



Characterization of materials by 2D, 3D and 4D X-ray imaging

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In-situ processing and mechanical characterization of materials

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UNIQUE CAPABILITIES

- **3D characterization of materials,** using X-rays, NDT, correlative:
 - Microstructure and defect characterization, 3D and 4D
 - Microstructure and relationship with mechanical properties, **ex-situ** and **in-situ** testing
- Microstructure development during processing, in-situ devices

Aided by X-rays (lab & synchrotron)

+ 4D evaluation (in-situ devices)











Creep testing device for high temperature and in-situ XCT/XRD. Resistive heating. Set-up at SLS Tomcat

Mechanical testing device for RT & high temperature and in-situ XCT & XRD. Induction heated

the engine of

scientific imaging 2

DRAGONFLY

Processing - In-situ HT infiltration for metals







Introducción a la imagen por rayos X

Nos puede revelar la estructura interna de los materiales de manera no destructiva

2D → Radiografía

-Proyección del volumen irradiado - Revela inhomogeneidades

- No provee resolución espacial

Descubiertos por W. Röntgen → Premio Nobel en física en 1901

> Una de las primeras imágenes publicadas: mano del anatomista Albert von Kölliker, 23 Enero, 1896



3D → Tomografía

- Imagen 3D del volumen irradiado

- Revela arquitectura interna del material

- Análisis cualitativo + cuantitativo

Desarrollada por Cormack y Housfield→ Premio Nobel Prize de Fisiología o medicina en 1979



TAC de una cabeza humana



Tomografía de rayos X

Metodología de medida estándar

Evaluación del daño en materiales compuestos con TAC

¿Porque evaluar el daño?

- Los mecanismos de deformación y producción de daño en materiales compuestos pueden ser muy complejos, incluso bajo solicitaciones simple de carga (fractura de matriz, deslaminación, rotura de fibra, etc).
- Para **mejorar** los materiales y los procesos de fabricación que tenemos hoy en día, es necesario **entender** lo mejor posible el comportamiento del material y sus modos de fallo.

• A partir de estos datos se pueden generar **modelos** computacionales precisos para determinar el comportamiento del material.

Evaluación de daño en materiales compuestos

Interlaminar fracture toughness

Sket F., et al. Compos. Sci. Technol., 2014, 90, 129-138

Vigueras G., et al. Compos. Struct., 2015, 125, 542-557

Impact damage

Enfedaque A, et al. J Compos Mater 2010;44:3051–68.

Tensile and shear loading

IMPACT IN COMPOSITE MATERIALS

- Composite materials subjected to impact loading during service conditions
- Threats include: hailstones, lightning strikes, bird impact, ice shedding, runaway debris, tools, etc.
- FRP subjected to out-of-plane forces (impact), detrimental for mechanical properties.
- Research to improve out-of-plane strength (development of new resins or toughening additions, hybrid composites, 3D woven architectures, etc.

Muñoz R, et al. Compos Struct 2015; 141:151-127.

Carbon fiber composites

https://www.ge.com/news/reports/the-art-ofengineering-the-worlds-largest-jet-engine-shows-offcomposite-curves

IMPACT IN COMPOSITE MATERIALS

Impact testing of composite materials: low velocity impact

• Energy dissipated (W) = area under the loaddisplacement curve

UNIT OF EXCELLENCE

MARÍA DE MAEZTU

• Linear mechanical response up to Pmax

dea

materials

- After Pmax, extensive damage development
- •For weight-critical application, W/ $\rho t\,$ should be compared.

2000 INDER INDICIDIO INDICATO, 7 IL LIGITO FOOLIYO

IMPACT IN COMPOSITE MATERIALS

Impact testing of composite materials: ballistic impact

$$Vr = (V_i^n - V_0^n)^{1/n}$$

- Energy dissipated (W) = difference between the initial and residual kinetic energies of the projectile
- $\bullet For weight-critical application, W/\rho t should be compared.$

EVALUATION OF IMPACT DAMAGE IN COMPOSITES

4.0

Techniques for impact damage assessment

Microscopy

+ High resolution, cross section, top section, etc.

- Time consuming, Destructive, 2D

Kadlec MR, et al. Appl Compos Mater 2012; 393:407-19

Ultrasonic testing

+ Standard, semi-3D, fast, portable, nondestructive, quantifiable

- Material dependent, saturation

Infrared Thermography

- + Non-destructive, fast, portable.
- Application of heat, limited

Boccardi S, et al. SPIE 2017; 10170

<u>Radiography</u>

+ Fast, nondestructive, high resolution, quantifiable - 2D, dye penetrant, size limit

8s 0.0 -0.8

Laser Shearography

- + Non-destructive, fast, portable
- Limited resolution, qualitative, 2D

Kadlec MR, et al. Appl Compos Mater 2012; 393:407-19

X-ray tomography

+ High resolution, 3D, nondestructive, quantifiable.

- Slow, size limit

INSPECCIÓN POR RADIOGRAFIA DE RAYOS X DE AVION MILITAR

Imagen cortesía de Eusebio Solórzano, Novadep NDT Systems

EVALUATION OF IMPACT DAMAGE BY XCT

EVALUATION OF IMPACT DAMAGE BY XCT

X-Ray Tomography

UNIT OF EXCELLENCE MARÍA DE MAEZTU

materials

Evaluación del daño en materiales metálicos con RX y TAC

Universidad materials
Universidad de Madrid
Universidad E.g.: Evaluation of intentionally introduced porosity created by AM to Universidad E.g.: Evaluation of intentionally introduced porosity created by AM to

- Quantification 3D: Volume, surface, distances, position 3D, shape, orientation, etc.

Relate microstructure before and after deformation

- Meshing and exporting for modelling

Dynamic experiments XCT in the lab – High velocity impact on AM materials

Aim: understand the effect of microstructure on high velocity impact of AM material

materials uc3m Universidad Universidad Carlos III de Madrid

Dynamic experiments

materials

Universidad

Carlos III

de Madrid

En colaboración con Prof. Jose Antonio Rodriguez Martinez (UC3M)

Evolution of the porous microstructure during shear-dominated loading

Split Hopkinson Compression bar

Dynamic shear fracture of porous printed metals: looking at the internal microstructure

In-situ dynamic shear compression simulations

Central section of the specimen: actual porous microstructure

Fine mesh to capture the shape of the voids

Large computational cost

Modelling the whole specimen to include the boundary conditions

Dynamic experiments

In-situ planar plate impact

Large hydrostatic stresses leading to unstable void growth

In-situ planar plate impact

In-situ planar plate impact

En colaboración con Prof. Jose Antonio Rodriguez Martinez (UC3M)

In-situ planar plate impact

XCT for internal damage assessment

Increasing impact speed: 225-750m/s

QUANTIFICATION OF VOID VOLUME FRACTION

Cuantificación propiedades Desarrrollo de herramientas de análisis

• Gestión y filtrado de datos en caracterización (2D, 3D, 4D). Desarrollo de múltiples herramientas para extracción automática de datos. Proyectos: FCAS, METALIA, BIOFUN3D, 3D-MetalJet.

Ejemplos: Cuantificación automática de defectos de AM por XCT (defectos, partículas, rugosidad superficial), incorporación a base de datos, DVC, etc.

Proyectos a futuro

IGNITE: Investigating Energetic Materials for Growth, Novelty, and Innovation in Technology and Energy

Red doctoral Europea - 15 PhD en formación

Spain, Italy, France, Germany, Poland, Denmark, Israel

Figure 1.1 Overview of the research program

Thank you for your attention