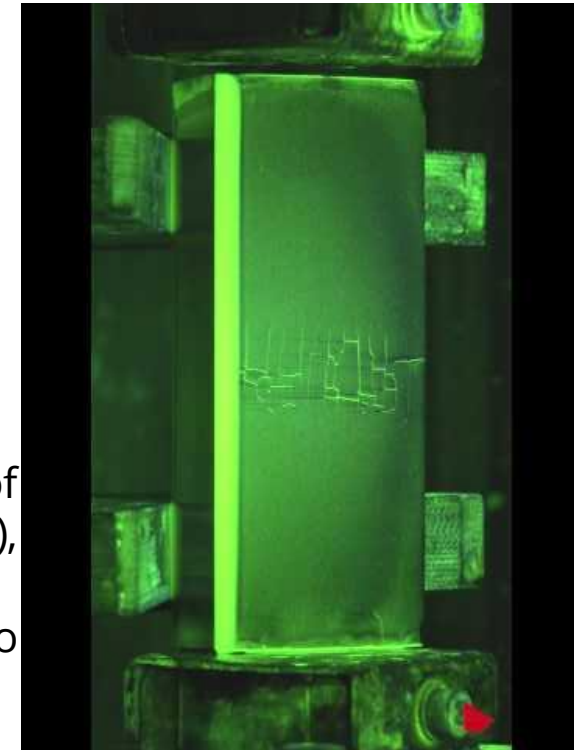


Surface Inspection



Magnetic Particle Inspection (MPI)

- **Principle:** Applying a magnetic field to a ferromagnetic part. Defects cause "flux leakage," attracting magnetic particles to form a visible indication.
- **Material Limitation:** Only works on ferromagnetic materials.
NOT applicable for Titanium (Ti-6Al-4V) or Aluminum, which are common in aerospace.
- **Capability:**
 - Detects surface breaking cracks and near-surface defects
- **The AM Challenge:** Surface Roughness
 - As-built AM surfaces are rough. Magnetic particles can physically get trapped in the valleys of the roughness profile (mechanical entrapment), creating false indications (background noise), similar to the issue in Penetrant Testing.
 - Solution: Parts often require machining or surface finishing (grinding/polishing) before MPI to be effective.



Volumetric Inspection - Ultrasonic Testing (UT)



- **Challenge:** Sound attenuation and scattering.
- **Grain Structure Effect:** AM parts (especially Ti-6Al-4V) have columnar grain structures that scatter sound waves, reducing Signal-to-Noise Ratio (SNR).
- **Advanced Solution:**
 - **Phased Array UT (PAUT):** Focusing the beam electronically.
 - **Full Matrix Capture (FMC) / Total Focusing Method (TFM):** Recent studies show TFM improves defect detection in rough AM blocks compared to standard PAUT.
- **Laser Ultrasonics (LUT):** Non-contact generation of ultrasound using lasers. Effective for detecting subsurface defects (0.1–0.5 mm deep) without couplant.



Volumetric Inspection - Ultrasonic Testing (UT)



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Laser Ultrasonics (LUT) - Sub-surface Inspection

- **Mechanism:** A pulsed laser hits the surface, creating a thermal shock that generates an ultrasonic wave (sound) inside the metal. A second laser (interferometer) listens to the echoes.

- **Key Benefit:**

- **No Couplant:** No need for water or gel (unlike traditional UT).
- **Small Defects:** Capable of detecting defects as small as 100-300 μm .
- **Depth Profiling:** Can determine the depth of a crack using Rayleigh waves.
- **Emerging Application:** Can be used during the build (layer-by-layer) or after the build.



Radiographic Testing (RT) & Digital Radiography (DRT)



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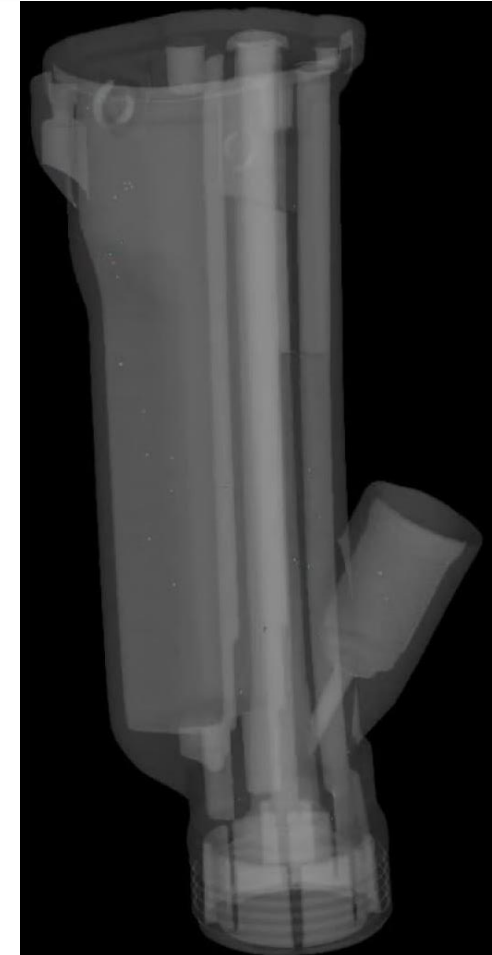


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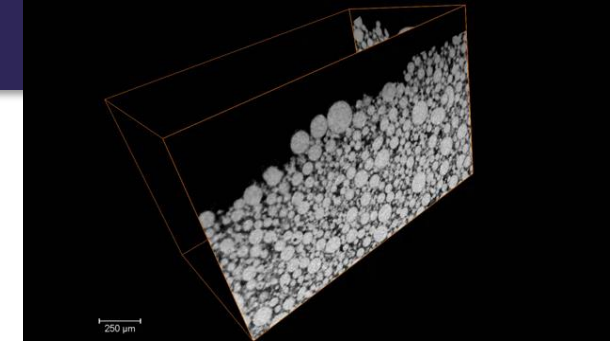


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- **Principle:** Utilizing X-rays or Gamma rays to penetrate the part. Differential absorption reveals internal density changes
- **Methods:**
 - **Traditional RT:** Uses film (slower, requires chemical processing).
 - **Digital Radiography (DRT):** Uses flat panel detectors (immediate image, higher dynamic range).
- **Capabilities (NASA & Literature):**
 - Effective for detecting macro-porosity, inclusions, and large lack of fusion defects.
 - Standard for welding, but challenged by AM complexity.
- **Major Limitations in AM:**
 - **2D Projection:** A 3D object is compressed into a 2D image. Complex internal lattice structures overlap, masking individual defects (Superposition effect).
 - **Orientation Dependence:** Planar defects (cracks/LOF) parallel to the X-ray beam might be invisible (lower sensitivity).



The Ultimate Verification - X-Ray CT (Computed Tomography)

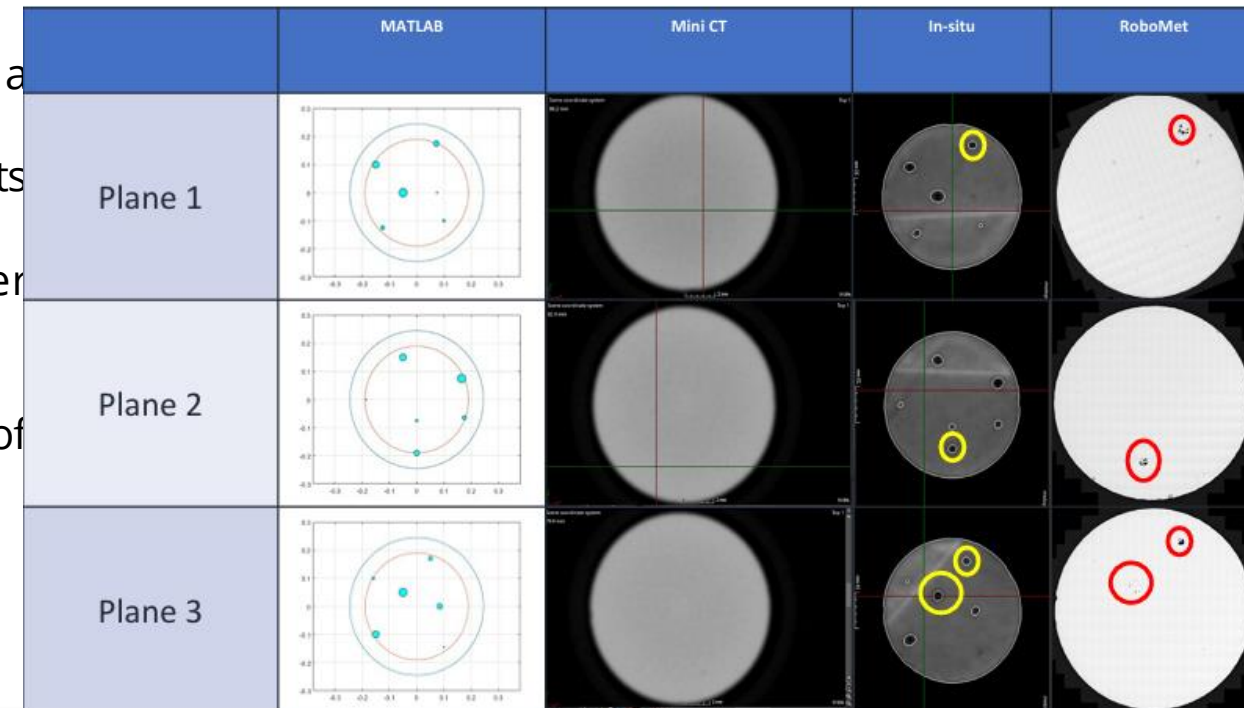


- **Capability:** Full 3D volumetric inspection. Can see internal lattice failures and trapped powder.

- **Case Study:** NASA "Seeded Defect" Experiment.

- Setup: Designed artificial internal voids (80μm - 280μm) in a test block.
- Result: Standard industrial Micro-CT failed to detect defects smaller than 200μm in some orientations.
- Reason: "Healing" effect (melt pool remelting the layer below) or resolution limits due to part density/thickness.

- **Takeaway:** CT is powerful but not infallible. Probability of Detection (POD) decreases as part thickness increases.



Process Compensated Resonance Testing (PCRT)



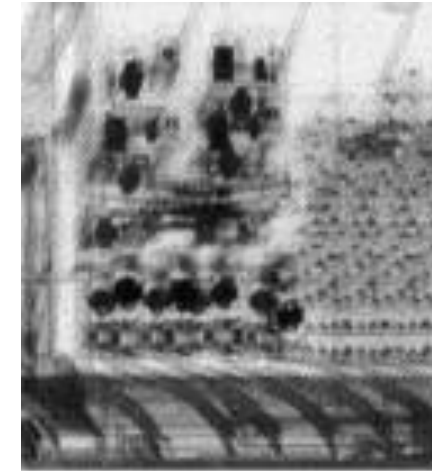
- **Applicability:** Best for Group 4 & 5 (Complex/Lattice parts) where CT takes too long.
- **Principle:** Measures the eigenfrequencies (natural vibration modes) of the part.
- **Logic:** A defect (crack/void) changes the stiffness → changes the resonant frequency.
- **Pros:** Fast (seconds), whole-body inspection.
- **Cons:** Requires a "Golden Sample" (perfect part) for comparison. Cannot locate where the defect is, just that it exists.



X-Ray Backscatter Technology (XBT)



- Difference from CT: CT requires access to both sides of the part (transmission). XBT requires access to only one side.
- **Principle:** Measures the radiation scattered back from the material.
- **Advantage in AM:**
 - **Surface Roughness Immunity:** Less affected by the rough surface of AM parts compared to Ultrasound.
 - **Complex Geometries:** Can inspect large structures (like rocket tanks) where you cannot put a detector inside.
 - **Crack Detection:** Studies show it can detect sub-surface cracks (0.025 mm width) under a deposit layer.



Transmission



Backscatter

The "Inspectability" Limit: NASA Geometric Complexity Groups



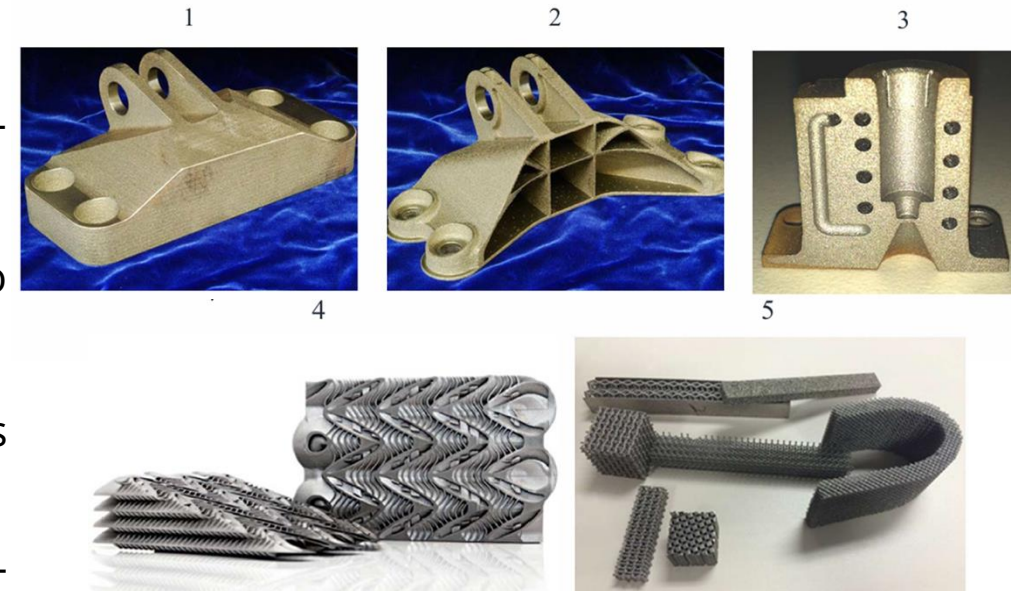
- **Concept:** Not all AM parts are inspectable. Inspection depends on complexity.

- **The NASA Classification (NASA-STD Framework):**

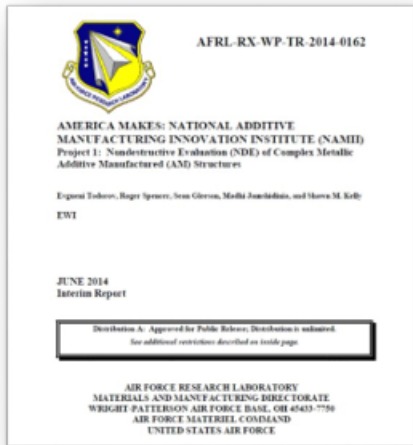
- Group 1 & 2 (Simple): Plates, cylinders. → Standard UT/PT works.
- Group 3 (Embedded Features): Internal cooling channels. → Line-of-sight lost (Visual/PT fails).
- Group 4 (Topology Optimized): Organic shapes. → UT is difficult due to curvature.

- Group 5 (Lattice Structures): Thousands of struts. → "Traditional NDT is Blind".

- **Conclusion:** For Group 4 & 5, only CT (Computed Tomography) and PCRT (Resonance Testing) are viable options,.



The "Inspectability" Limit: NASA Geometric Complexity Groups



NDE Technique	Geometry Complexity Group					Comments
	1	2	3	4	5	
VT	Y	Y	P ^(c)	NA	NA	
LT	NA	NA	Y	Y	NA	Screening
PT	Y	Y	P ^(a)	NA	NA	
PCRT	Y	Y	Y	Y	Y	Screening: size restrictions (e.g., compressor blades)
EIT	Y	Y	NA	NA	NA	Screening: size restrictions
ACPD	Y	Y	P ^(c)	NA	NA	Isolated microstructure and/or stresses
ET	Y	Y	P ^(c)	NA	NA	
AEC	Y	Y	P ^(c)	NA	NA	
PAUT	Y	Y	P ^(b)	NA	NA	
UT	Y	Y	P ^(b)	NA	NA	
RT	Y	Y	P ^(d)	NA	NA	
X-Ray CT	Y	Y	Y	Y	NA	
X-ray Micro CT	Y	Y	Y	Y	Y	

Key:

Y = Yes, technique applicable

P = Possible to apply technique given correct conditions

NA = Technique Not applicable

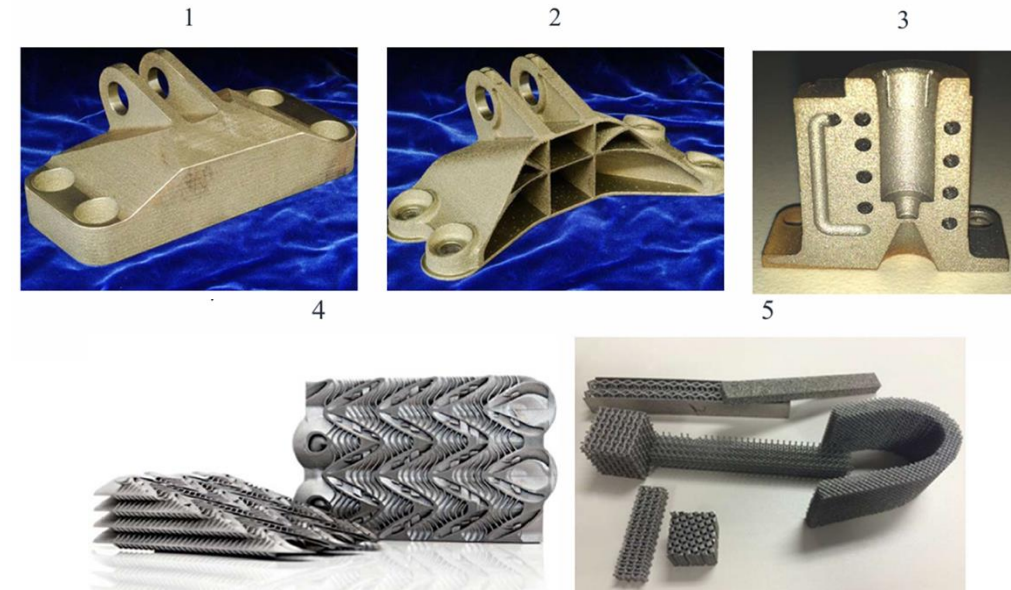
Notes:

(a) Only surfaces providing good access for application and cleaning

(b) Areas where shadowing of acoustic beam is not an issue

(c) External surfaces and internal surfaces where access through conduits or guides can be provided

(d) Areas where large number of exposures/shots are not required



NDE options for
design-to-constraint parts
and lattice structures:
PCRT, CT/ μ CT, and LT

USAF/AFRL-RX-WP-TR-2014-0162 NDE of Complex AM Structures

In-Situ Process Monitoring Strategies



- **Concept:** Monitoring is not a single action; it is a multi-scale observation strategy.

- **Level 1:** Powder Bed Monitoring (Layer-wise):

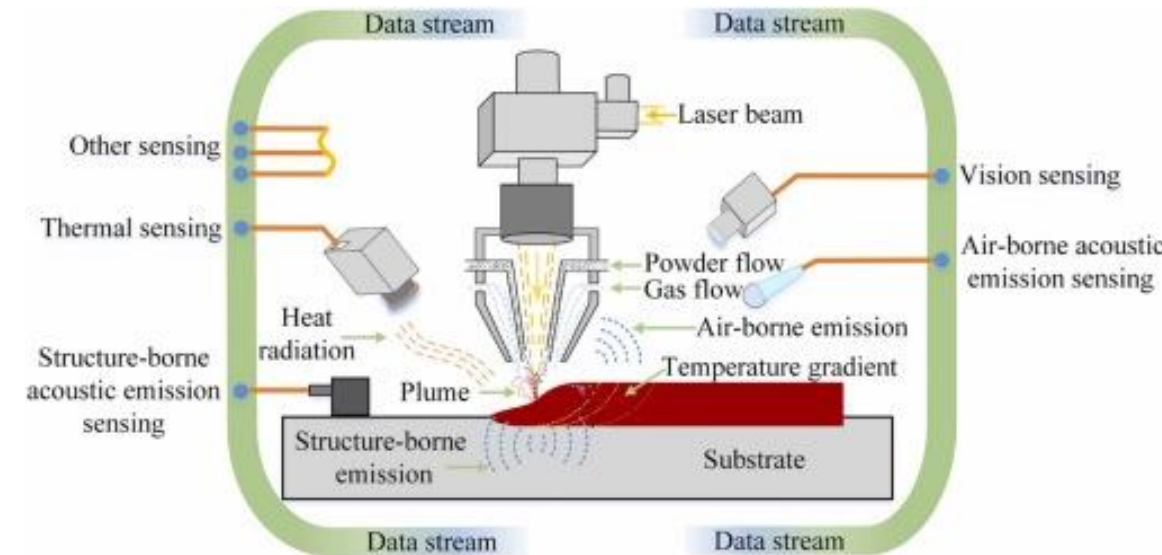
- Target: Recoater streaks, short feed, debris, superelevation.
- Sensor: High-res visual cameras (Off-axis).

- **Level 2:** Slice/Track Monitoring (Scan-wise):

- Target: Geometrical distortions, local overheating (hotspots).
- Sensor: IR Cameras, Optical Tomography.

- **Level 3:** Melt Pool Monitoring (Point-wise / Real-time):

- Target: Melt pool stability, keyhole formation, lack of fusion.
- Sensor: Co-axial Photodiodes, Pyrometers, High-speed Cameras.



Optical Monitoring - Vision Systems



- **Setup Types:**

- Off-Axis: Camera mounted on the chamber corner. Good for full bed overview but suffers from perspective distortion and lower resolution per pixel.
- Co-Axial: Sensor integrated into the laser optical path (using beam splitters). Allows "macro" view of the melt pool but field of view is very limited (only sees the laser spot).

- **What it detects:**

- **Spatter:** High-speed cameras can track particle ejection velocities. Excessive spatter correlates with surface roughness and lack of fusion.
- **Plume:** Metal vaporization interferes with the laser; monitoring plume density helps predict energy absorption losses.

Thermal Monitoring - Pyrometry & Thermography

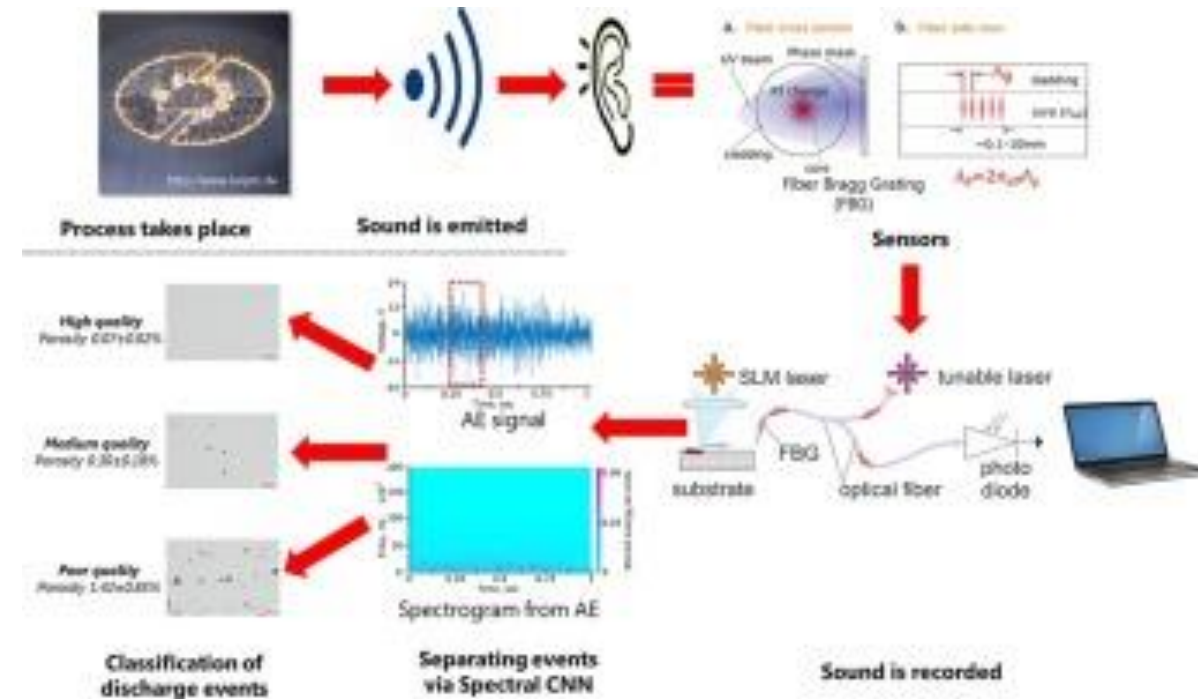


- **The Physics:** Cooling rates determine the microstructure (grain size → mechanical strength).
- **Two-Color Pyrometry:**
 - Problem: Single-color pyrometers need known emissivity (which changes constantly in AM from powder to liquid).
 - Solution: Ratio pyrometers measure two wavelengths to cancel out emissivity errors, providing "True Temperature".
- **Key Application: Detecting "Hotspots".**
 - If heat accumulates (e.g., in overhang areas), cooling slows down → Coarse grains & dimensional distortion.



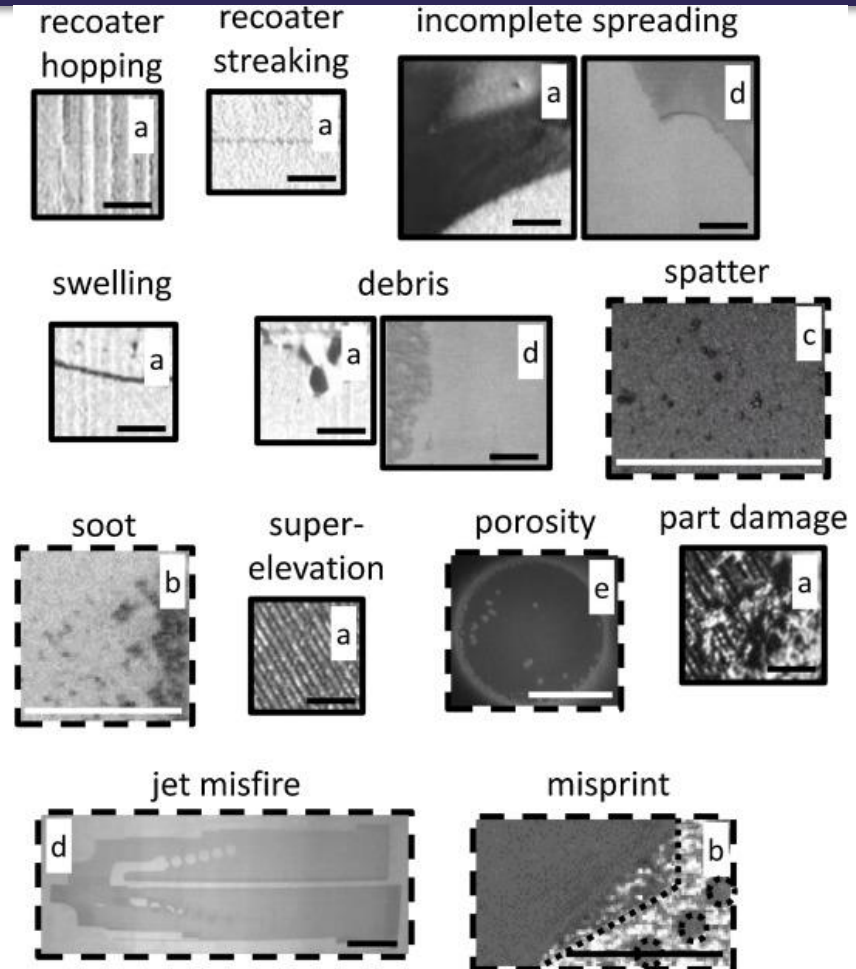
Acoustic Emission (AE)

- **Principle:** When a material cracks or undergoes phase transformation, it releases transient elastic stress waves (sound).
- **Study Case: Gaja & Liou (2016):**
 - Setup: Sensors attached to the build plate.
 - Analysis: Used K-Means Clustering unsupervised learning.
- **Findings:**
 - Porosity: Low amplitude, short decay time signals.
 - Cracks: High amplitude, high energy bursts.
- **Advantage:** Can detect internal defects that optical cameras cannot see (e.g., sub-surface cracks).



Layer-wise Inspection - Powder Bed Quality

- **Method:** Taking images before laser scanning (after recoating).
- **Common Defects:**
 - **Recoater Hopping:** Creates wave patterns on the bed.
 - **Incomplete Spreading:** Leaves voids or previous layer exposed.
 - **Debris:** Spatter from previous layer falling onto the fresh powder.
- **Algorithm:** Image segmentation allows automated detection.
 - Darker spots: Usually indicate depressions/shadows.
 - Brighter spots: Reflections from solid metal (short feed).



Advanced Analytics - Machine Learning & Sensor Fusion



- **The Big Data Problem:** Terabytes of data per build. Human analysis is impossible.

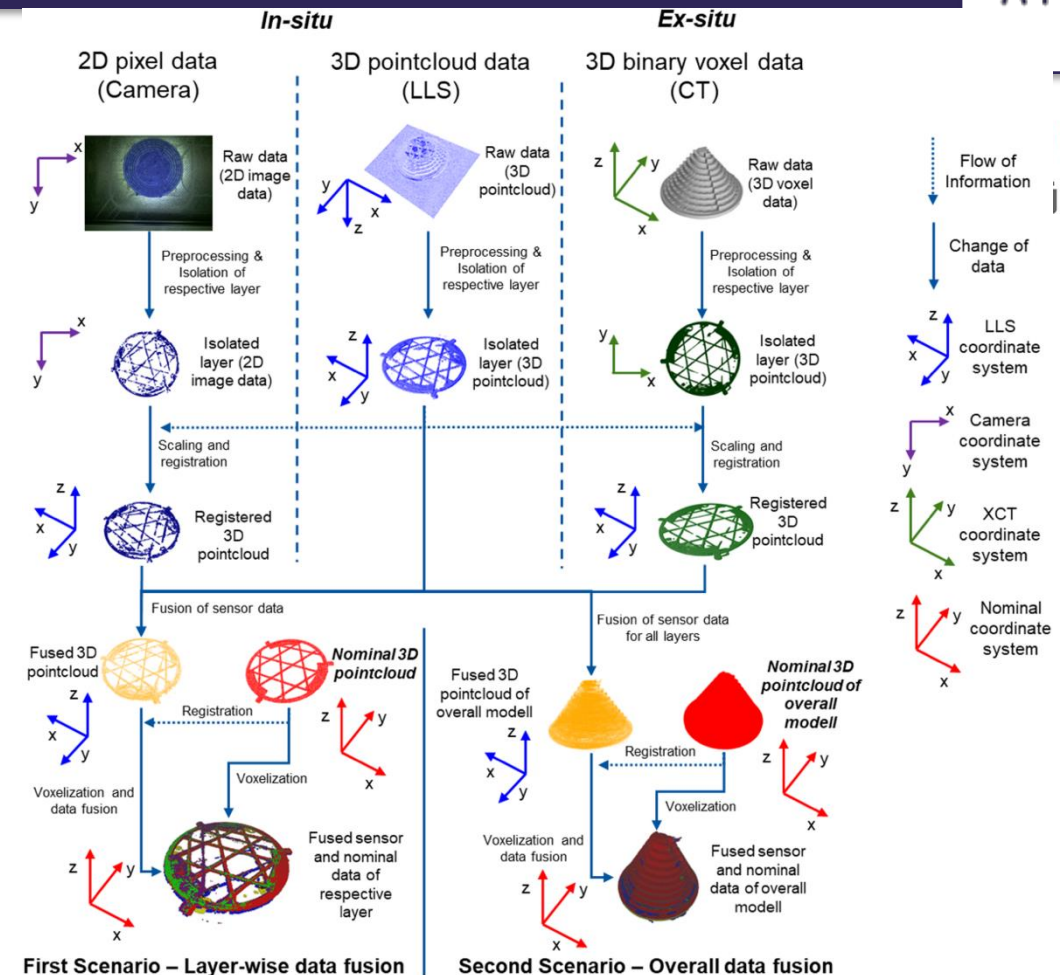
- **Machine Learning (ML) Applications:**

- CNN (Convolutional Neural Networks): Classifying melt pool images as "Keyhole", "Conduction", or "Lack of Fusion" modes.

- Unsupervised Learning: Detecting anomalies without labeled data (e.g., K-Means, PCA).

- **Sensor Fusion (Pandiyan et al. 2022):**

- Combining Optical + Thermal + Acoustic data.
 - Result: Higher probability of detection (POD) and reduced false alarms compared to single-sensor approaches.



The Future: Multisensor Fusion & Virtual Quality Maps



- **Concept:** Combining Vision + Acoustic + Thermal data to create a 3D Digital Twin.

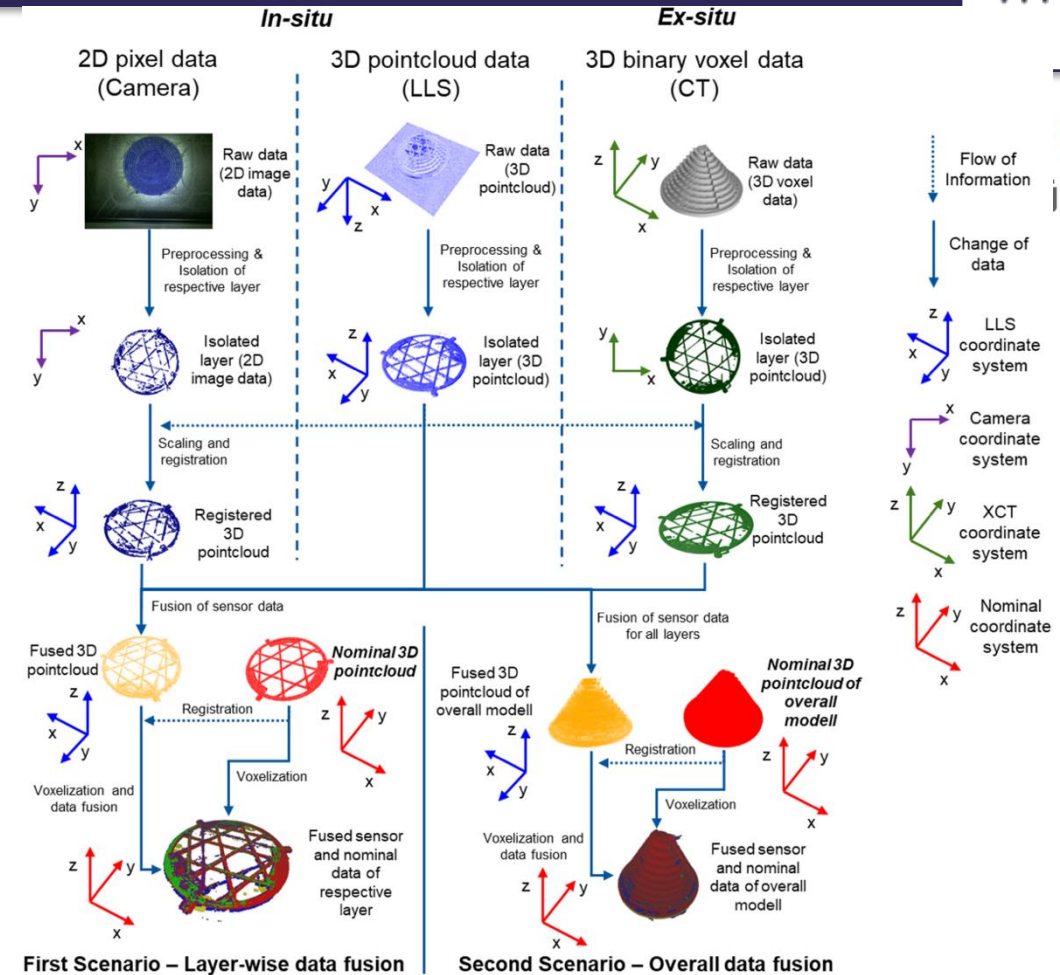
- **Process:**

1. Extract Features: Melt pool size (Vision), Peak Frequency (Acoustic), Temperature (Thermal).

2. Spatiotemporal Registration: Mapping every sensor signal to a specific X,Y,Z coordinate on the part.

3. Virtual Quality Map: Generating a colored 3D map showing "Good" (Blue) vs. "Defective" (Red) zones without scanning the part physically.

- **Result:** Prediction of Keyhole pores and Cracks with >96% accuracy.



The Future: Digital Twin & Virtual Quality Maps



- **Definition:** A Digital Twin in AM is not just a CAD file; it is a dynamic, multi-physics simulation updated in real-time by in-situ sensor data.

- **The Workflow (Chen et al., 2024):**

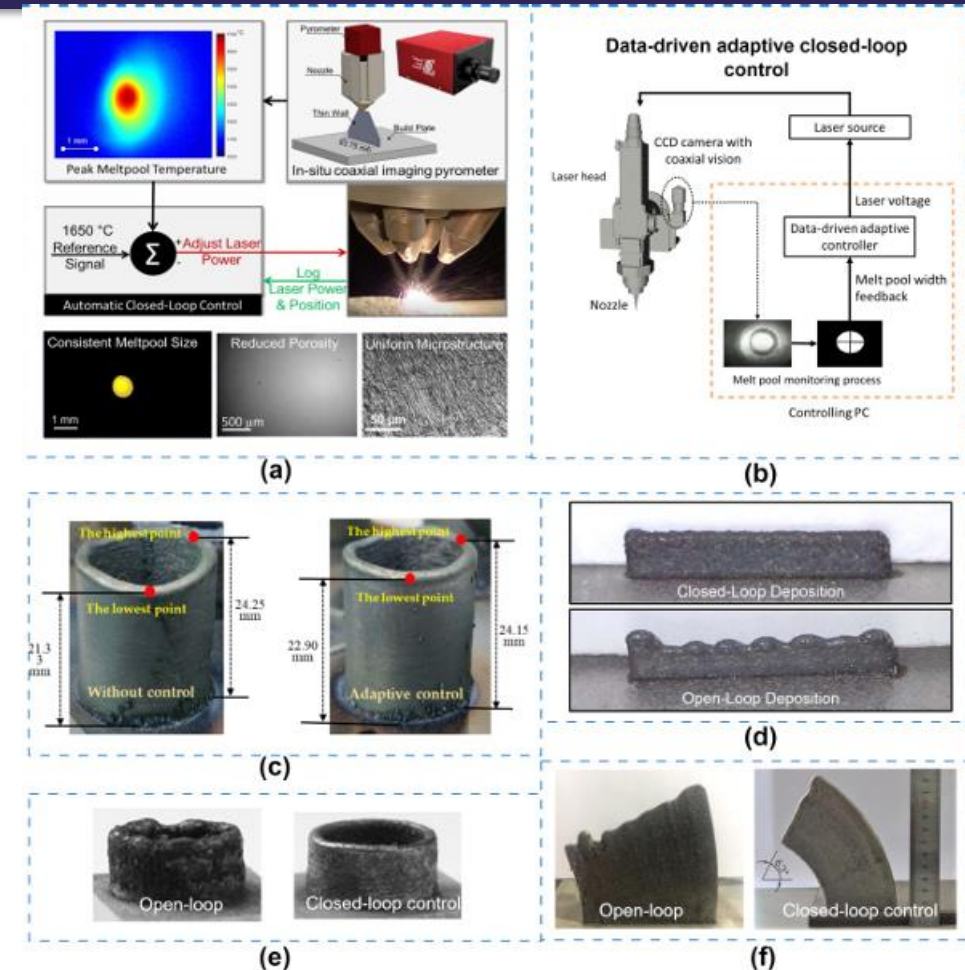
- 1. Multisensor Data Acquisition:** Collecting Acoustic, Optical, and Thermal signals simultaneously.

- 2. Spatiotemporal Registration:** Mapping every millisecond of sensor data to a specific X, Y, Z coordinate on the part.

- 3. Virtual Quality Map:** Generating a colored 3D voxel map showing "Safe" (Blue) vs. "Defective" (Red) zones without physical scanning.

- **Key Benefit:**

- Moves from Reactive (detecting defects) to Proactive (predicting performance).
 - Acts as a "Birth Certificate" for the part, reducing the need for 100% CT scanning.





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