APTIME
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Universidad Rey Juan Carlos

IO1: Design of Module Advanced Materials and Materials for ALM
Mechanical characterization of materials processed by ALM

FRACTURE AND FATIGUE RESISTANCE

With the support of the Erasmus+ Programme of the European Union

This project has received funding from the European Union’s ERASMUS+ Programme under the Strategic Partnerships for Higher Education Action. The sole responsibility of this publication lies with the author. The European Union is not responsible for any use that may be made of the information contained therein.

Outline

- **Introduction to Fracture Mechanics Approach**
    - Approach to design
    - Fracture Mechanics approaches
        - Linear Elastic Fracture Mechanics
        - Elastic- Plastic Fracture Mechanics
        - Post-Yield Fracture Mechanics
    - Standards for determination of fracture parameters
- **Fracture of additive manufactured materials**
    - Metals: Ti-6Al-4V, Stainless Steel, Al-12Si alloy
    - Ceramics: Al_2O_3
    - Polymers: PA12

Fracture Mechanics

Fracture mechanics studies the load-bearing capacity of structures in the presence of initial defects.

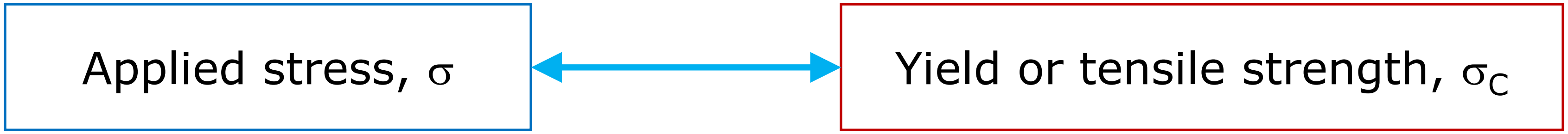
The defects in form of cracks are assumed to exist in structures and Fracture Mechanics studies the conditions of initiation, growth and arrest of cracks.

The defects can appear in the structure by three ways:

- They can exist in a material due to its composition (second-phase particles, debonds in composites, etc).
- They can be introduced in a structure during fabrication.
- They can be created during the service life of a component (fatigue cracks, Environment assited or creep cracks, etc).

Approach to design

Conventional strength of materials approach



Applied stress, σ

Yield or tensile strength, σ_C

Fracture mechanics approach

Can fracture be prevented by constructing a structure that has no defects?

Absolutely no

To attain **safe design of structures**:

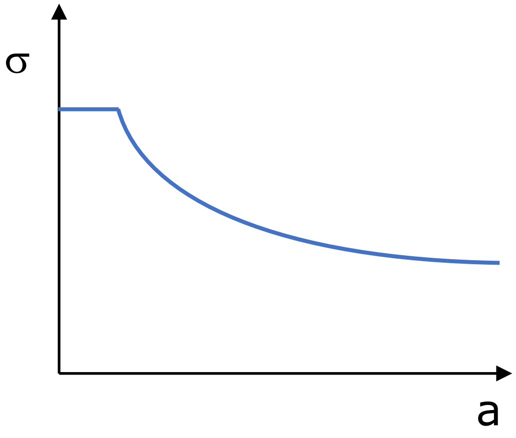
- The safe operating load should be determined for a crack of a given size, assumed to exist in the structure
- Given the operating load, the size of the crack that is created in the structure should be determined.

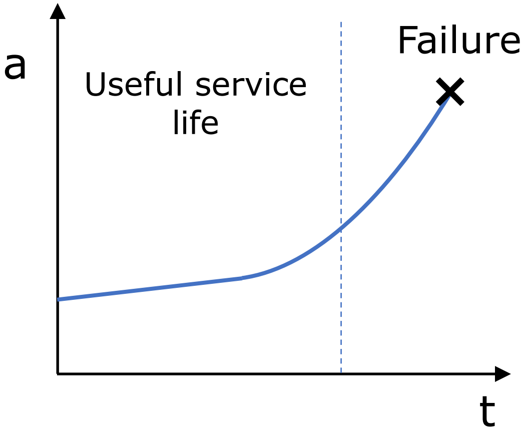
Approach to design

Fracture mechanics approach

For **safe design**, some questions are to be answered:

1. what is the maximum crack size that a material can sustain safely?
2. What is the strength of a structure as a function of crack size?
3. How does the crack size relate to the applied loads?
4. What is the critical load required to extend a crack of known size, and is the crack extensión stable or unstable?
5. how does the crack size increase as a function of time?





Approach to design

Fracture mechanics approach

Objective: to determine the **crack driving force** that allows to determine the force as a function of the material behaviour, crack size, structural geometry and loading conditions.

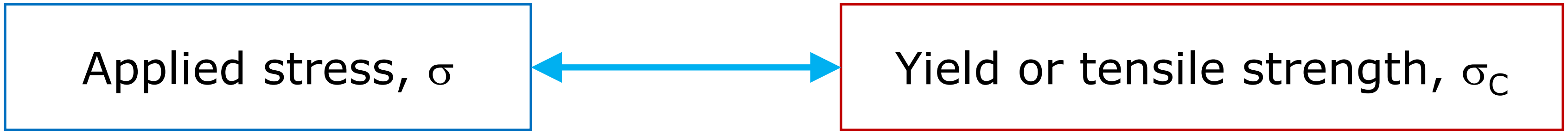
$$K, G, J, \delta, w = f(\sigma, a, geometry, loding\ condition)$$

The critical value of this parameter is named fracture toughness (material´s property), and the failure occurs

$$K = K_C$$
$$G = G_C$$
$$J = J_C$$
$$\delta = \delta_C$$
$$w_f = w_e$$

Approach to design

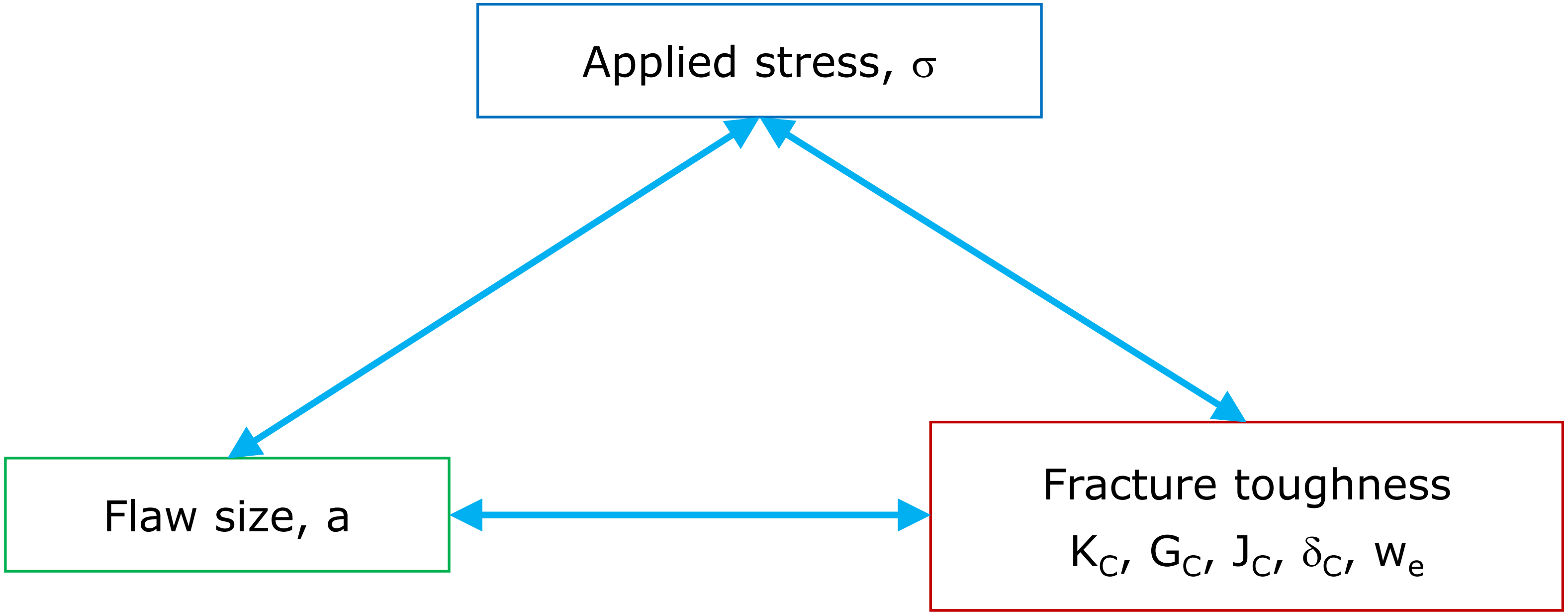
Conventional strength of materials approach



Applied stress, σ

Yield or tensile strength, σ_C

Fracture mechanics approach



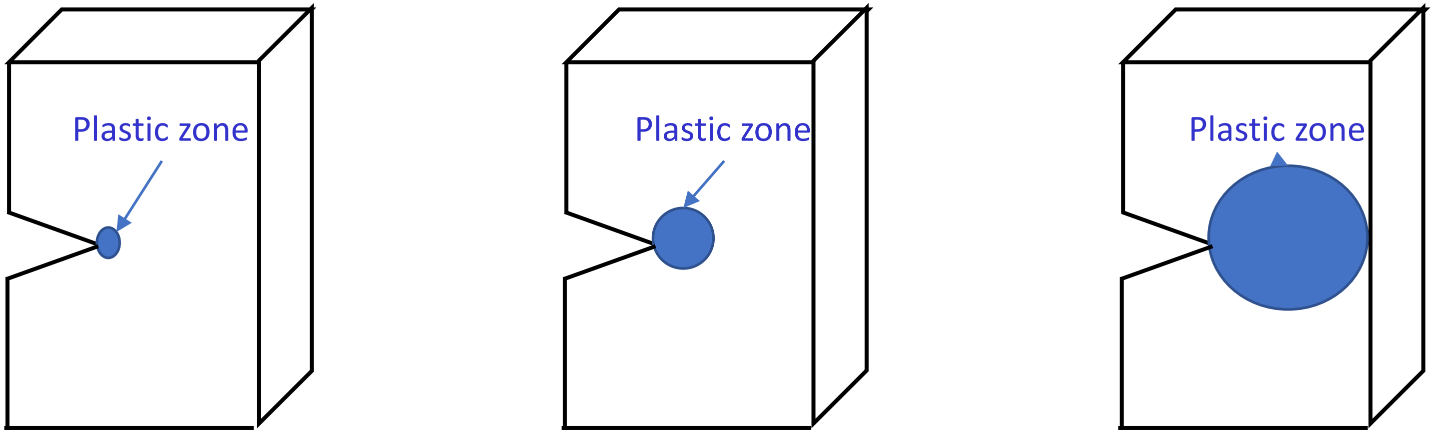
Applied stress, σ

Flaw size, a

Fracture toughness

K_C, G_C, J_C, δ_C, w_e

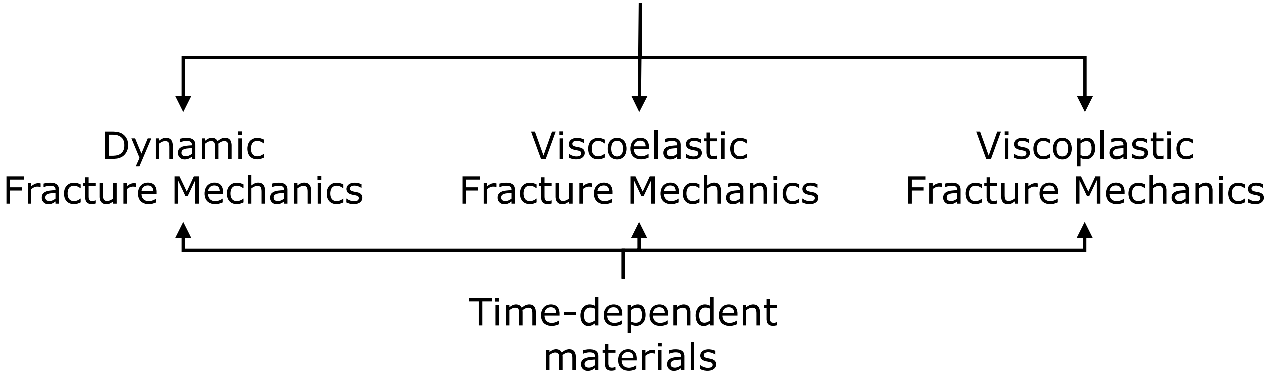
Effect of material properties on fracture: Fracture Mechanics Approaches



Linear Elastic
Fracture Mechanics
LEFM

Elastic-Plastic
Fracture Mechanics
EPFM

Post-Yield
Fracture Mechanics
PYFM



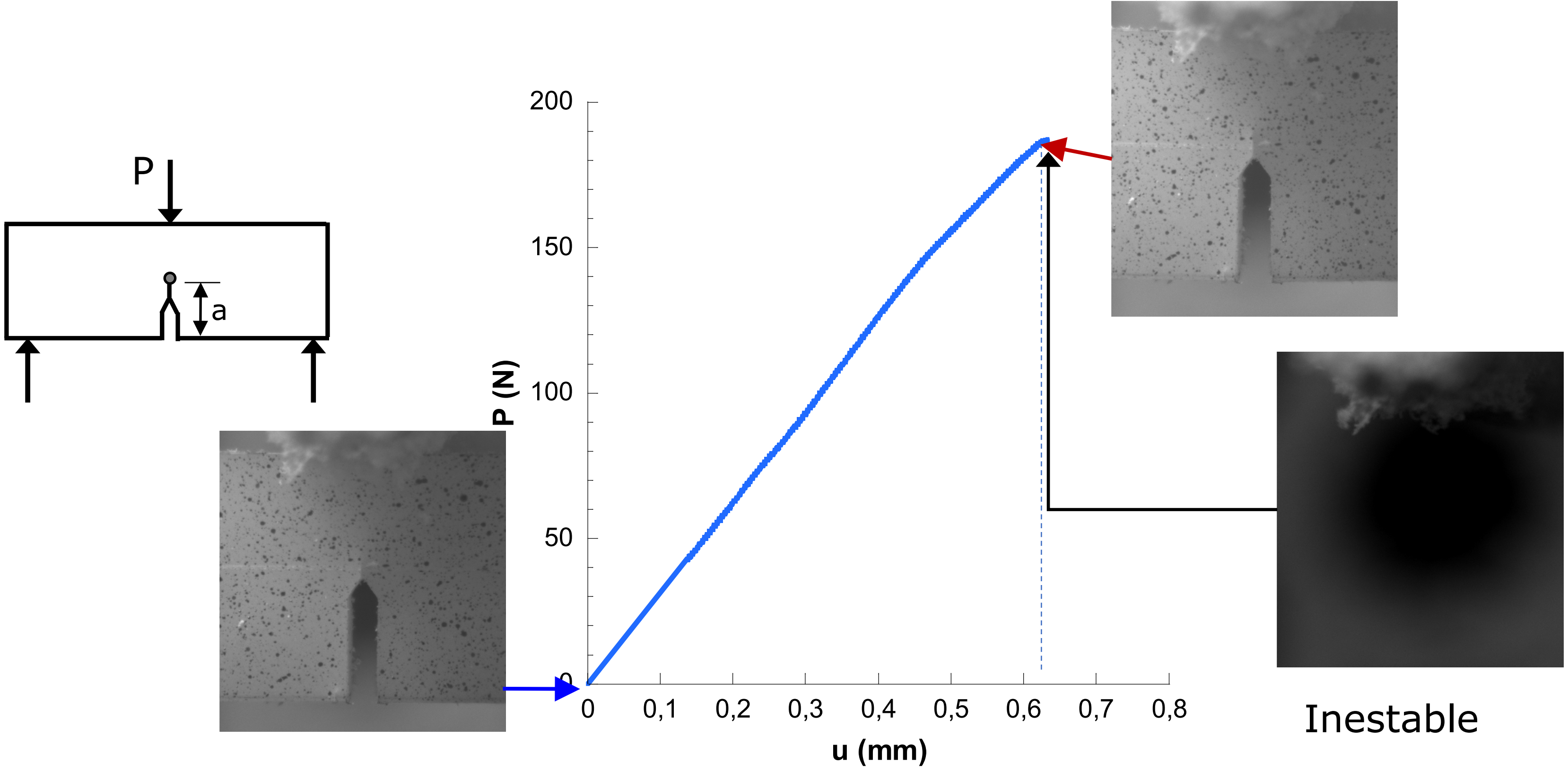
Dynamic
Fracture Mechanics

Viscoelastic
Fracture Mechanics

Viscoplastic
Fracture Mechanics

Time-dependent
materials

Linear Elastic Fracture Mechanics, LEFM



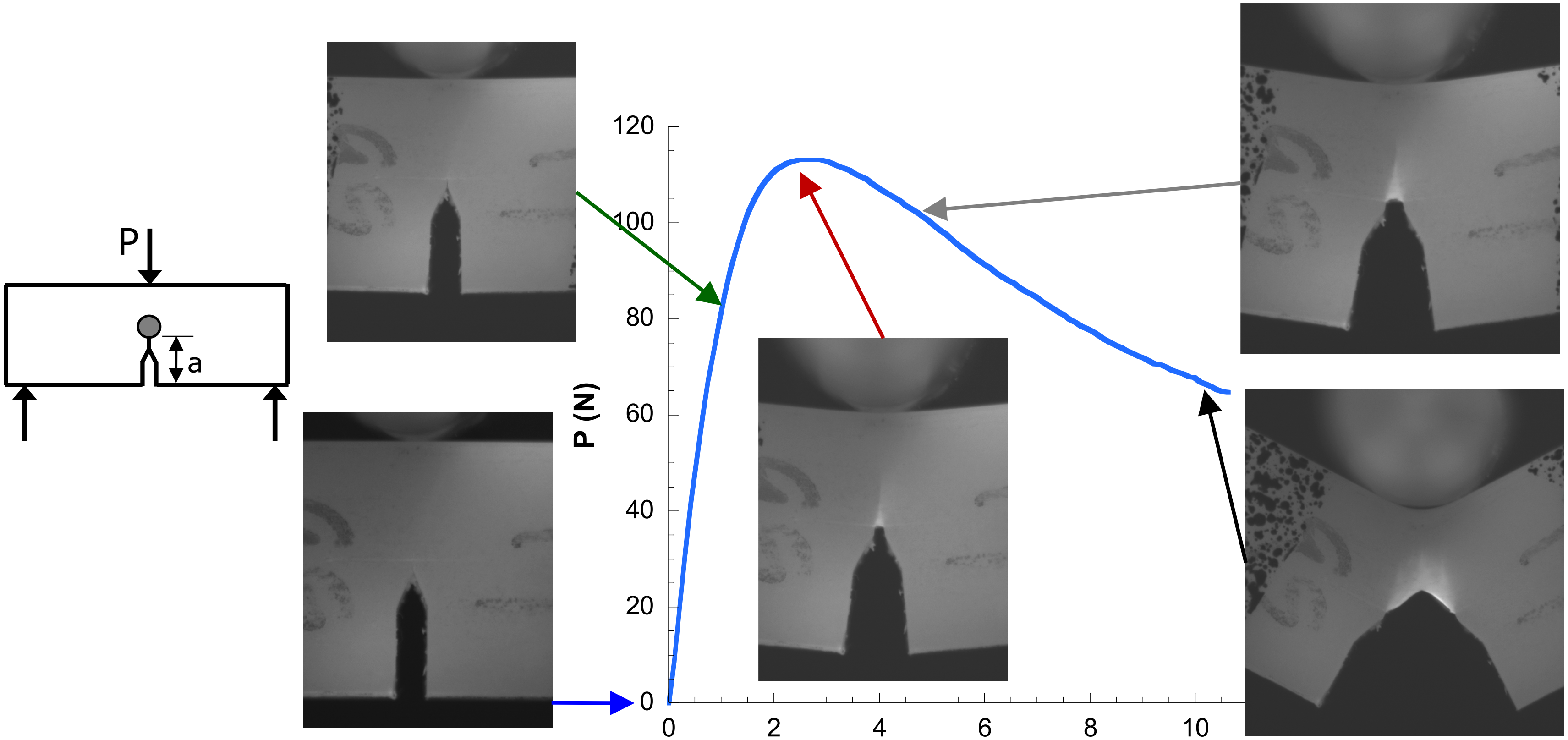
Crack driving forces

Energy approach: Energy release rate, G

Stress approach: Stress intensity factor,K

High strength Steel, Polymers below *Tg* (viscoelastic), Monolithic ceramics, Ceramic composites

Elastic-Plastic Fracture Mechanics, EPFM



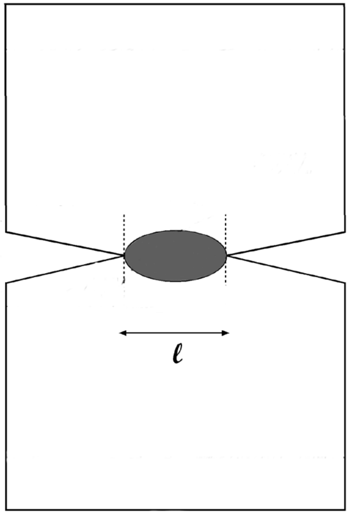
Crack driving forces

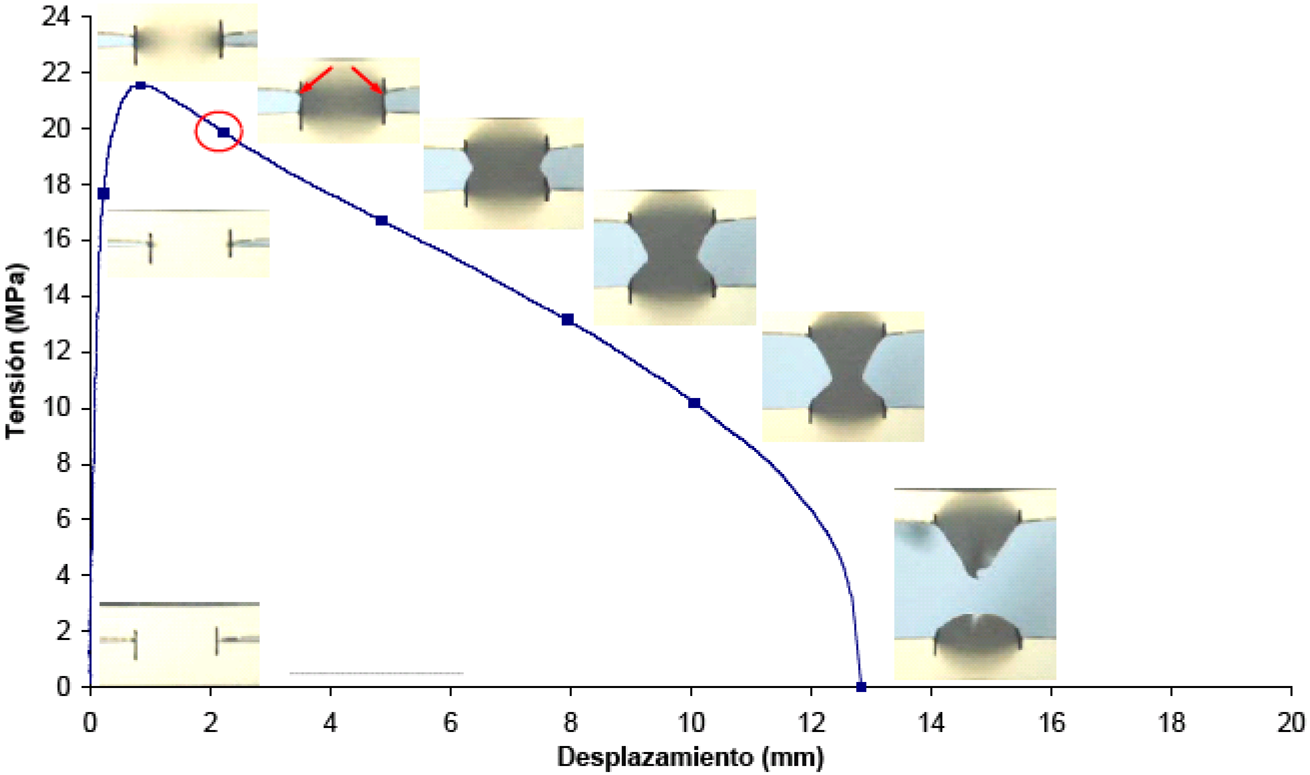
Crack Tip Opening Displacement, δ

J-contour integral

Low- and medium-strength steel, Polymers above *Tg* (viscoelastic)

Post-Yield Fracture Mechanics, PYFM





Crack driving force: specific work of fracture, w_f

Plastic films

Fracture toughness testing

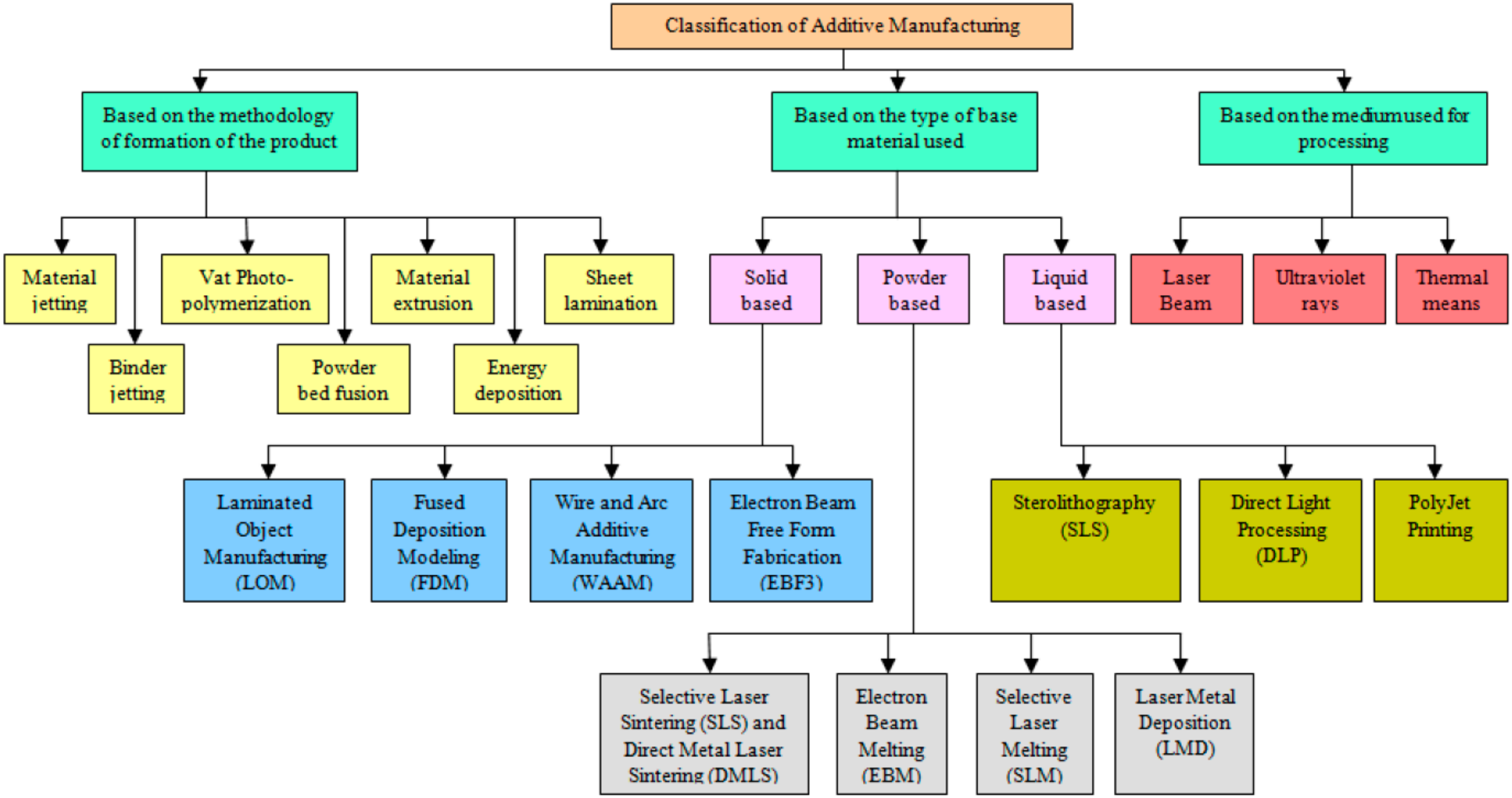
POLYMERS	
ISO 13586	Plastics — Determination of fracture toughness (G_{IC} and K_{IC}) — Linear elastic fracture mechanics (LEFM) approach
ASTM D5045	Standard test method for plane-strain fracture toughness and energy release rate of plastic materials
ASTM D6068	Standard Test Method for Determining J-R Curves of Plastic Materials

CERAMICS	
ASTM C1421	Standard Test Methods for Determination of Fracture Toughness of Advanced Ceramics at Ambient Temperature

Fracture toughness testing

METALS	
ASTM E399	Standard test method for linear-elastic plane-strain fracture toughness K_{IC} of metallic materials.
ISO 12737	Metallic materials – determination of plane-strain fracture toughness.
ASTM E1820	Standard test method for measurement of fracture toughness.
ISO 12135	Metallic materials – unified method of test for the determination of quasistatic fracture toughness.
ASTM E561	K-R curve determination testing.
ASTM E1304	Standard test method for plane-strain (chevron-notch) fracture toughness of metallic materials

Additive Manufacturing Techniques



- Classification of Additive Manufacturing
  - Based on the methodology of formation of the product
    - Material jetting
    - Binder jetting
    - Vat Photo-polymerization
    - Powder bed fusion
    - Material extrusion
    - Energy deposition
    - Sheet lamination
  - Based on the type of base material used
    - Solid based
      - Laminated Object Manufacturing (LOM)
      - Fused Deposition Modeling (FDM)
      - Wire and Arc Additive Manufacturing (WAAM)
      - Electron Beam Free Form Fabrication (EBF3)
    - Powder based
      - Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS)
      - Electron Beam Melting (EBM)
      - Selective Laser Melting (SLM)
      - Laser Metal Deposition (LMD)
    - Liquid based
      - Sterolithography (SLS)
      - Direct Light Processing (DLP)
      - PolyJet Printing
  - Based on the medium used for processing
    - Laser Beam
    - Ultraviolet rays
    - Thermal means

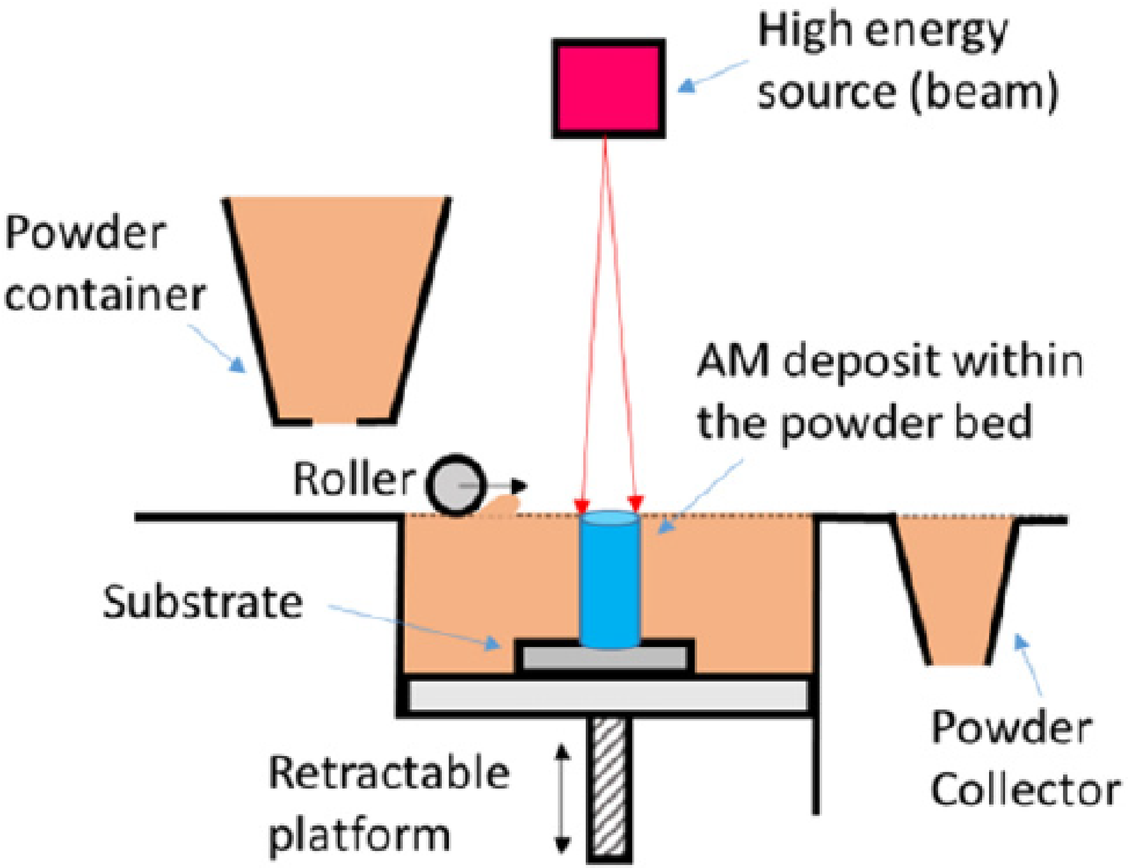
Metal Additive Manufacturing Techniques

- Powder-bed fusion (PBF)
  - Selective Laser Melting (SLM)
  - Direct metal laser Sintering (DMLS)
  - Selective Laser Sintering (SLS)
  - Electron Beam Melting (EBM)
- Directed Energy Deposition (DED)
  - Powder-fed system
    - Laser engineered net shaping (LENS)
    - Direct Metal Deposition (DMD)
    - Laser Metal Deposition (LMD)
    - Laser Free-form Fabrication (LF3)
  - Wire-fed system
    - Electron Beam Freeform Fabrication (EBF3) system
    - Shaped Metal Deposition (SMD)
- Sheet Lamination (SL)
  - Laminated Object Manufacturing (LOM)
  - Ultrasonic Additive Manufacturing (UAM)

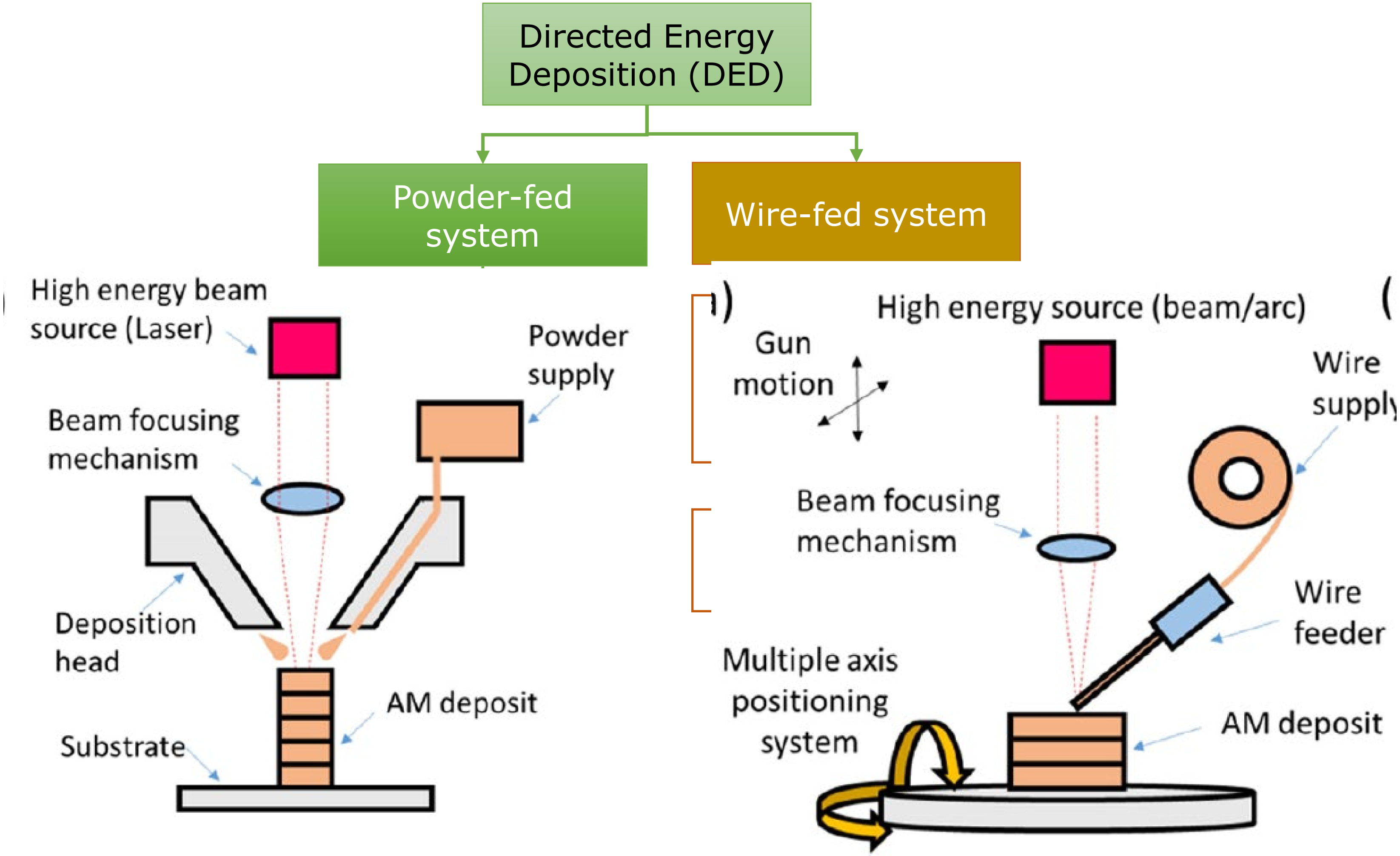
Metal Additive Manufacturing Techniques

Powder-bed fusion (PBF)

- Selective Laser Melting (SLM)
- Direct metal laser Sintering (DMLS)
- Selective Laser Sintering (SLS)
- Electron Beam Melting (EBM)



Metal Additive Manufacturing Techniques



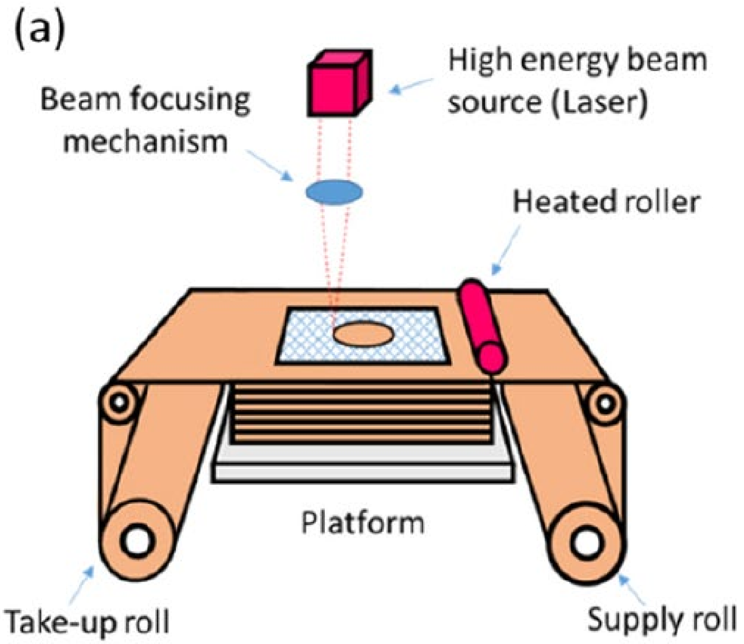
Directed Energy Deposition (DED)

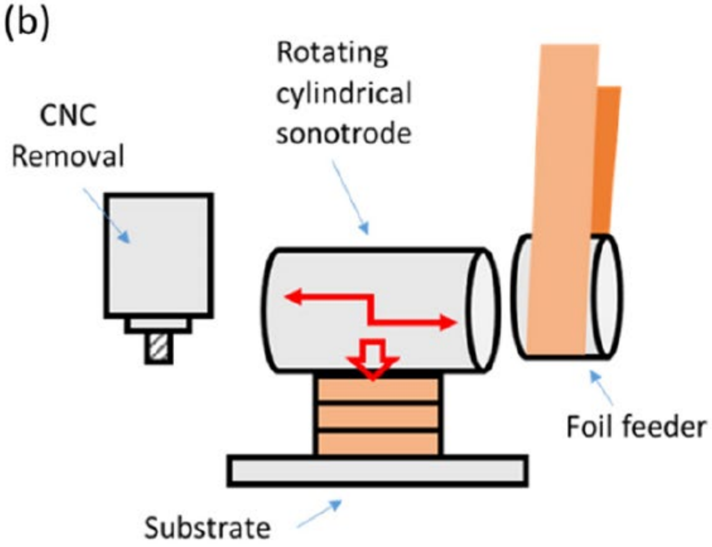
Powder-fed system

Wire-fed system

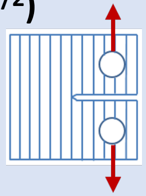
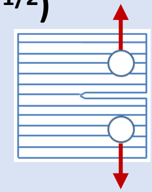
Metal Additive Manufacturing Techniques

- Sheet Lamination (SL)
  - Laminated Object Manufacturing (LOM)
  - Ultrasonic Additive Manufacturing (UAM)



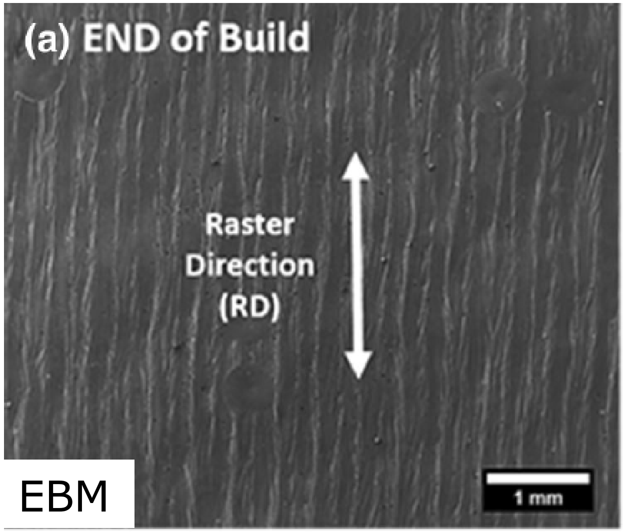


Fracture properties of AM metals

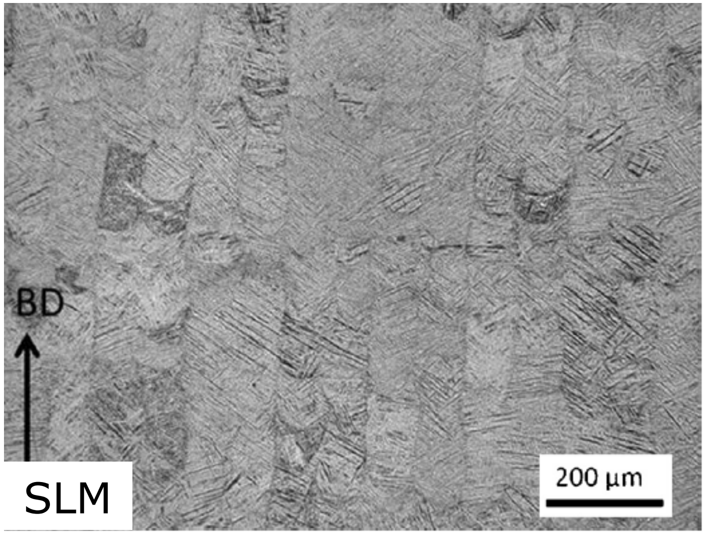
Ti-6Al-4V					
Technique	**Condition**	**K_{IC} Parallel ($MPam^{1/2}$)** 	**K_{IC} Perpendicular ($MPam^{1/2}$)** 	**Anisotropy**	
SLM	As-built	28 ± 2	16–23	17.9	Cain et al Addit Manuf 5 (2015)
	Stress-relieved	28 ± 2	30–31 ± 2	-10.9	
	Heat-treated	41 ± 2	49 ± 2	-19.5	
	As-built	66.9 ± 2.6	41.8–64.8 ± 16.9	3.1	Edwards Fatigue Fract Eng Mater Struct 38 (2015)
EBM	As-built	110 ± 7.4	102 ± 8.9	7.3	Edwards et al J. Manuf Sci Eng 135 (2013)
	As-built	67–80	65	18.8	Seifi et al JOM 65 (2017)
Wrought	44-66				ASM International
Cast	88-110				

Fracture properties of AM metals

Anistropy in Ti-6Al-4V



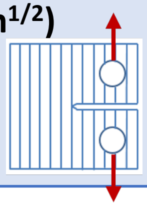
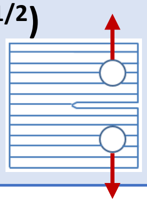
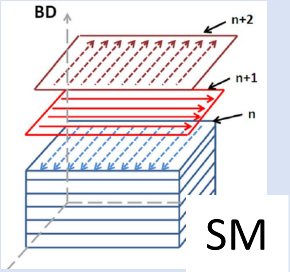
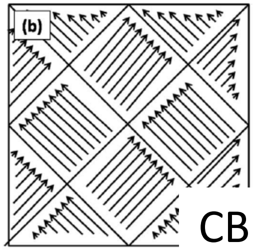
EBM



SLM

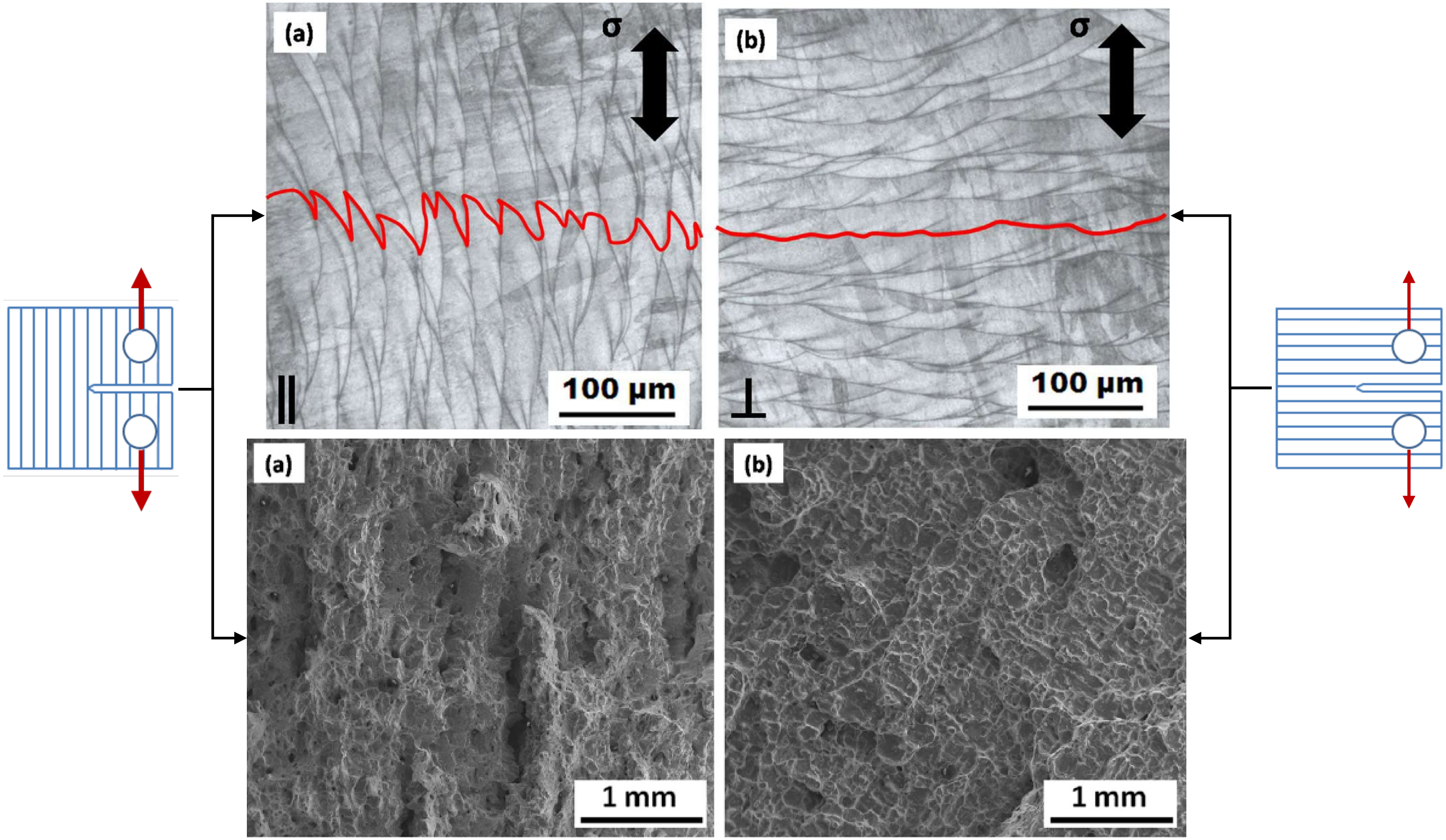
- Grain morphology: epitaxial columnar grain growth, caused by heterogeneous recrystallization and layer banding during the AM process.
- Heterogeneous recrystallization due to heteregeneous residual stresses within the metal parts.
- Lack-of-fusion defects.

Fracture properties of AM metals

306 L Stainless steel					
Technique	**Condition**	**K_{IC} Parallel ($MPam^{1/2}$)** 	**K_{IC} Perpendicular ($MPam^{1/2}$)** 	**Anisotropy**	
Conventional	112-278				Int J Adv Manuf Technol 51 (2010)
SLM + stress relieving (500ºC 1 h)	 SM	72.3	62.9	15	Suryawanshi et al Mater Sci A 696 (2017)
	 CB	86.8	79.6	9	

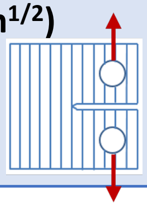
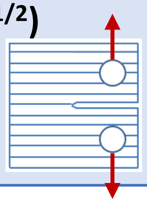
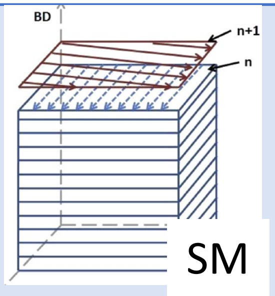
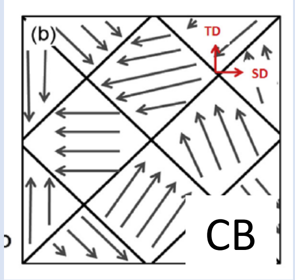
Fracture properties of AM metals

306 L Stainless steel



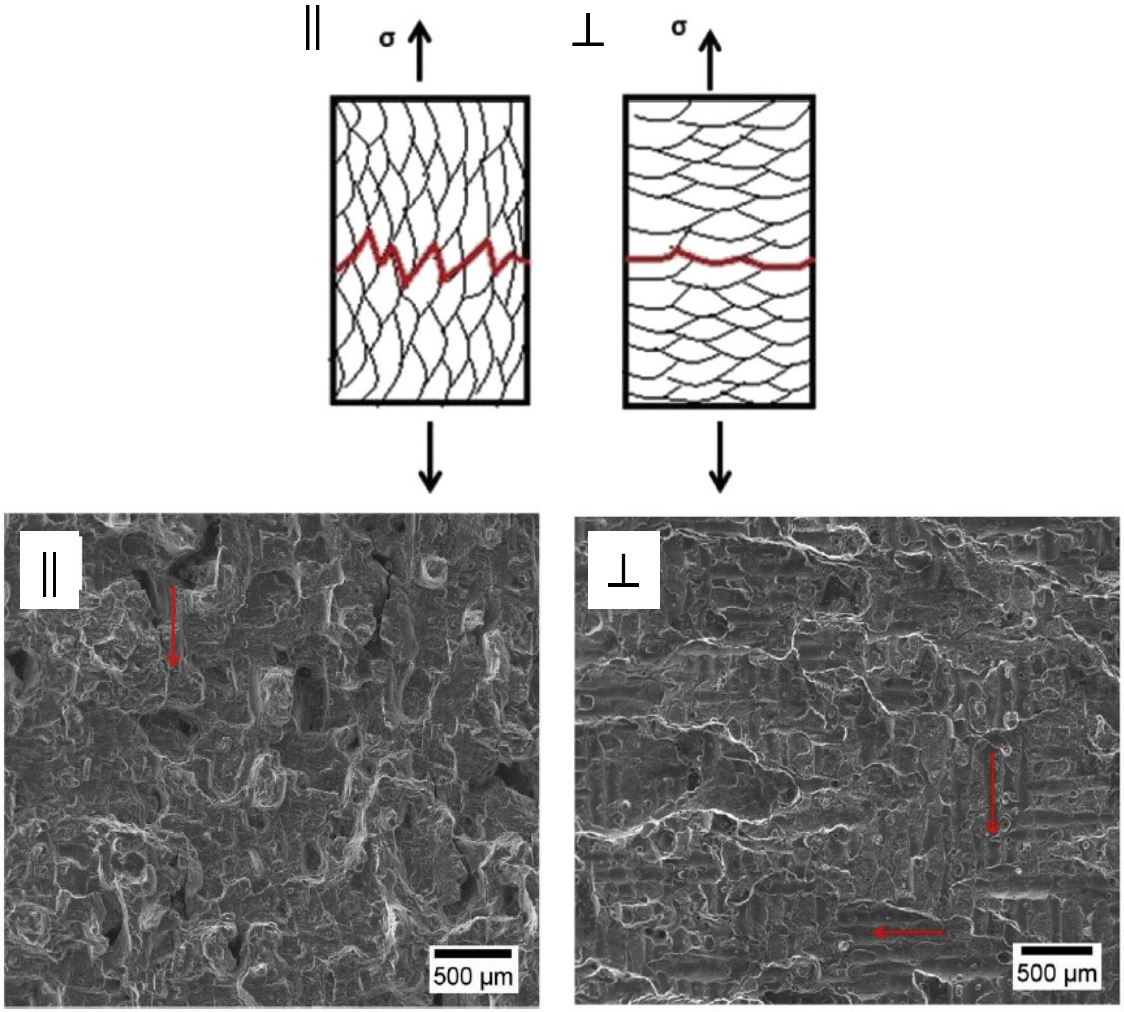
Fracture properties of AM metals

Al-12Si alloy

Technique	Condition	K_{IC} Parallel ($MPam^{1/2}$) 	K_{IC} Perpendicular ($MPam^{1/2}$) 	Anisotropy	
Conventional	11.1				Suryawanshi et al Acta Materialia 115 (2016)
SLM		46.7	37.9	23	
		21.7 (heat treatment)	19.3 (heat treatment)	12	
		47.0	34.5	36	

Fracture properties of AM metals

Al-12Si alloy



Ceramic Additive Manufacturing Techniques

Single-step processes		Multi-step processes						
Bedless	***Bed***	***Bed***			***Bedless***			
Directed Energy Deposition	Powder Bed	Fusion	Binder Jetting	Sheet Lamination	Material Extrusion		Material Jetting	Vat Photopolymerization
LENS	Powder-dLS	Powder-iLS	Powder-BJ	LOM	Wax-based	Water-based	Solvent-DIP	SL
	Slurry-dLS	Slurry-iLS	Slurry-BJ	CAM-LEM				DLP/LCM
					FDC	RC/DIW	Wax-DIP	SPPW
					MJC	FEF		2PP
					T3DP	CODE		
					PHASE	3DGP		

LENS: Laser Engineering Net Shaping
Dls/iLS: direct/indirect Laser Sintering
BJ: Binder Jetting
LOM: Laminated Object Manufacturing
CAM-LEM: Computed-Aided manufacturing of Laminated Engineering Materials
SL: Stereolithography
DLP: Digital Light Projection
LCM: Lithography-based Ceramic Manufacturing
SPPW: Self-Propagating Photopolymer Waveguide
2PP: Two-Photon Photopolymerisation
FDC: Fused Deposition Ceramics
MJS: Multiphase Jet Solidification

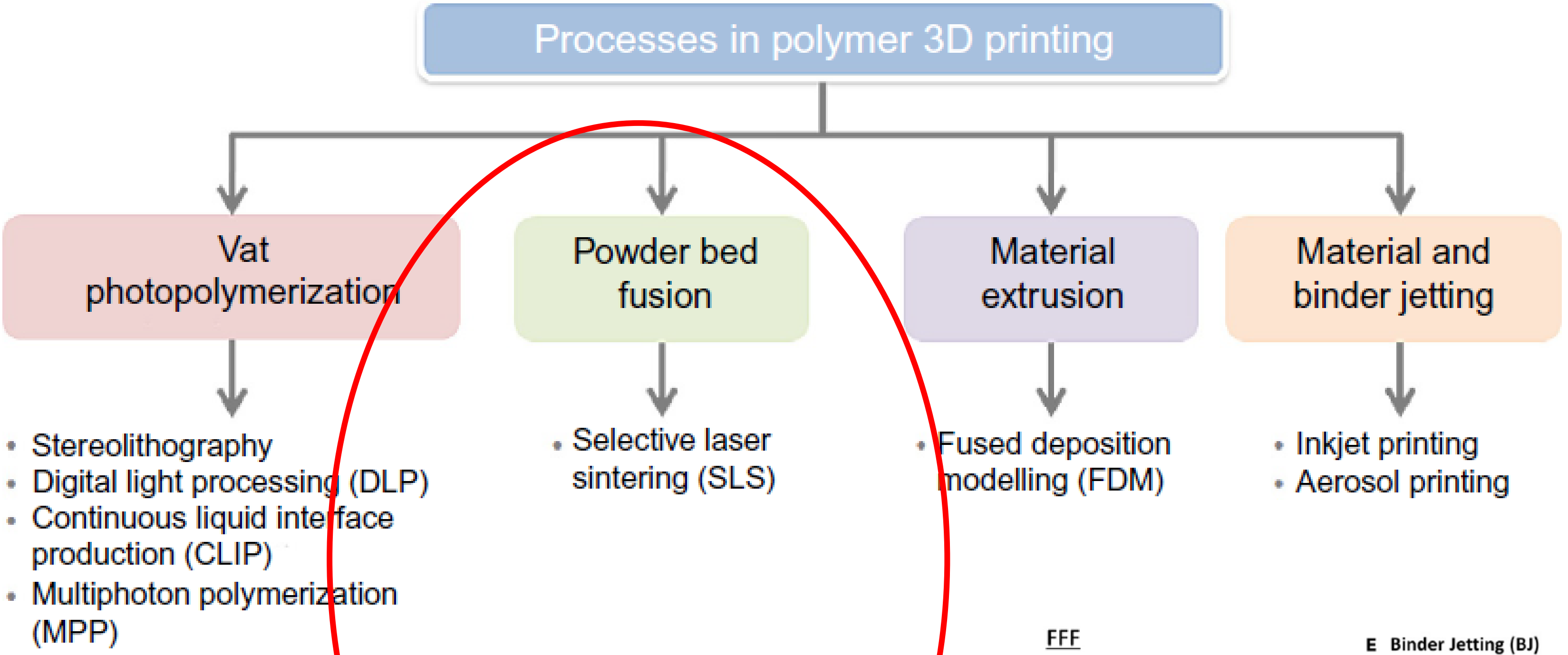
T3DP: Thermoplastic 3D Printing
PHASE: Photopolymerisation-Assited Extrusion
RC: Robocasting
DIW: Direct Ink Writing
FEF: Freeze-Form Extrusion Fabrication
CODE: Ceramic on Demand Extrusion
3DGP: 3D Gel Printing
DIP: Direct Inkjet Printing

Ceramic Additive Manufacturing Techniques

Al_2O_3

Technique		**Remarks**	**Sintered density (%)**	**K_{IC} ($MPam^{1/2}$)**	
Conventional		Slip casting	>99.7	3.7	Hotta et al Powder Technol 149 (2005)
		Tape casting	98.1	4.29 ± 0.06	Yu et al Ceram Int 41 (2015)
Single Step	LENS	As-fabricated	94	2.1 ± 1.3	Balla et al Int J Appl Ceram Technol 5 (2008)
		Heat treatment (1600 °C, 5 h)	98	4.4 ± 1.4	
Multiple step	Material extrusion process: RC	1.40 µm average grain size	97	3.31 ± 0.23	Feilden et al J Eur Ceram Soc 36 (2016)
	Material extrusion process: CODE	Equiaxed grains 5 µm.	98	4.5 ± 0.1	Ghazanfari et al Int J Appl Ceram Technol 14 (2017)
	Direct Inkjet printing: PSD	1.6 ± 0.3 GPa compressive strength	93.7	4.7 ± 0.3	DeVries et al J Eur Ceram Soc 38 (2018)

Polymer Additive Manufacturing Techniques



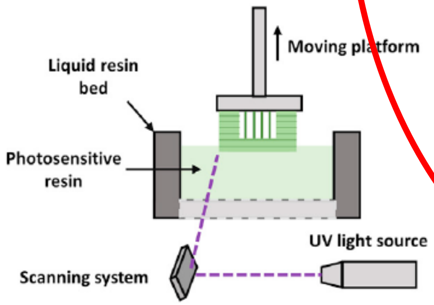
Processes in polymer 3D printing

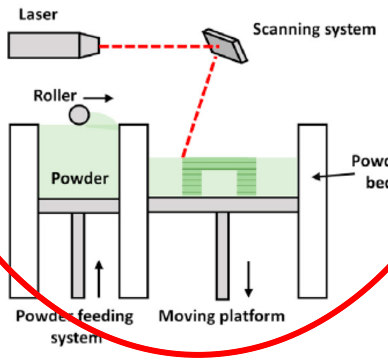
Vat photopolymerization
- Stereolithography
- Digital light processing (DLP)
- Continuous liquid interface production (CLIP)
- Multiphoton polymerization (MPP)

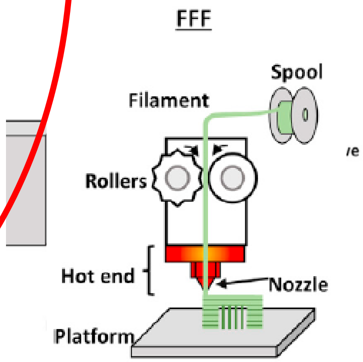
Powder bed fusion
- Selective laser sintering (SLS)

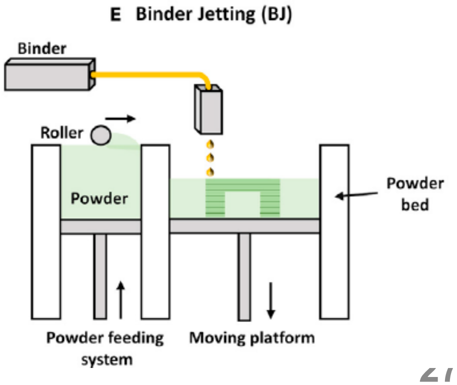
Material extrusion
- Fused deposition modelling (FDM)

Material and binder jetting
- Inkjet printing
- Aerosol printing









Polymer Additive Manufacturing Techniques

PA12

		Processing parameters	**Testing conditions**	**K_{IC} (MPa·m$^{1/2}$)**	**J_{IC} (kJ/m^2)**
SLS	Hitt et al Proc Inst Mech Eng Part B 48 (2012)	PA2200. EOS Formiga P100 Power 21 W; Laser scan 2.5 m/s; Layer height 250 μm; Building chamber 172 °C	(SENB)		2.9-4.3
	Brugo et al. Polym Test 50 (2016)	PA2200, EOS Formiga P100 Power 21 W Laser scan 2.5 m/s Layer height 100 μm Building chamber 172 °C	Load parallel to the layers (CT)	4.5-4.8	
			Load perpendicular to the layers (CT)	3.3-4.0	
	Seltzer et al. Mater Sci Eng A 528 (2011)	Duraform 3D Systems	Dry (SENB)	3.00 ± 0.05 (PA-12) 3.6 ± 0.1 (25wt% short fibers) 3.40 ± 0.04 (43wt% glass beads)	
			Saturated in water (SENB)	0.70 ± 0.05 (PA-12) 2.6 ± 0.1 (25wt% short fibers) 2.6 ± 0.2 (43wt% glass beads)	
	Salazar et al. Comp Part B Eng 59 (2014)	Duraform 3D Systems	Dry at 23 °C (CT)	3.2 ± 1.2	
			Dry at -50 °C(CT)	2.7 ± 0.2	
			Saturated in water at 23 °C (CT)	1.3 ± 0.2	
	Crespo et al J Strain Anal Eng Des 54 (2019)	PA2200 EOS Formiga P100	Load parallel to the layers(SENT)	3.2 ± 0.3 (2 mm/min) 2.1 (5·10^5 mm/min)	

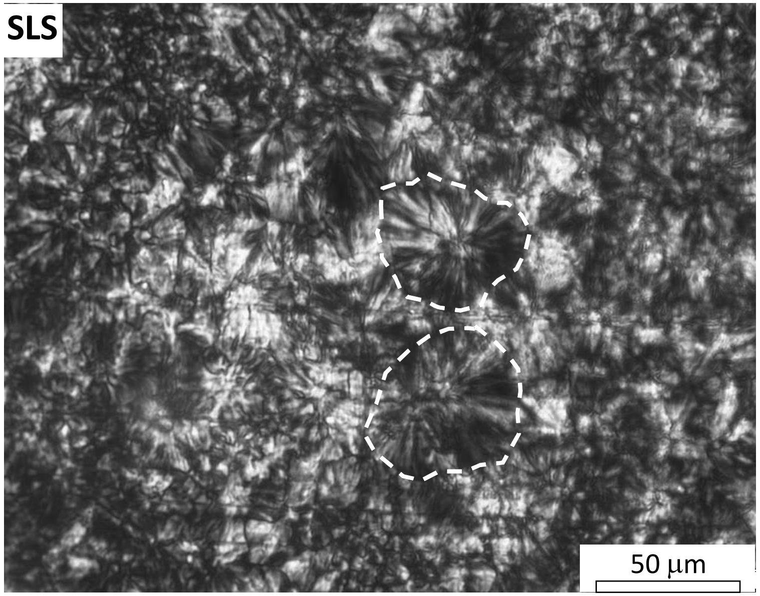
Polymer Additive Manufacturing Techniques

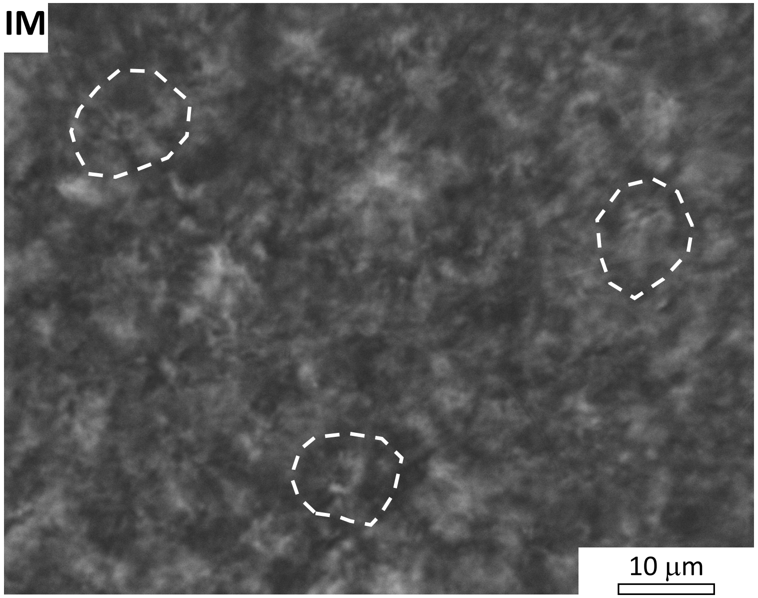
PA12

		Processing parameters	Testing conditions	K_{IC} (MPa·m$^{1/2}$)	J_{IC} (kJ/m^2)
SLS	Linul et al Theor Appl Fract Mech 106 (2019)	PA2200 Power 21-25 W Laser scan 1.5-2.5 m/s Layer height 150 μm Building chamber 170 °C	Load perpendicular to the layers (SENB)	2.282 (25 W, 1.5 m/s)	
			Load parallel to the layers (SENB)	1.098 (25 W, 1.5 m/s)	
	Schneider and Kumar Polym Test 86 (2019)	Duraform 3D Systems; Power 2.8 W Laser scan $4\cdot10^4$ points /s Layer height 100 μm Building chamber 147 °C	Load parallel to the layers (DENT)	4.1 ± 0.5	
			Load perpendicular to the layers (DENT)	4.2 ± 0.6	
	Stoia et al Polymers 11 (2019)	PA2200; EOS Formiga P100 Power 25W; Laser scan 1.5 mm/s Layer height 250 μm Building chamber 170.5 °C	Load parallel to the layers(DCB)	2.3 ± 0.1	
			Load perpendicular to the layers (DCB)	0.9 ± 0.1	
FDM	Fonseca et al Compos Struct 214 2019	Tronxy X5 3D printer, 0,4 mm nozzle diameter, layer height 0,3 mm, extrusión temperatura 260 °C, bed temperatura 90°C	Load perpendicular to the layers (DCB)		0.80 ± 0.08
IM	Hitt et al Proc Inst Mech Eng Part B 48 (2012)	Rilsan AMNO PA12 pellets Negri-Bossi NB62 machine Mould temperature 40 °C Melt injected at 240 °C	SENB		2.9-4.3

Polymer Additive Manufacturing Techniques

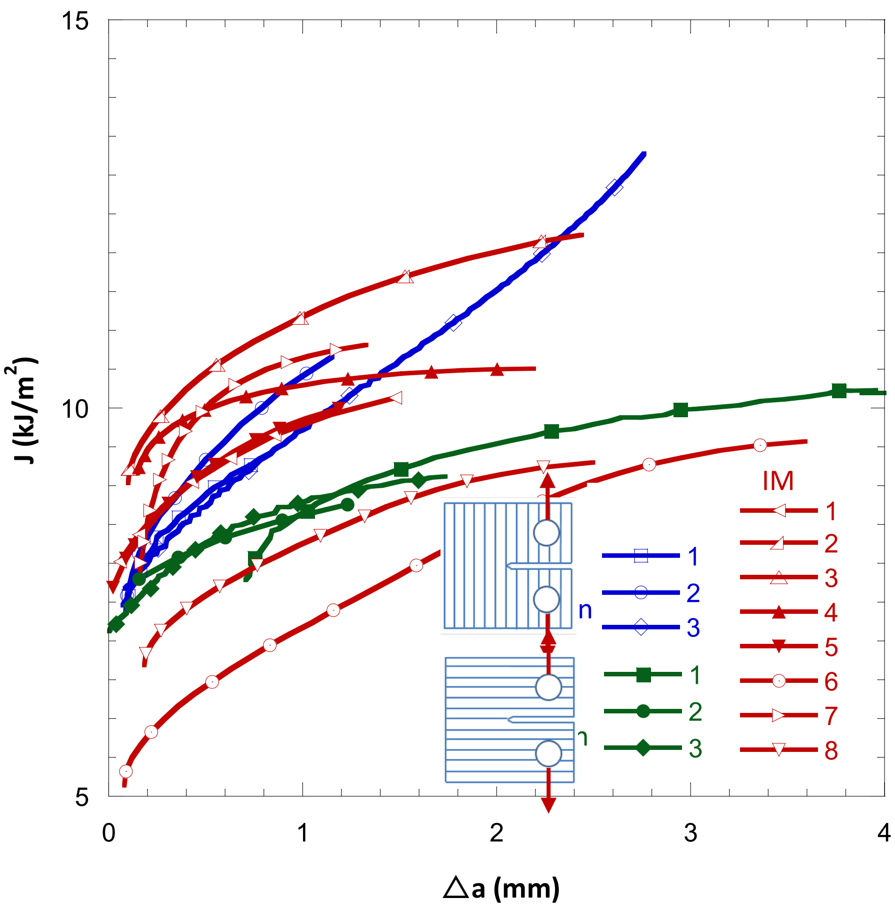
SLS PA12			
Technique	**Density (g/cm³)**	**Porosity (%)**	**Spherulity size (µm)**
Conventional Injection Moulding - IM	1.018 ± 0.005	0.2	13 ± 3
SLS	0.982 ± 0.005	3.7	50 ± 10

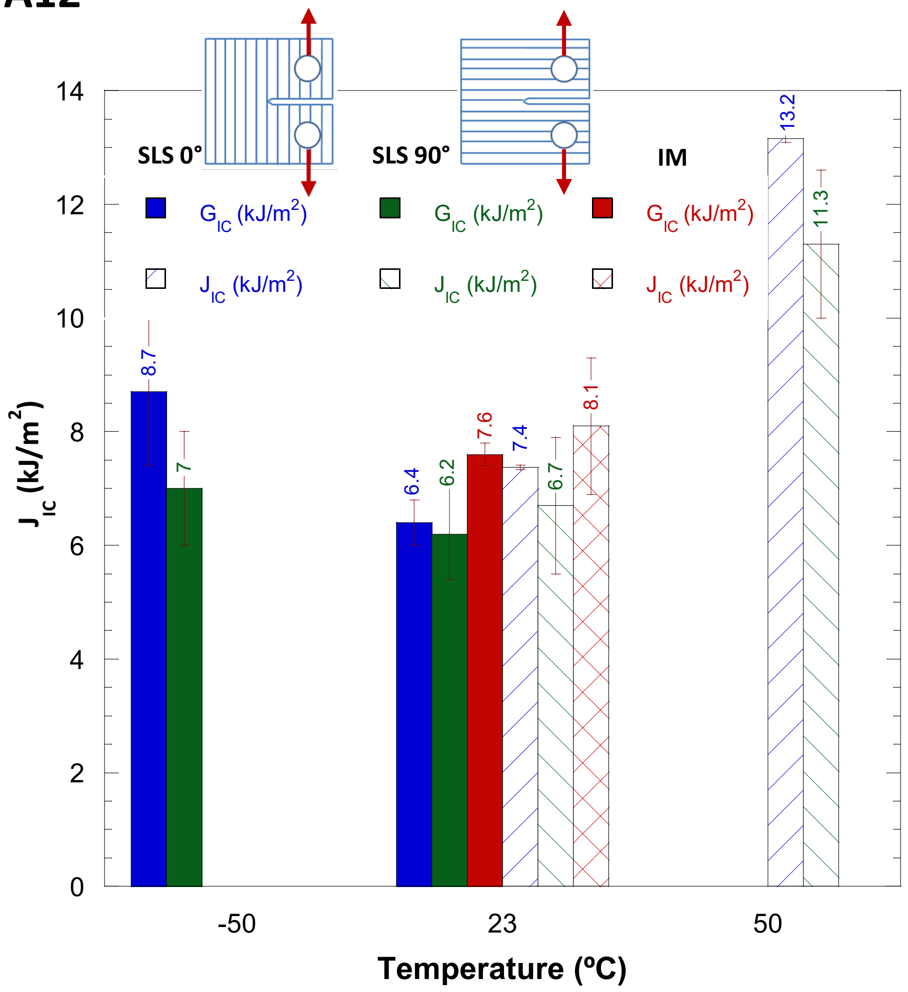




Polymer Additive Manufacturing Techniques

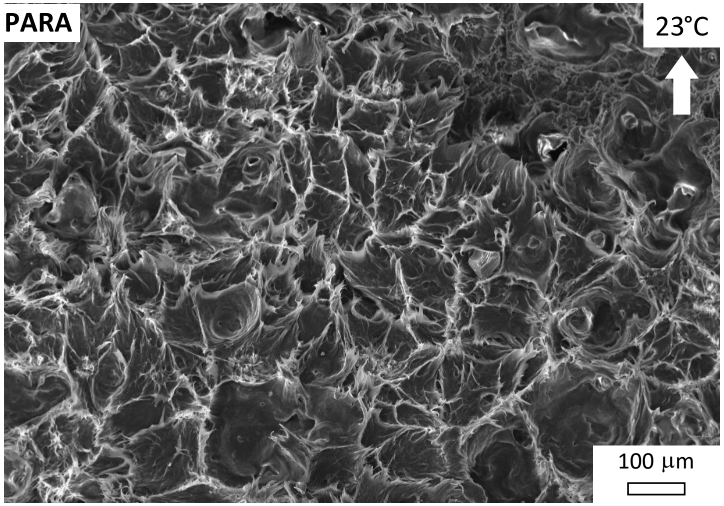
SLS PA12





Polymer Additive Manufacturing Techniques

SLS PA12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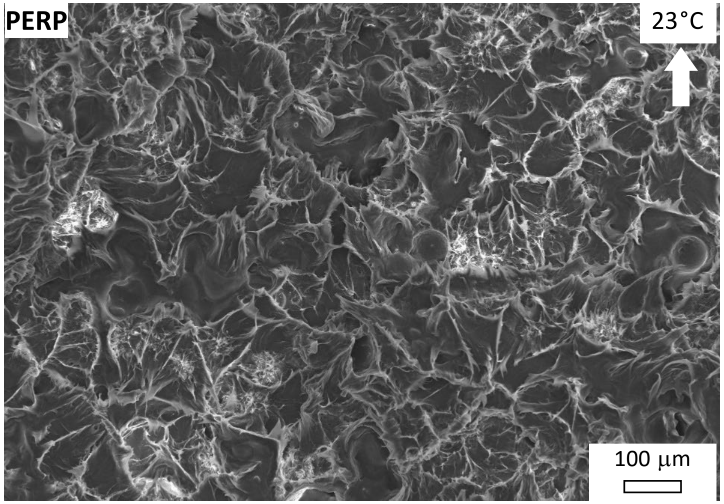
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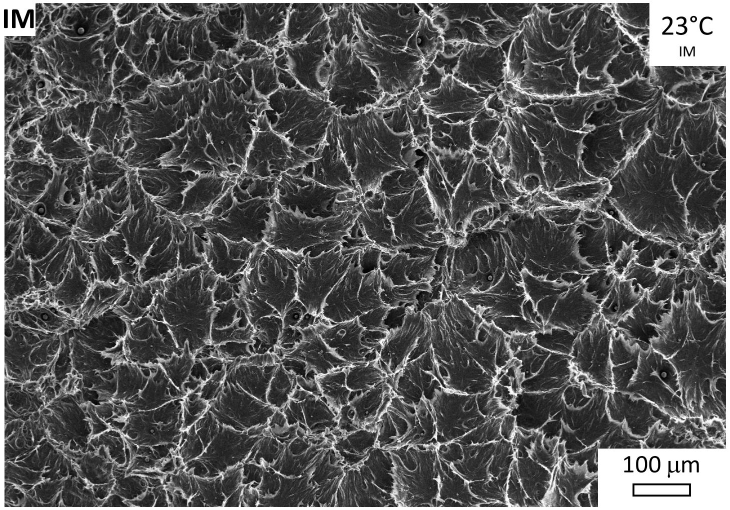
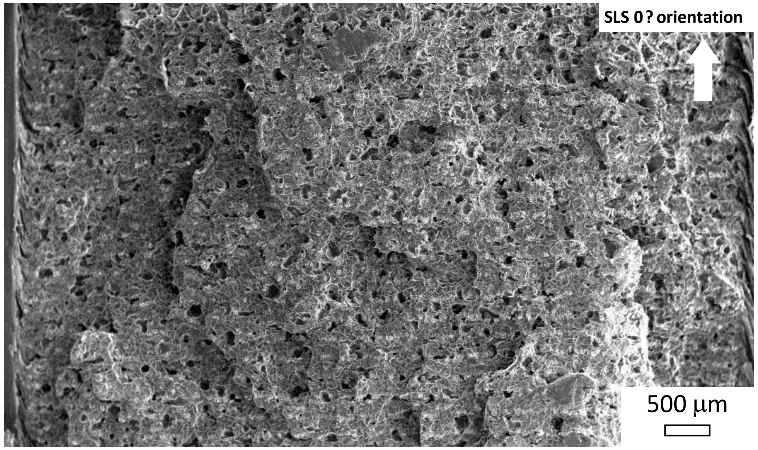

IM

Polymer Additive Manufacturing Techniques

SLS PA12



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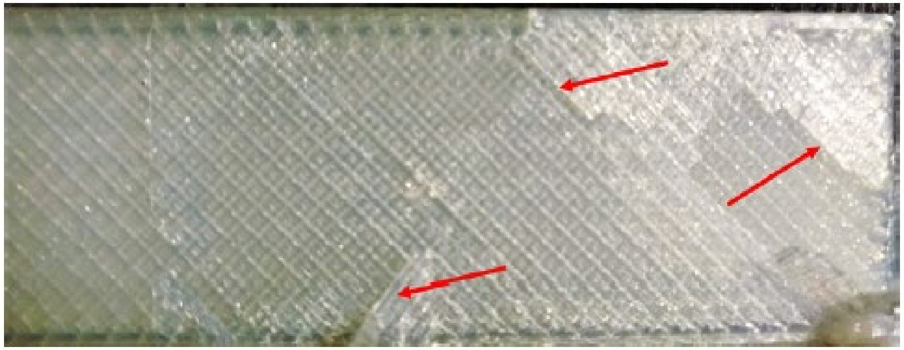

IM PA12