# Mechanical Properties of Metallic Components Additively Manufactured by Directed Energy Deposition Laser with Powder as Feedstock Material

Master thesis Project

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# AGENDA



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# INTRODUCTION

Additive manufacturing, mechanical design and mechanical properties of metallic materials

# INTRODUCTION

## What is additive manufacturing?

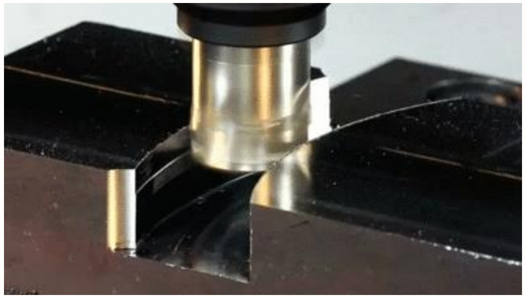
**Additive Manufacturing (AM)**: "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing"

(ISO/ASTM 52900:2015(E))

Additive Manufacturing

Source: http://www.reddit.com/r/gifs/comments/221wog/large_scale_multi_axis_3d_printing_in_metal/

Subtractive Manufacturing



Source: https://plus.google.com/communities/113275241163938593797/stream/3bea93dc-f151-4ade-bab0-11ab6d7c4577

# INTRODUCTION

## Main process advantages

**Additive Manufacturing**

Reduced total cost for small batches

(VOLPATO et al., 2017)

- Compared to process with dependence on tooling
  - Moulds
  - Dies

Reduced time between ideation and production

(VOLPATO et al., 2017)

- Model -> Data -> Production
- Digital process
- Reduced supply chain

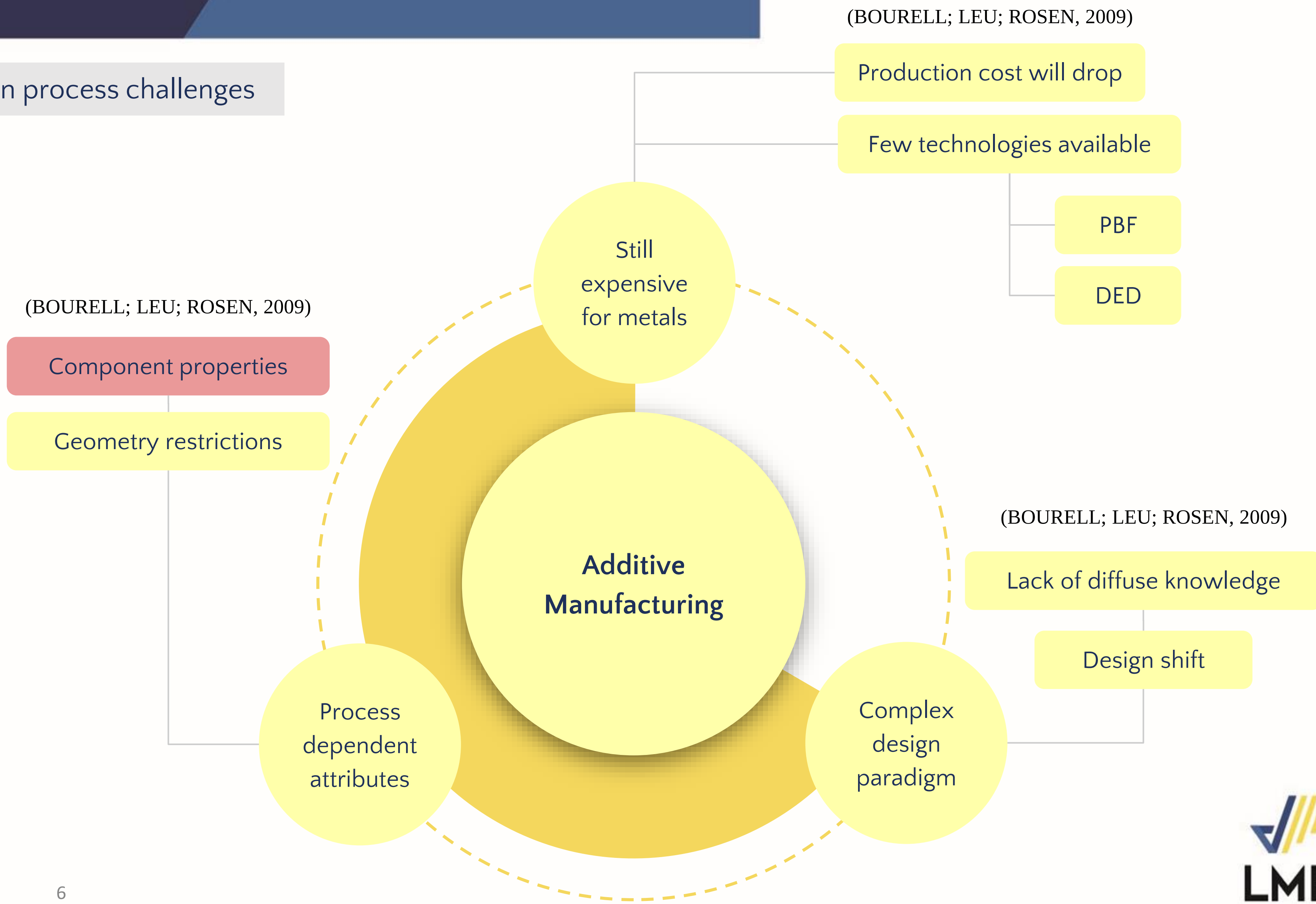
Design freedom

(ZHANG; LIU; TO, 2017)

- Part count reduction
- Design optimization

# INTRODUCTION

## Main process challenges



# INTRODUCTION

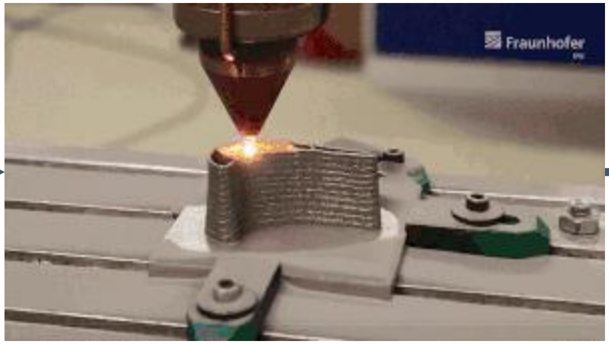
Process analysis

Model - Boundary conditions - Solution

Processing parameters

Material

Input




(Fraunhofer IPK, 2019)

https://www.linkedin.com/posts/max-biegler-051152123_additivemanufacturing-ded-industrialam-activity-6597026784695341056-nj2I

Geometry

Distortion

Mechanical properties ?

Results

# INTRODUCTION

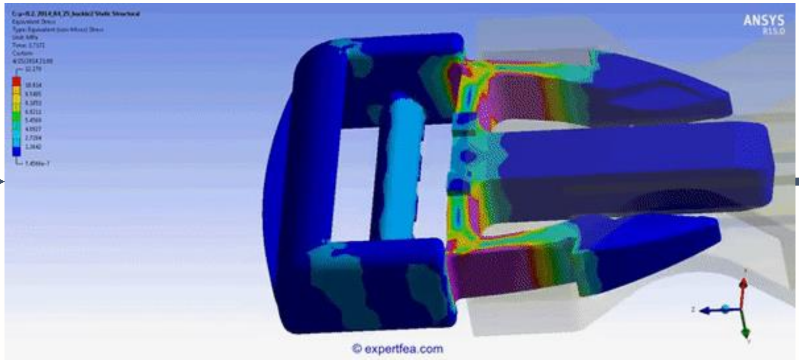
## Structural analysis

Model - Boundary conditions - Solution

Mechanical properties

Geometry

Input




Stress

Strain

Deformation

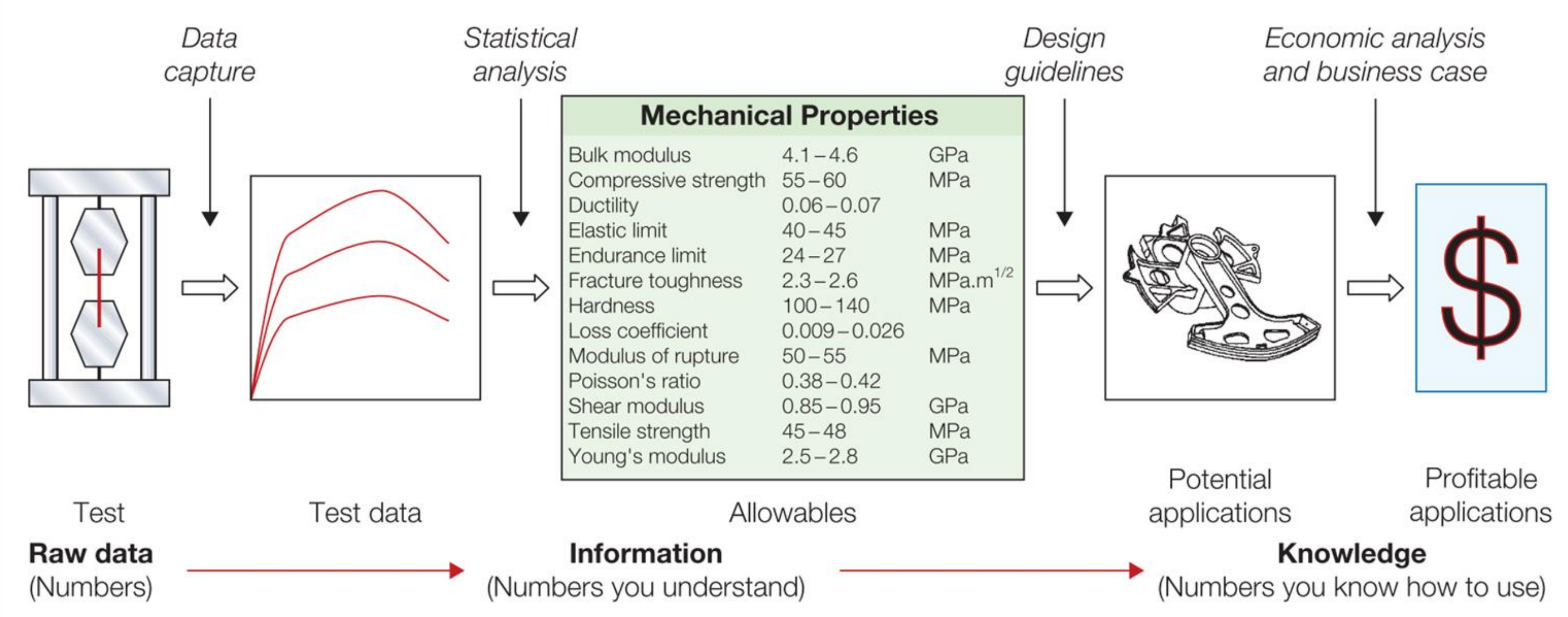
Results

Source:

https://gfycat.com/plainanguishedhyracotherium

# INTRODUCTION

## Structural properties and design phase




| Mechanical Properties | | |
|---|---|---|
| Bulk modulus | 4.1 – 4.6 | GPa |
| Compressive strength | 55 – 60 | MPa |
| Ductility | 0.06 – 0.07 | |
| Elastic limit | 40 – 45 | MPa |
| Endurance limit | 24 – 27 | MPa |
| Fracture toughness | 2.3 – 2.6 | $MPa.m^{1/2}$ |
| Hardness | 100 – 140 | MPa |
| Loss coefficient | 0.009 – 0.026 | |
| Modulus of rupture | 50 – 55 | MPa |
| Poisson's ratio | 0.38 – 0.42 | |
| Shear modulus | 0.85 – 0.95 | GPa |
| Tensile strength | 45 – 48 | MPa |
| Young's modulus | 2.5 – 2.8 | GPa |

(ASHBY, 2011)

# INTRODUCTION

## General objective

Propose a method to map the effects of key geometrical and processing parameters on the mechanical properties of samples produced by DED-LP.

# INTRODUCTION

## Specific objectives

1. Select from the literature, critical geometric features that can induce variation in mechanical properties (e.g. aspect ratio, wall thickness, curvature radius and part height)

2. Select from the literature, critical processing parameters (e.g. processing speed, laser power, processing strategies and overlap distance) that can induce mechanical property variation;

3. Define processing parameter levels that result in a stable process for manufacturing the selected geometric features;

4. Successfully manufacture geometries with selected features and machine local samples for uniaxial tensile tests;



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# INTRODUCTION

## Specific objectives

5. Conduct mechanical tests to characterize:
   a. Elastic modulus (E);
   b. Elastic limit (Se);
   c. Tensile strength (Su);
   d. Elongation at fracture (ε);

6. Report the dependency of the measured values on the build direction and other geometric and process parameters;

7. Compare properties with those manufactured by a conventional process;

# AGENDA



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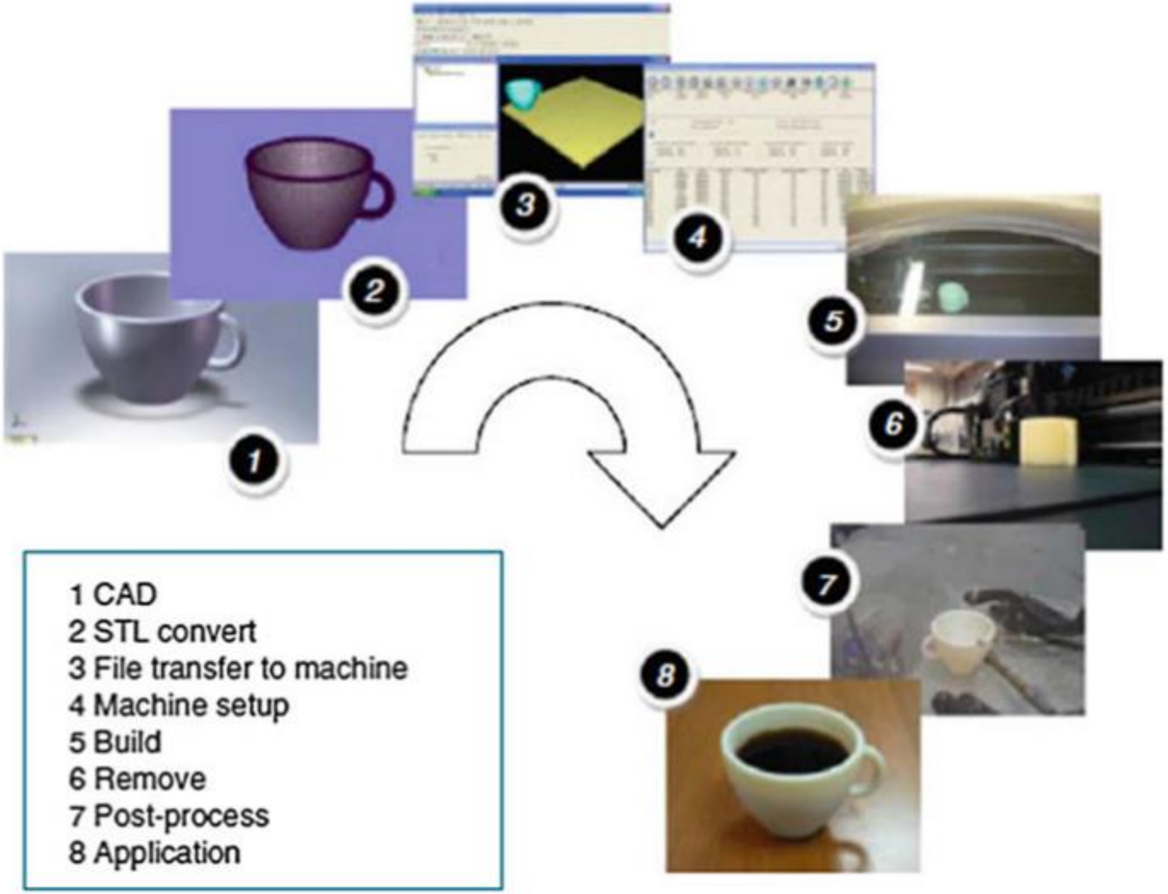
# LITERATURE REVIEW

Directed Energy Deposition, laser technology, process description and resulting properties

# LITERATURE REVIEW

## Additive Manufacturing




*(GIBSON; ROSEN; STUCKER, 2015)*

# LITERATURE REVIEW

## Additive Manufacturing

**2015**

- 01 VAT Photopolymerization
- 02 Powder Bed Fusion
- 03 Binder Jetting
- **04 Directed Energy Deposition**
- 05 Sheet Lamination
- 06 Material Jetting
- 07 Material Extrusion

"DED is an additive manufacturing process in which **focused thermal energy is used to fuse materials by melting as they are being deposited**."

(ISO/ASTM 52900-15)

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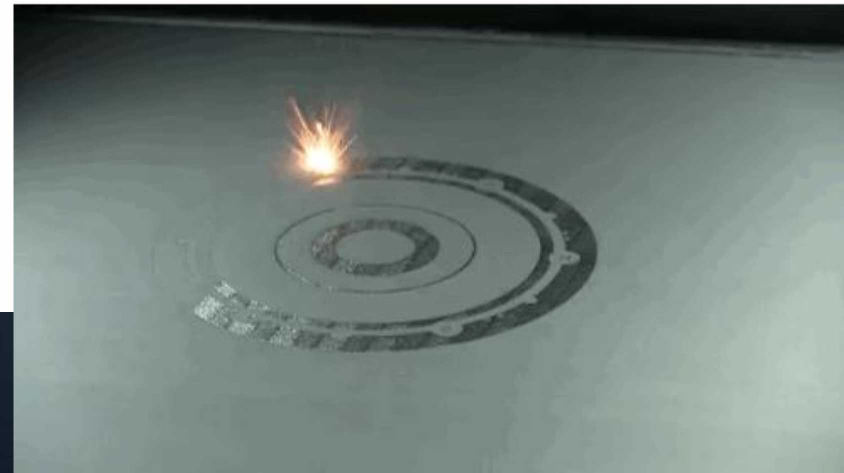
# INTRODUCTION

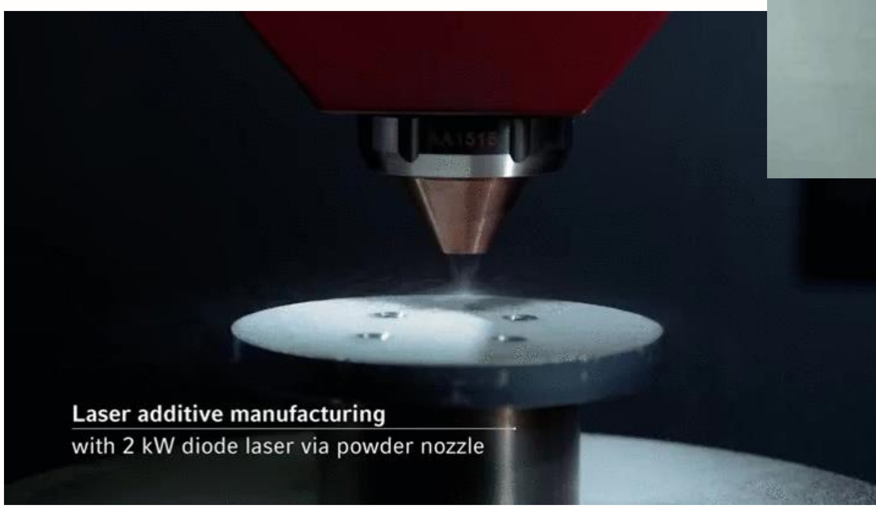
## Additive Manufacturing – DED and PBF technologies

### Powder Bed Fusion (PBF)



Source: https://giphy.com/gifs/ge-3d-printing-aviation-jet-engine-5xA4HomdGgi2Y

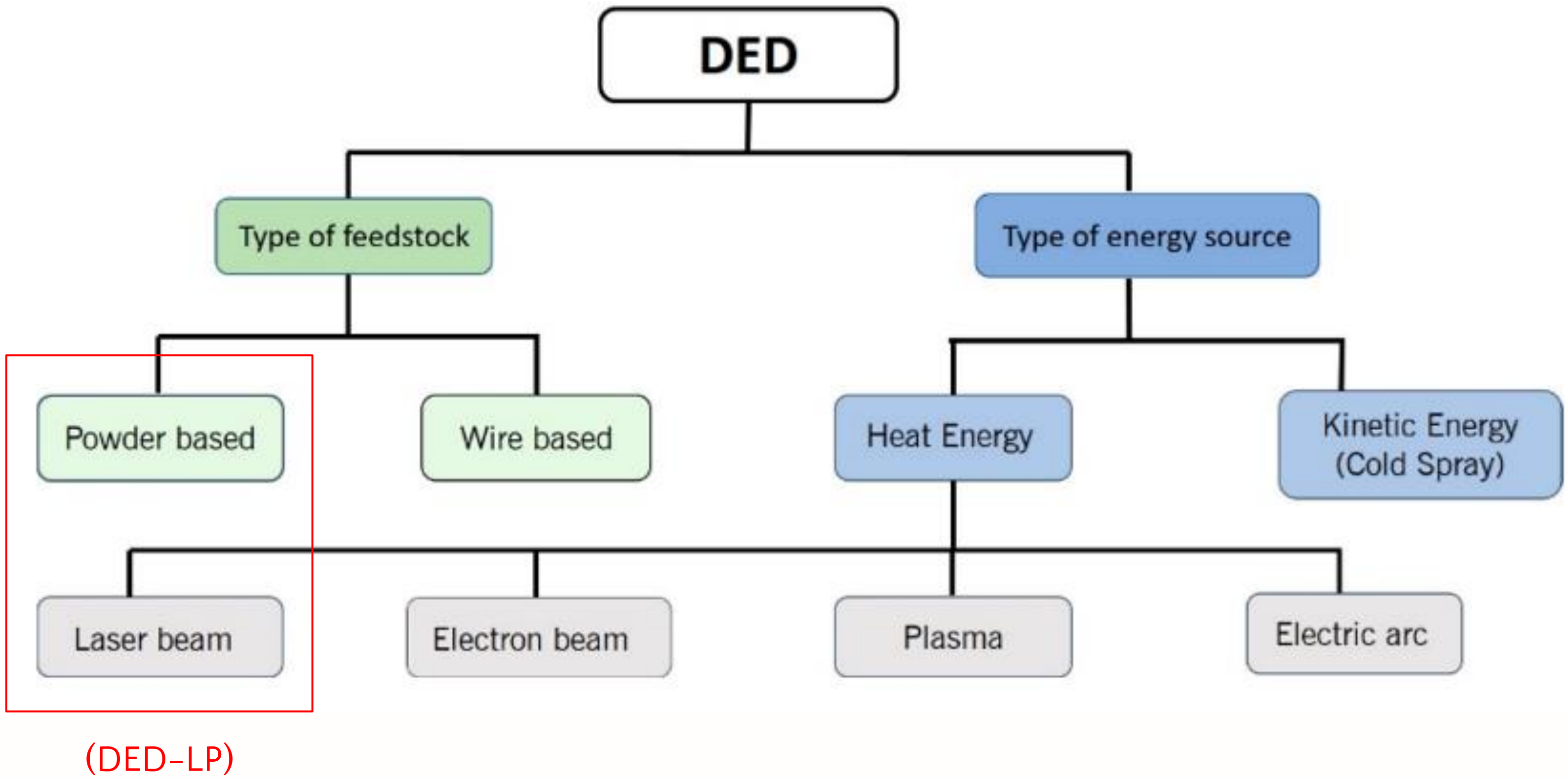
### Directed Energy Deposition (DED-LP)




Source: http://imgur.com/gallery/QkZgH

# LITERATURE REVIEW

Additive Manufacturing – Directed Energy Deposition Laser with Powder as feedstock (DED-LP)




*(DASS; MORIDI, 2019)*

# LITERATURE REVIEW

Laser Technology – What is Laser and when it was created?

# LASER

**L**ight **A**mplification **S**timulated by **E**mission of **R**adiation

First activity reported in 1960 by Theodore Harold Maiman

"A special type of light"

(HITZ; EWING; HECHT, 2012)

- Wavelength (λ)
- Intensity (I)

# LITERATURE REVIEW

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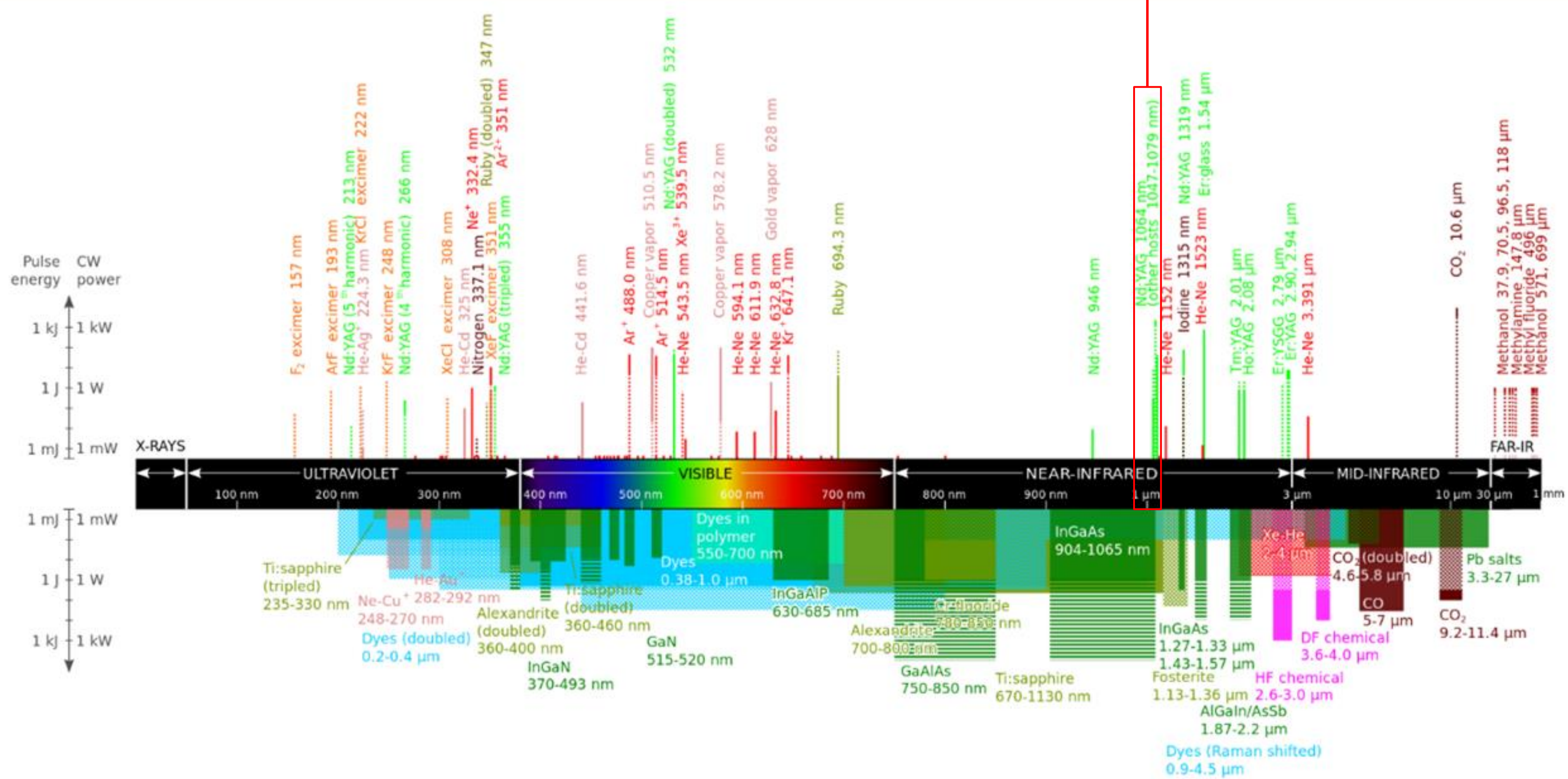
## Laser Technology – Commercially available lasers (λ, I)

I ≤ 10 kW
λ = 1070 a 1080nm




*(DANH, 2009)*



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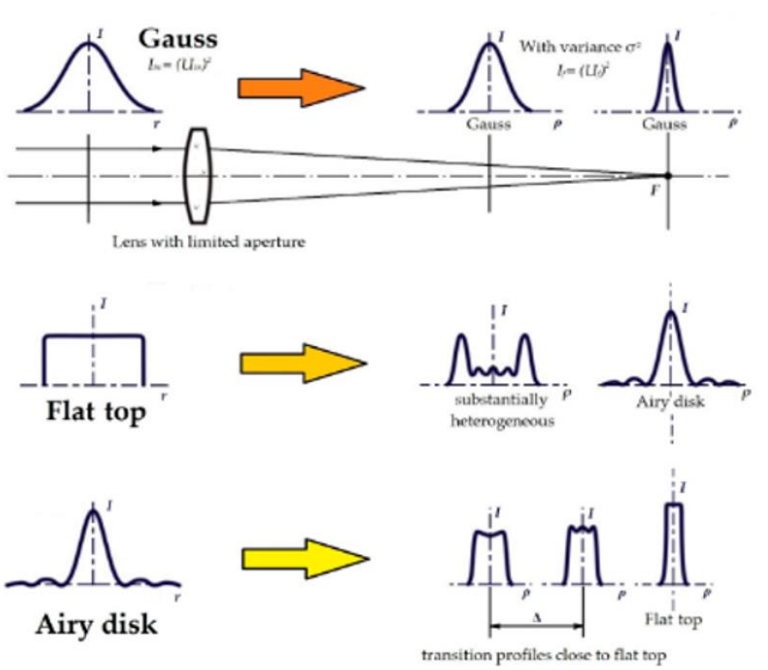
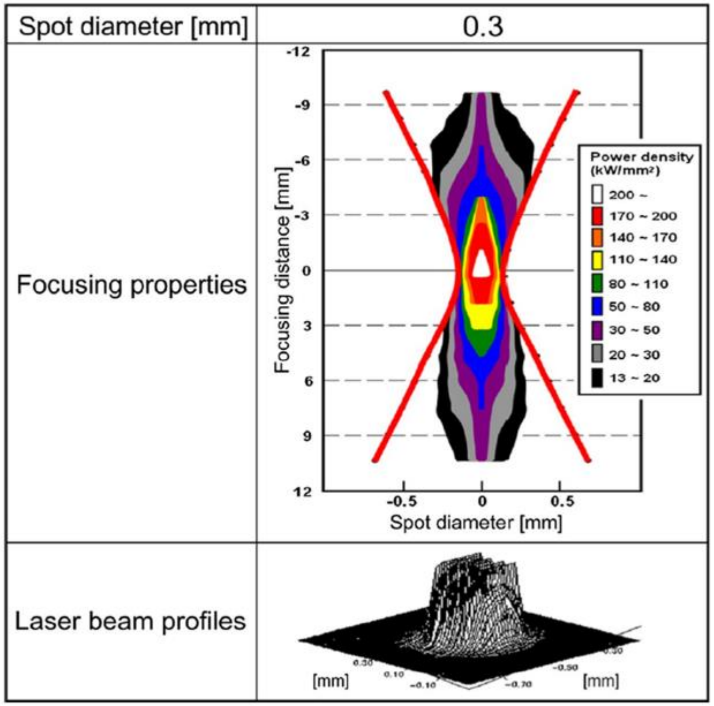
# LITERATURE REVIEW

## Laser Technology – Optics and energy distribution

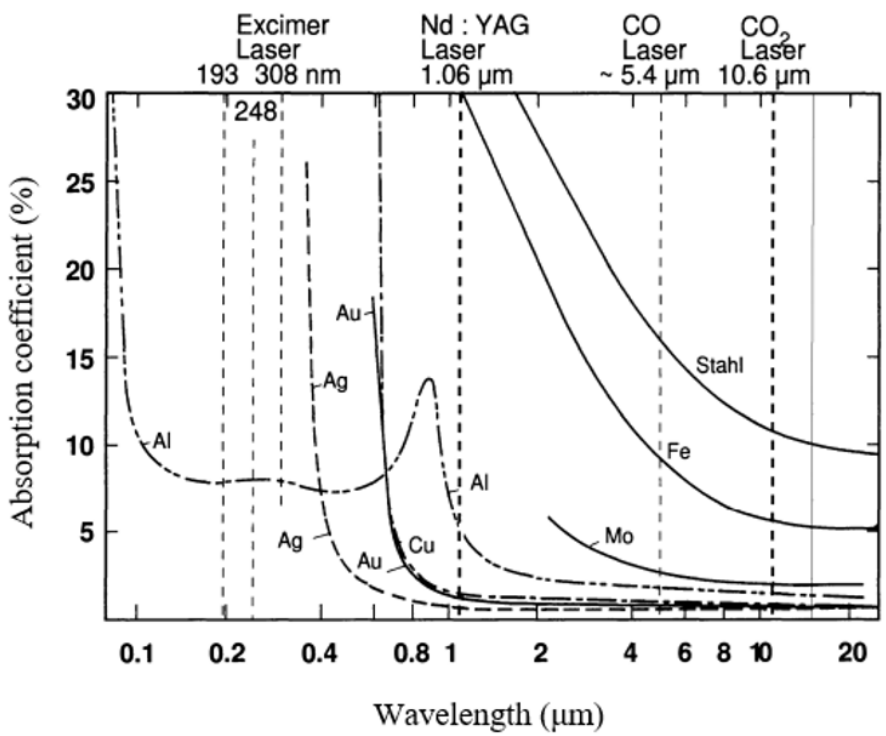



*(KAWAHITO et al., 2016)*

# LITERATURE REVIEW

## Laser Technology – Material processing and energy conversion




*(HERZIGER; WEBER, 1998)*

"... fundamental principles involved in laser material processing is related to **absorption of light by the workpiece and its partial conversion to heat.**"

Absorption depends on

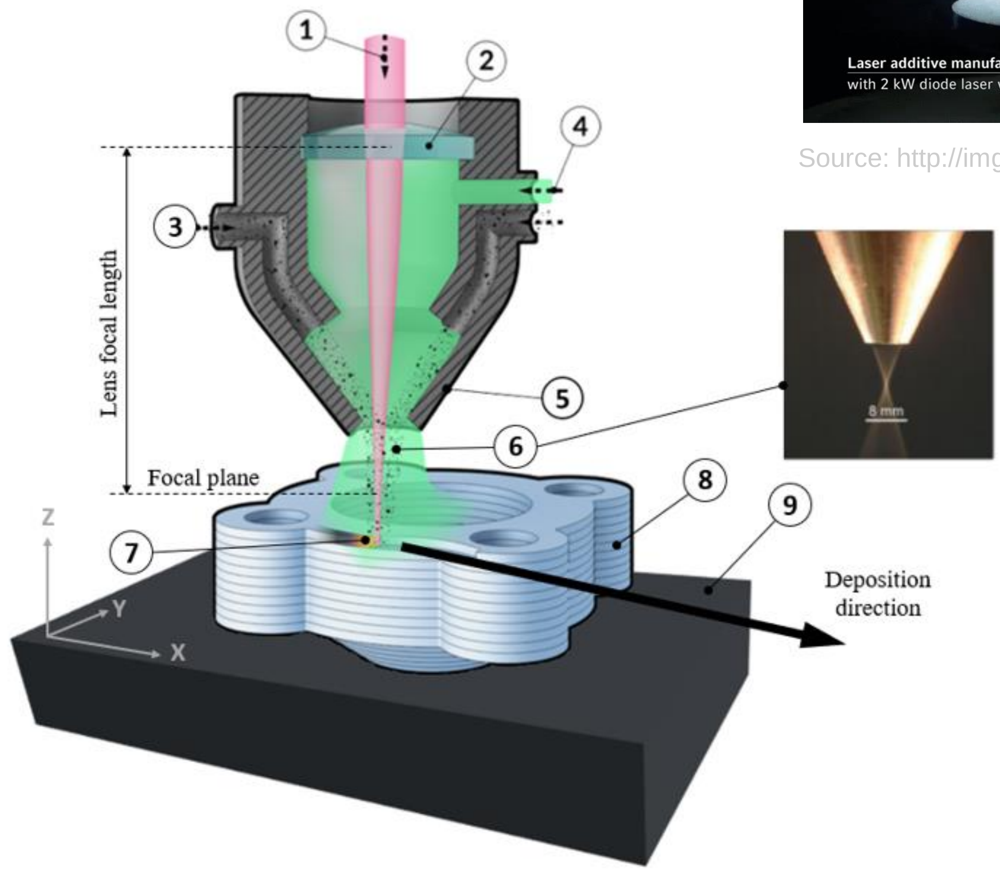
- Wavelength
- Polarization
- Material physical properties
- Workpiece surface

(POPRAWE, 2016)

# LITERATURE REVIEW

## DED-LP: Process description

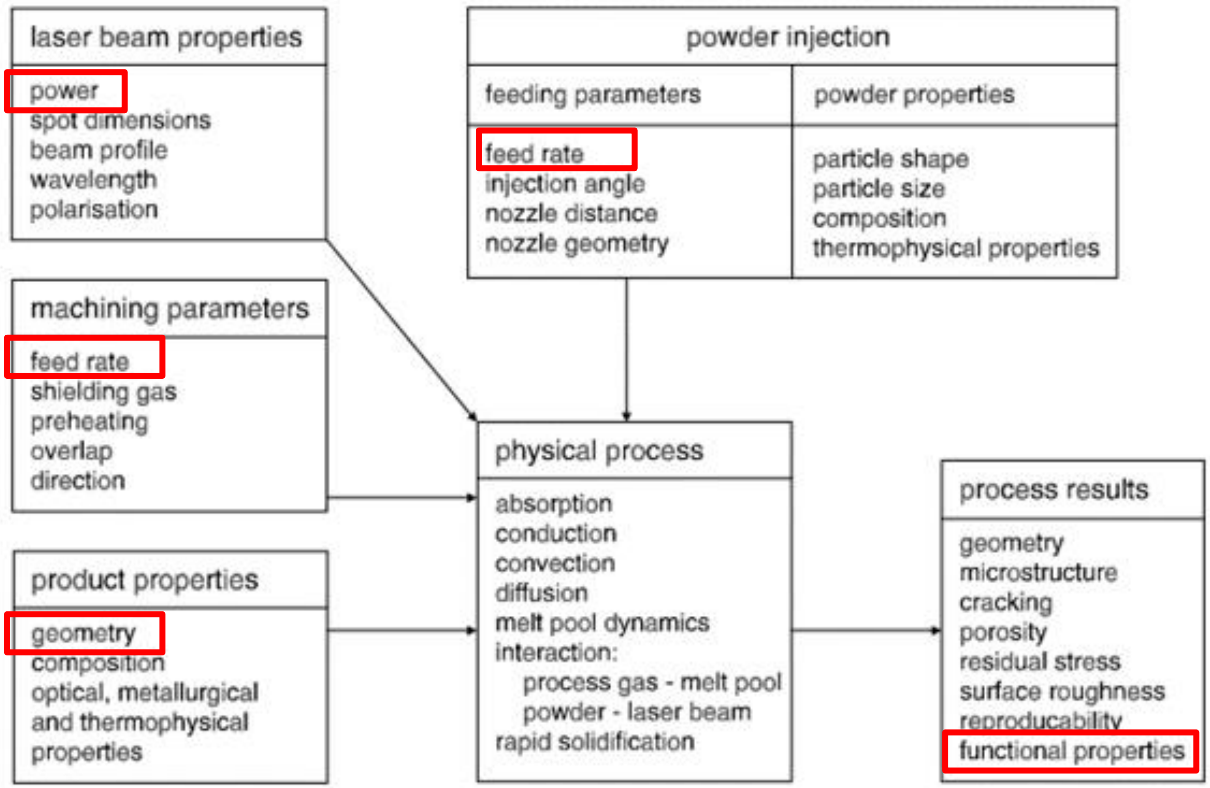

Source: http://imgur.com/gallery/QkZgH




Adapted from *(MANUFACTURING GUIDE) and (POPRAWE, 2016)*

# LITERATURE REVIEW

## DED-LP: Process description

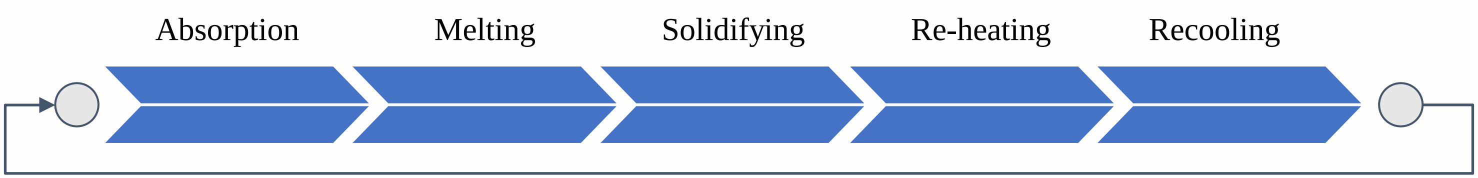



Objetivo

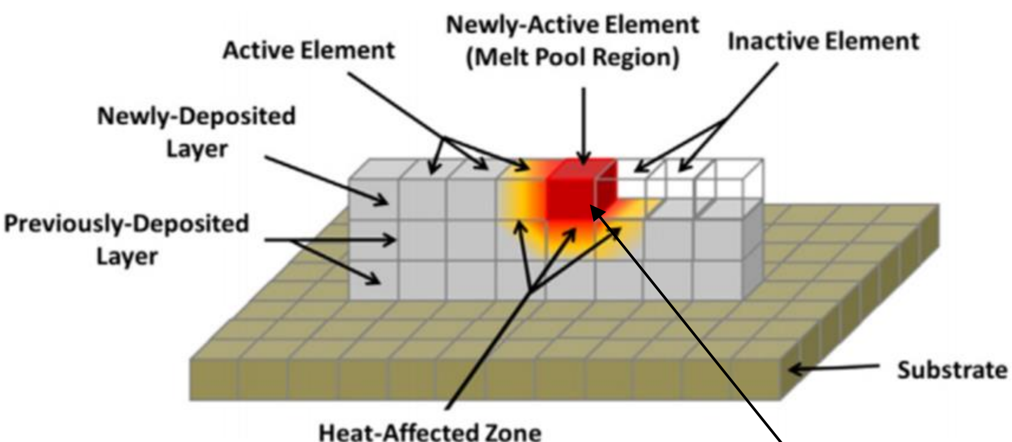
*(SCHNEIDER, 1998)*

# LITERATURE REVIEW

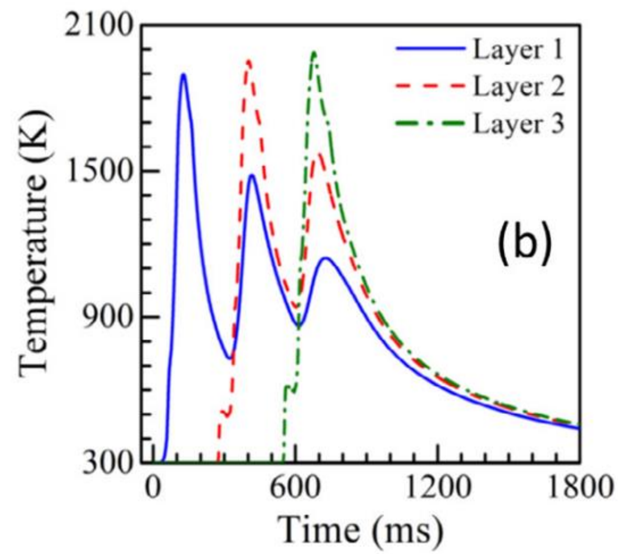
## Thermal cycles, microstructure refinement and heterogeneity




Thermal Cycle




*(THOMPSON, 2015)*




*(MANVATKAR; DE; DEBROY, 2014)*

Voxel
Maxel

# LITERATURE REVIEW

## Thermal cycles, microstructure refinement and heterogeneity

"Independently of the material, a fine-grained structure has usually been observed for AM in comparison to other processes (e.g. casting)"

(HERZOG et al., 2016)

"The effect can be explained by the high cooling rates of up to 12000 K/s when compared with 1 – 100 K/s for casting"

(DEBROY et al., 2017)

# LITERATURE REVIEW

## Thermal cycles, microstructure refinement and heterogeneity

"Temperature gradients are also affected by the property gradients along the voxels of the structure. The presence of solidified materials on previous layers typically increase the heat conduction in the build direction compared with other special directions, what can explain the observed **anisotropy** in microstructure and mechanical properties"

(HERZOG et al., 2016)

# LITERATURE REVIEW

## Porosity and mechanical properties

"As porosity facilitates crack propagation and deteriorates mechanical properties, the manufacture of parts with a high density, typically greater than 99.5%, is the first goal in AM process optimization"

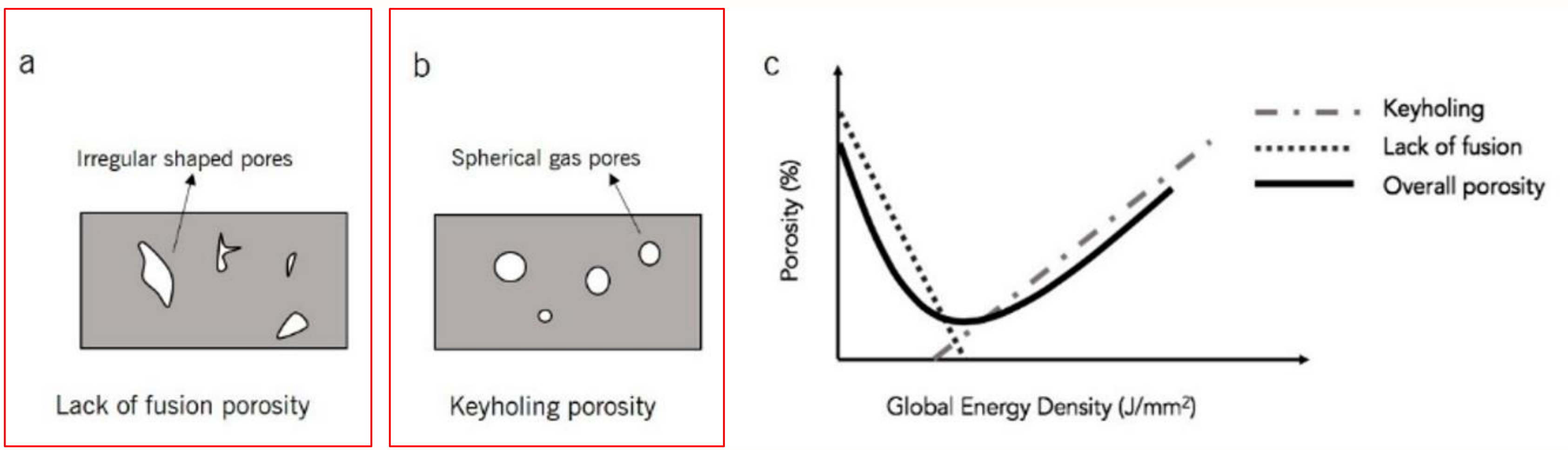
(HERZOG et al., 2016)

# LITERATURE REVIEW

## Processing parameters and porosity

Low energy density

High energy density




*(DASS; MORIDI, 2019)*

# LITERATURE REVIEW

## Processing parameters and porosity

"The static strength of Ti-6Al-4V and Inconel 625 do not vary significantly between AM porous and non-porous specimens compared with wrought specimens"

(RAZAVI et al., 2018a)(KOIKE et al., 2017)

# LITERATURE REVIEW

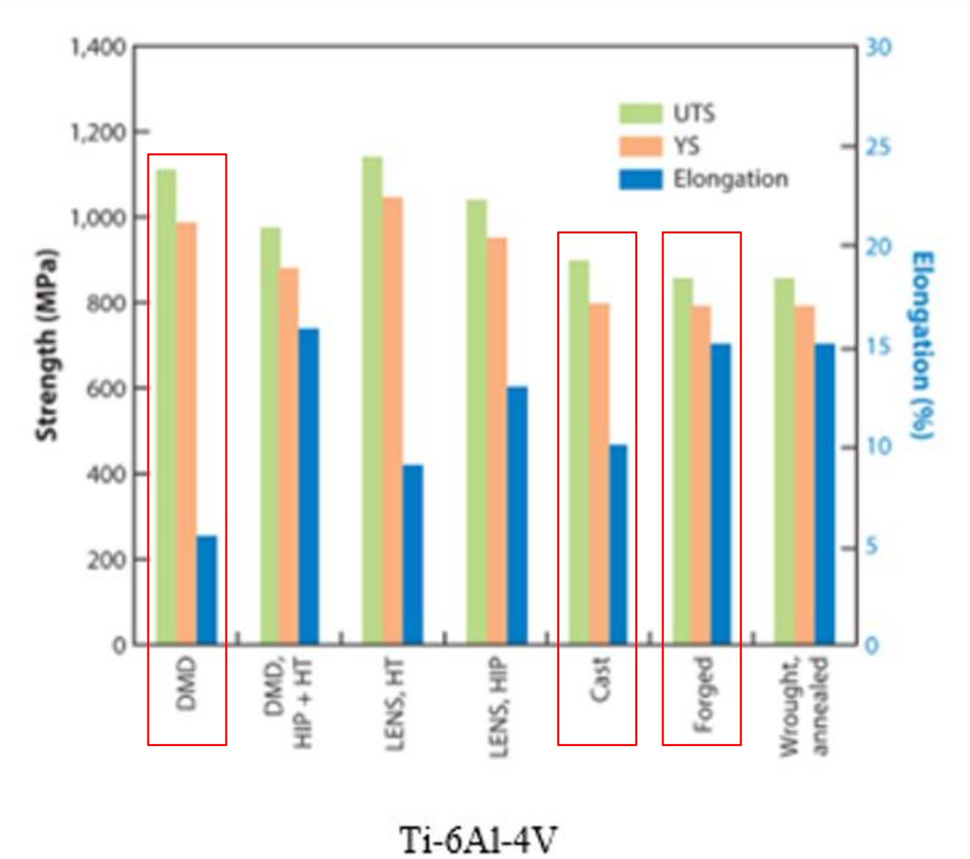
## Processing parameters and porosity

On the other hand, the presence of stress raisers reduce the ductility of materials significantly and for this reason, fatigue strength of porous specimens reduce significantly as the presence of stress raisers facilitates fatigue crack initiation and fatigue crack propagation along the sample

(RAZAVI et al., 2018b)

# LITERATURE REVIEW

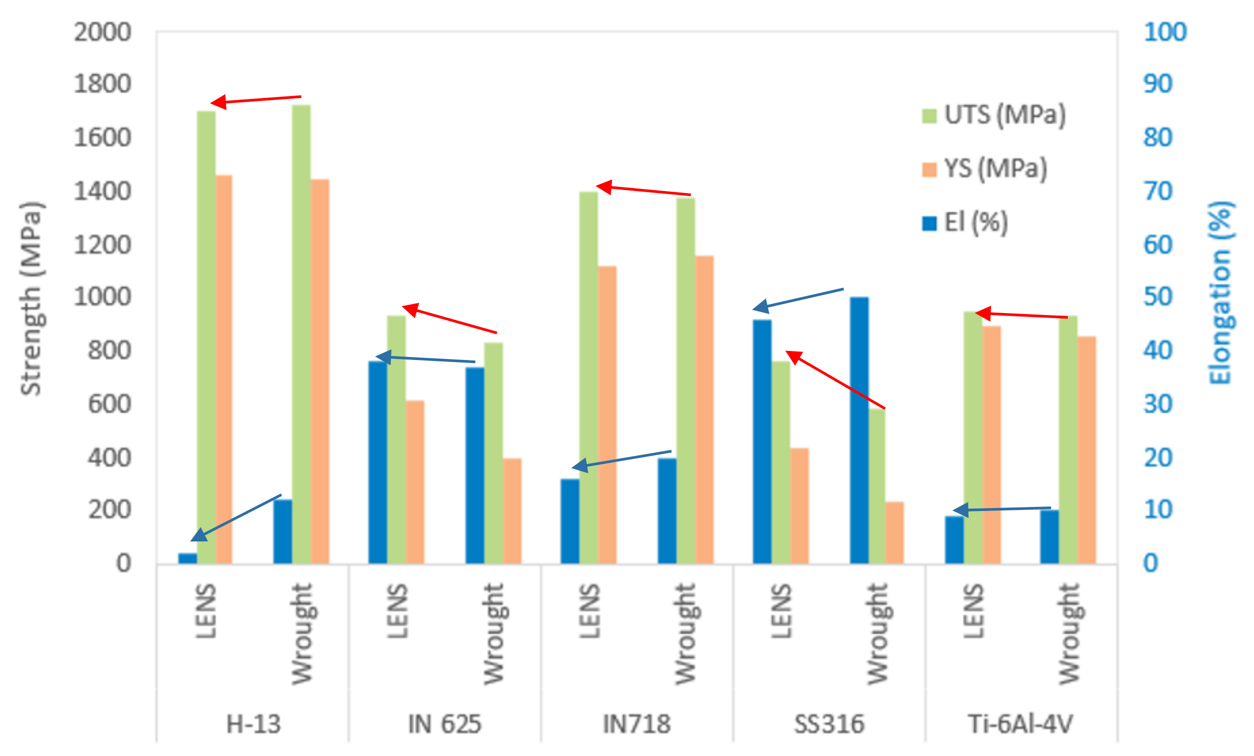
## Reported mechanical properties




(LEWANDOWSKI; SEIFI, 2016)

# LITERATURE REVIEW

## Reported mechanical properties

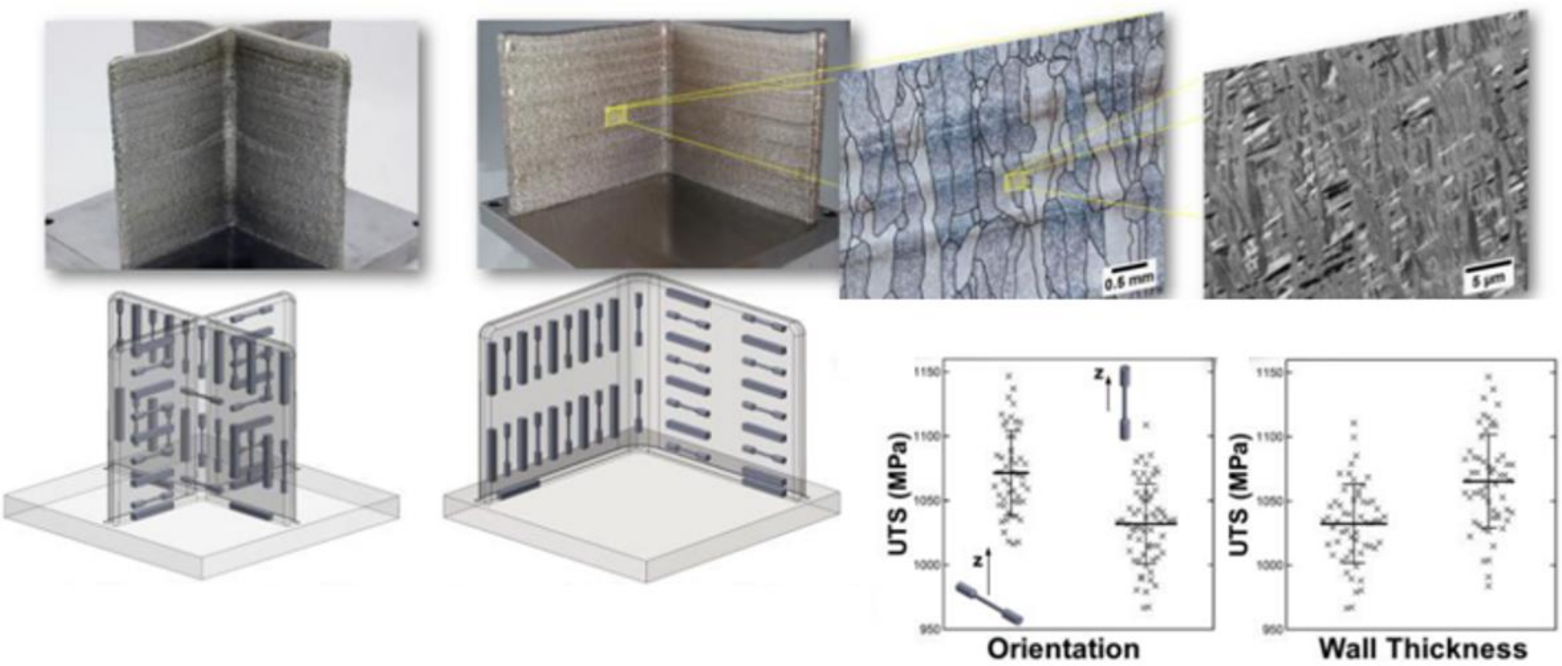



Adapted from *(GRIFFITH et al., 2000)*

# LITERATURE REVIEW

## Geometry and Mechanical Properties

*Ti-6Al-4V*

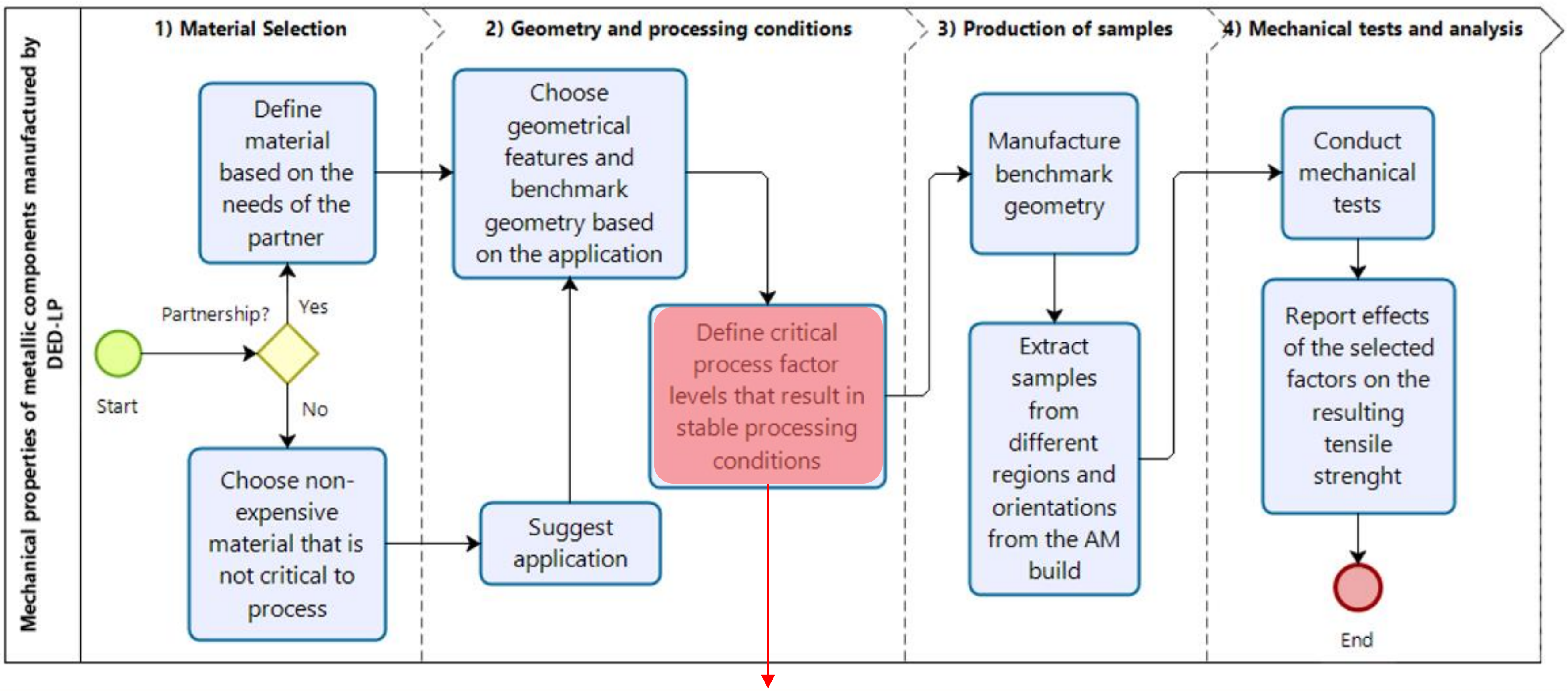



(KEIST; PALMER, 2016)

# AGENDA

# MATERIALS AND METHODS

## Summary of project phases

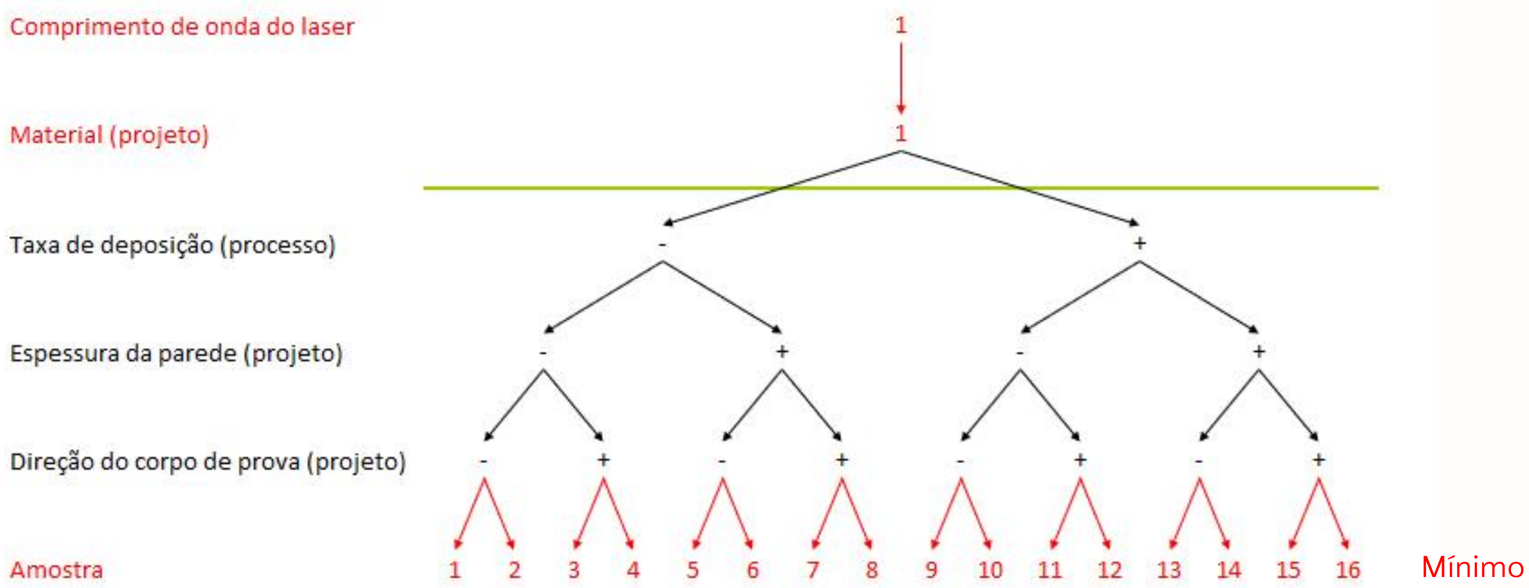


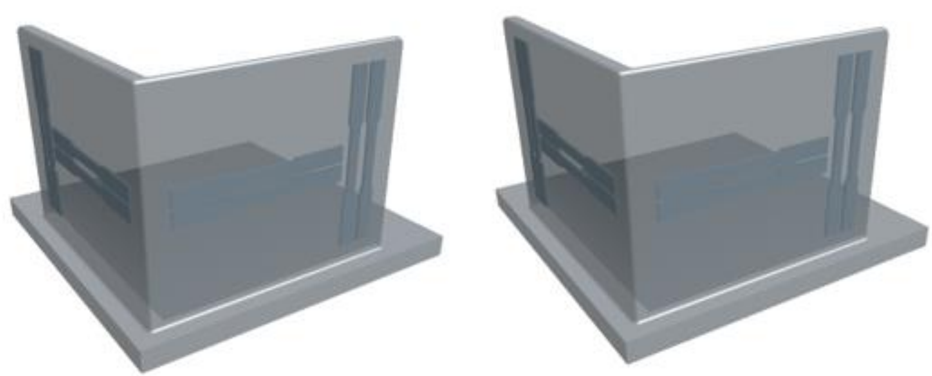

Preliminary tests:

- High density
- Stable process

# MATERIALS AND METHODS

## Summary of project phases

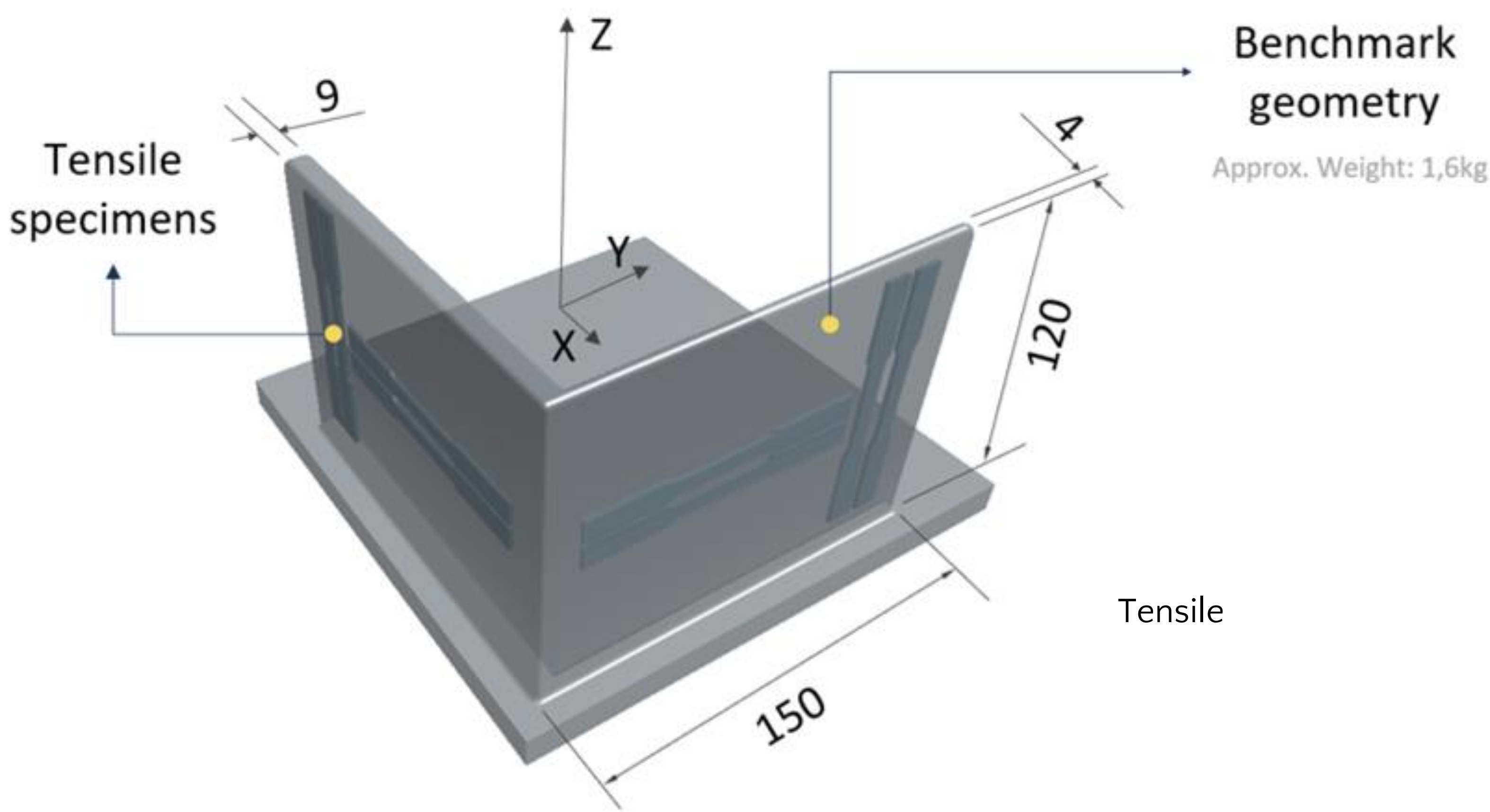


Limite de ensaios: 32
LabMat

# MATERIALS AND METHODS

## Benchmark Geometry




Tensile

# MATERIALS AND METHODS

## Resources – Equipments

| Activity | Equipment | Laboratory |
|---|---|---|
| Optical microscopy | Leica ® DM 4000 MLED | LabMat |
| Scanning electron microscopy | Hitachi ® Tabletop Microscope | CERMAT |
| Production of samples | Laser source | LMP |
| Production of samples | Powder feeder | LMP |
| Production of samples | CNC | LMP |
| Tensile test | MTS Criterion Model 45 | LabMat |
| Microdureza | Microdurômetro | CERMAT |



# MATERIALS AND METHODS

## Resources – Machining of tensile samples


Electrical Discharge Machining


CNC – Charles MVC955

# AGENDA



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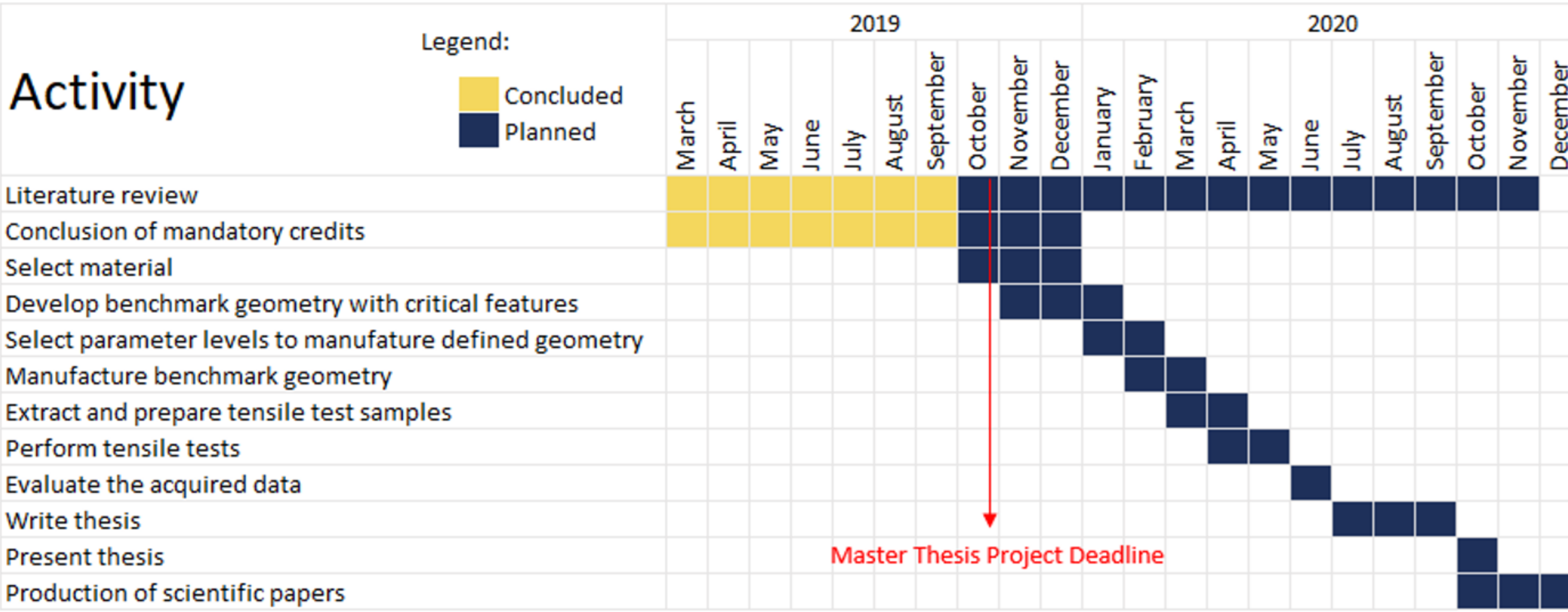
# SCHEDULE

## Detailed activities

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# AGENDA



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LABMAT

CERMAT CERÂMICA

USICON
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Universidade Federal de Santa Catarina

Amaral

# Obrigado!

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