Processing of Mg alloys by SLM technology

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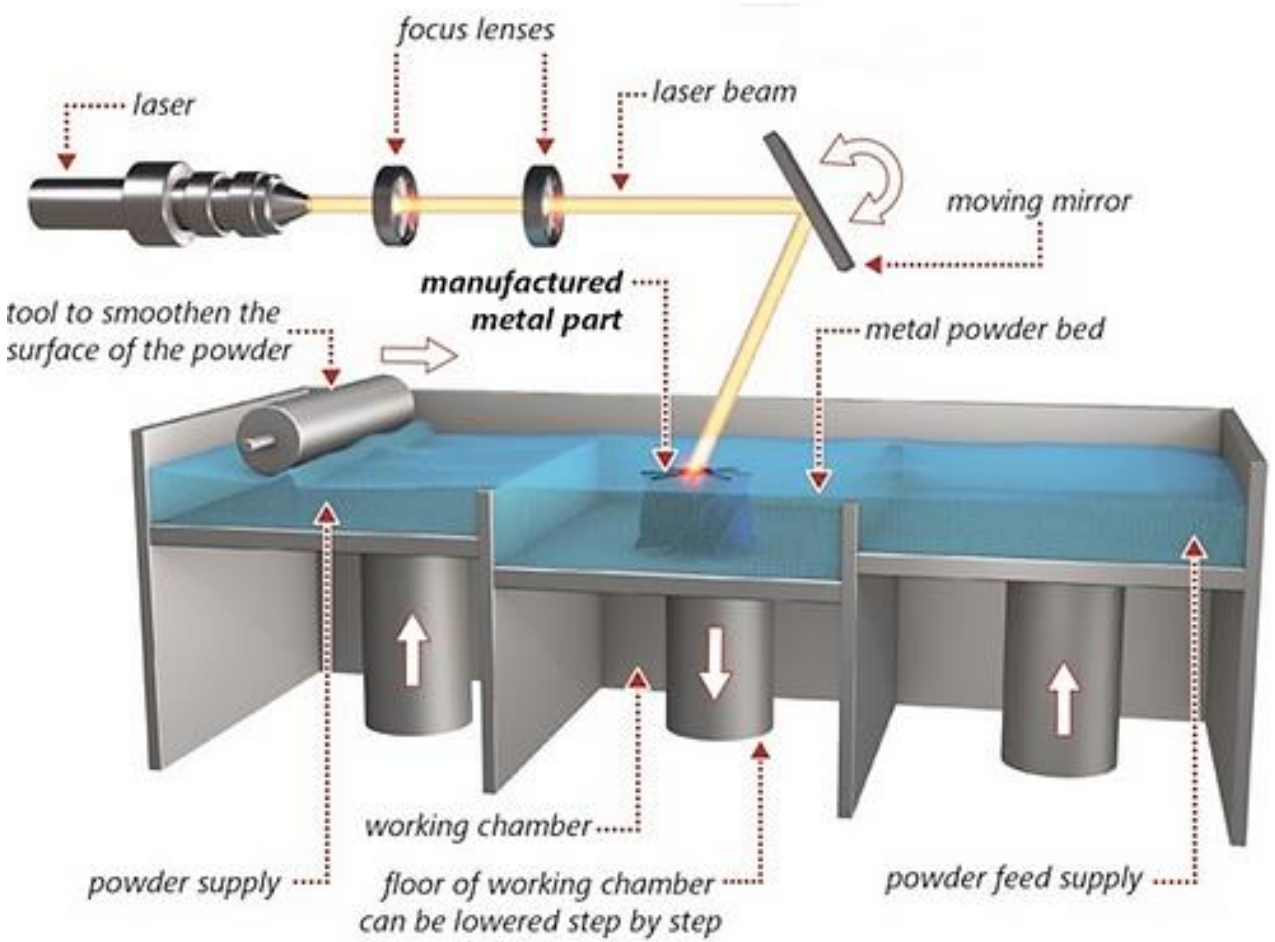
ÚSTAV
KONSTRUOVÁNÍ

Content

- Introduction and motivation
- State of art
- Main goals of the thesis
- Scientific questions
- Methodology
- Results and Discussion
- Conclusion



Motivation

Long Bone Fractures

Standard treatment

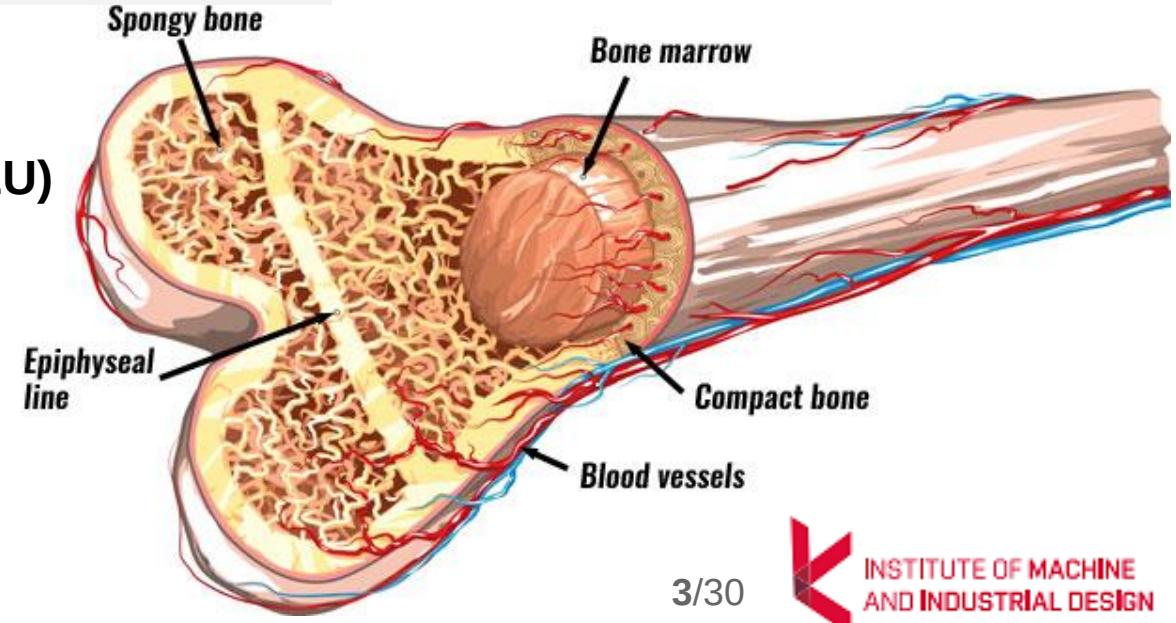
- Bolt fixation
- Necessity of reoperations
- Using of high-tensile and inert materials (Ti, CoCr, Cr-steels,...)

Treatment of long bone fractures is actual issue of orthopaedic surgery
(Singaram and Naidoo 2019)

Occurrence of fractures by patients older 50 years (EU)

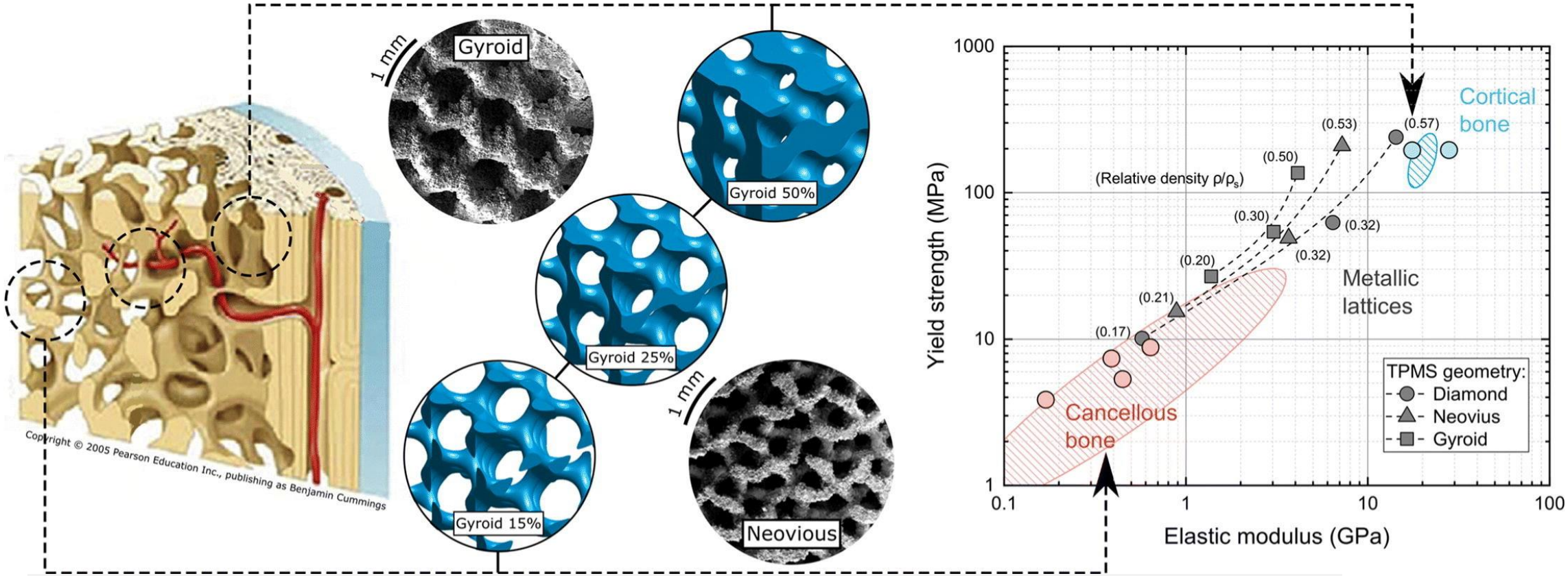
- 37.5 billions € per year of 2017
- 2.7 mil fractures per year of 2017
- Since 2030 increase of occurrence by 23 %

Statistics of six key EU countries
(https://www.osteoporosis.foundation/



Motivation

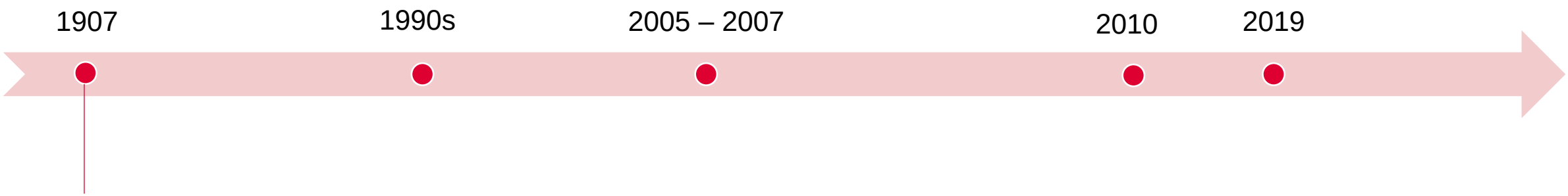
Collaboration with the SLM Method



Proposal of the metal bones by the additive technology
(Alabort 2019)

State of Art

Low Corrosion Resistance



Lambotte A., 1907

- Screw from Mg for human body
- Catastrophic galvanic corrosion
- Continue testing on the animals

State of Art

Low Corrosion Resistance

1907 — 1990s — 2005 – 2007 — 2010 — 2019

Development of new Mg alloys

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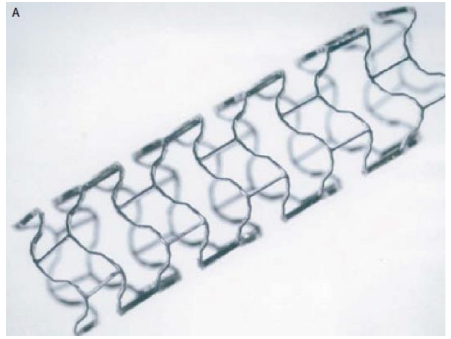
Zartner P, 2005; Erbel R., 2007

- Coronary artery stiffeners
- Successfully implanted



State of Art

Low Corrosion Resistance

1907 — 1990s — 2005 – 2007 — 2010 — 2019

Development of new Mg alloys

SLM of Mg alloys

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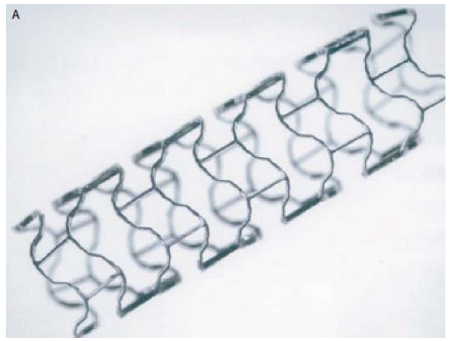
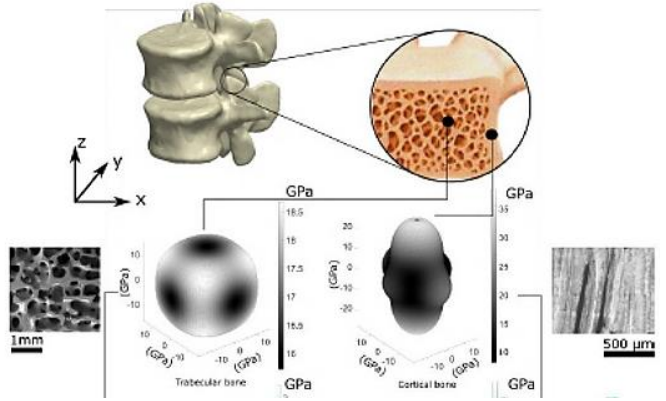


Alabort, 2019
- Proposal of metallic bones by additive technology



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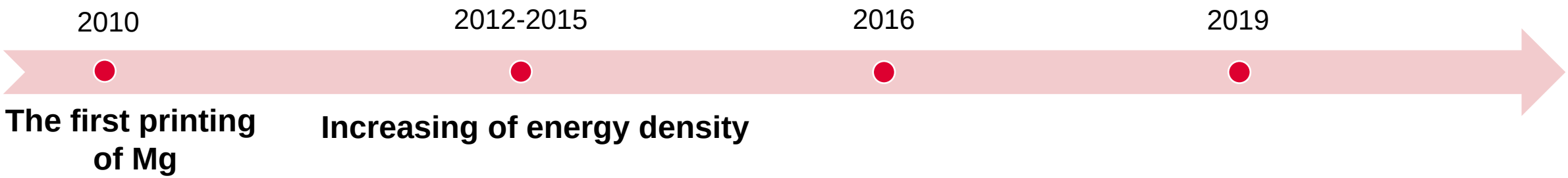
State of Art

Process Parameters



State of Art

Process Parameters

2010 — The first printing of Mg

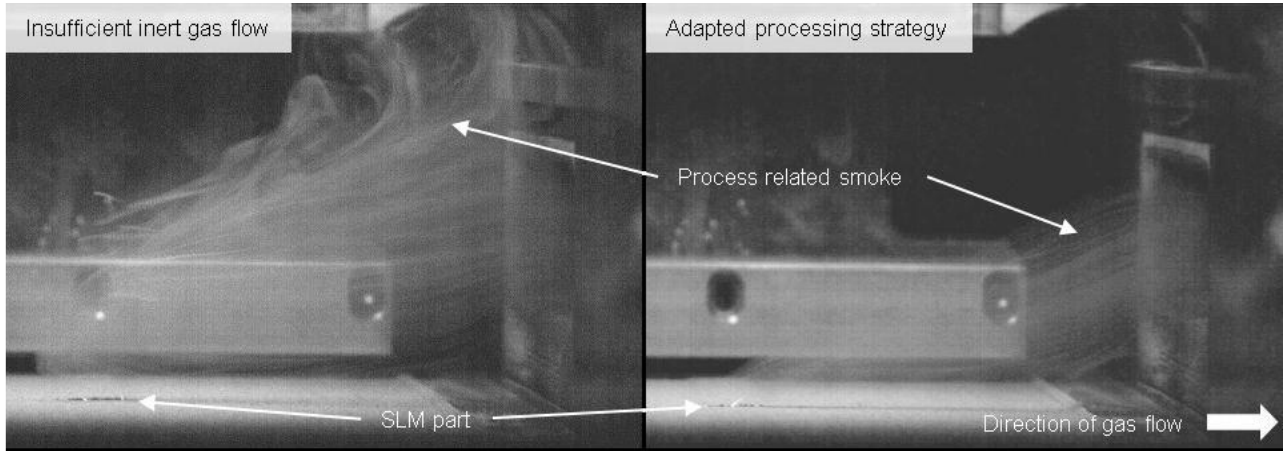
2012-2015 — Increasing of energy density

2016

2019

Jauer, 2016
- Continuation of the trend
- Upgrade the circuit in 3D printer

Tandon, 2016
- Different approach
- Used the lower energy than Al



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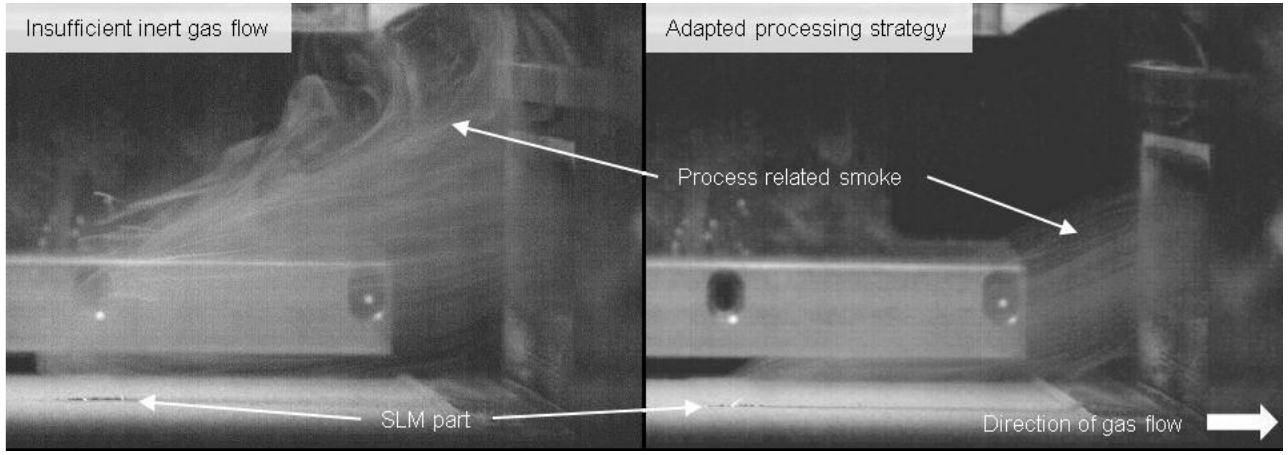
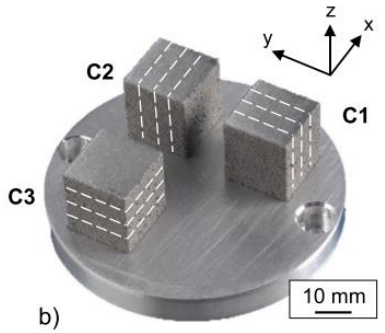
Zumdick, 2019; Gangireddy 2019
- Relative density of 99,5 %
- Different processing and printers





State of Art

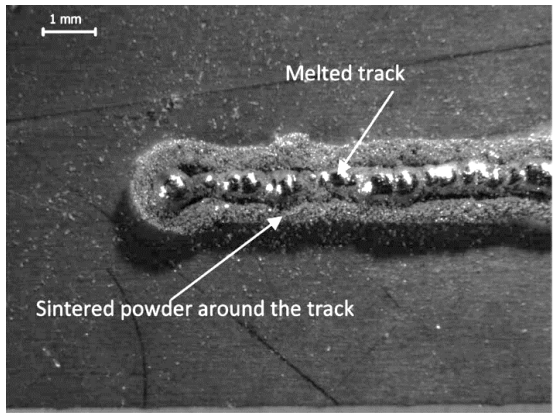
Corrosion Behavior

2010 — 2011-2018 — 2019

Development of material processing

C. C. Ng, 2010

- Sintering powder on the surface



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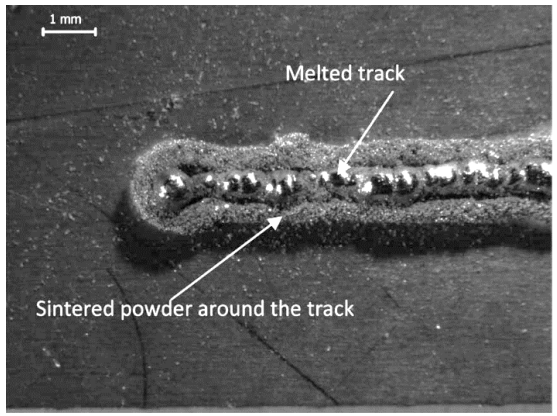
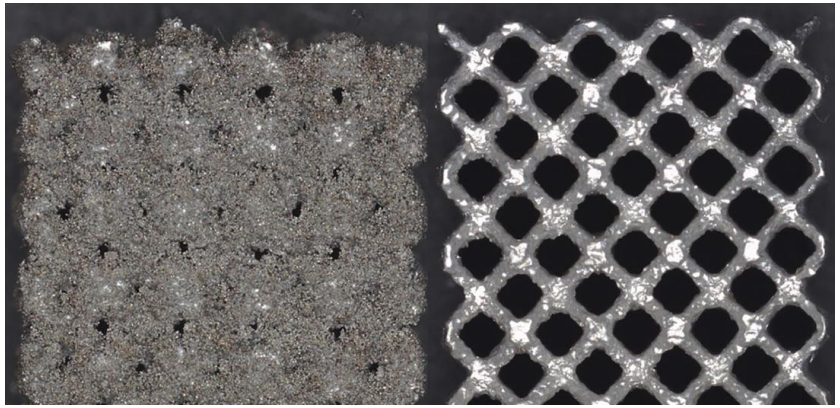


Kopp, 2019

- Surface quality of microstructures
- Ruptures after etching



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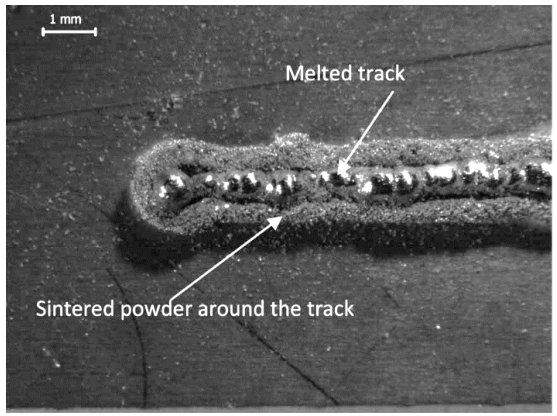

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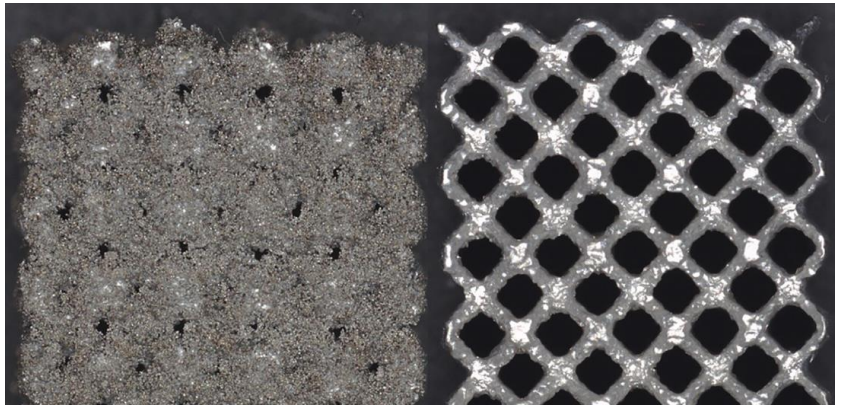
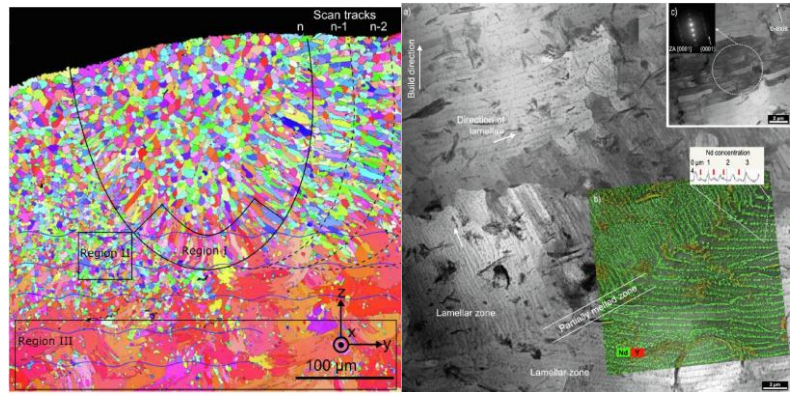


Bär, 2019

- Microstructural analysis of WE43 printed alloy

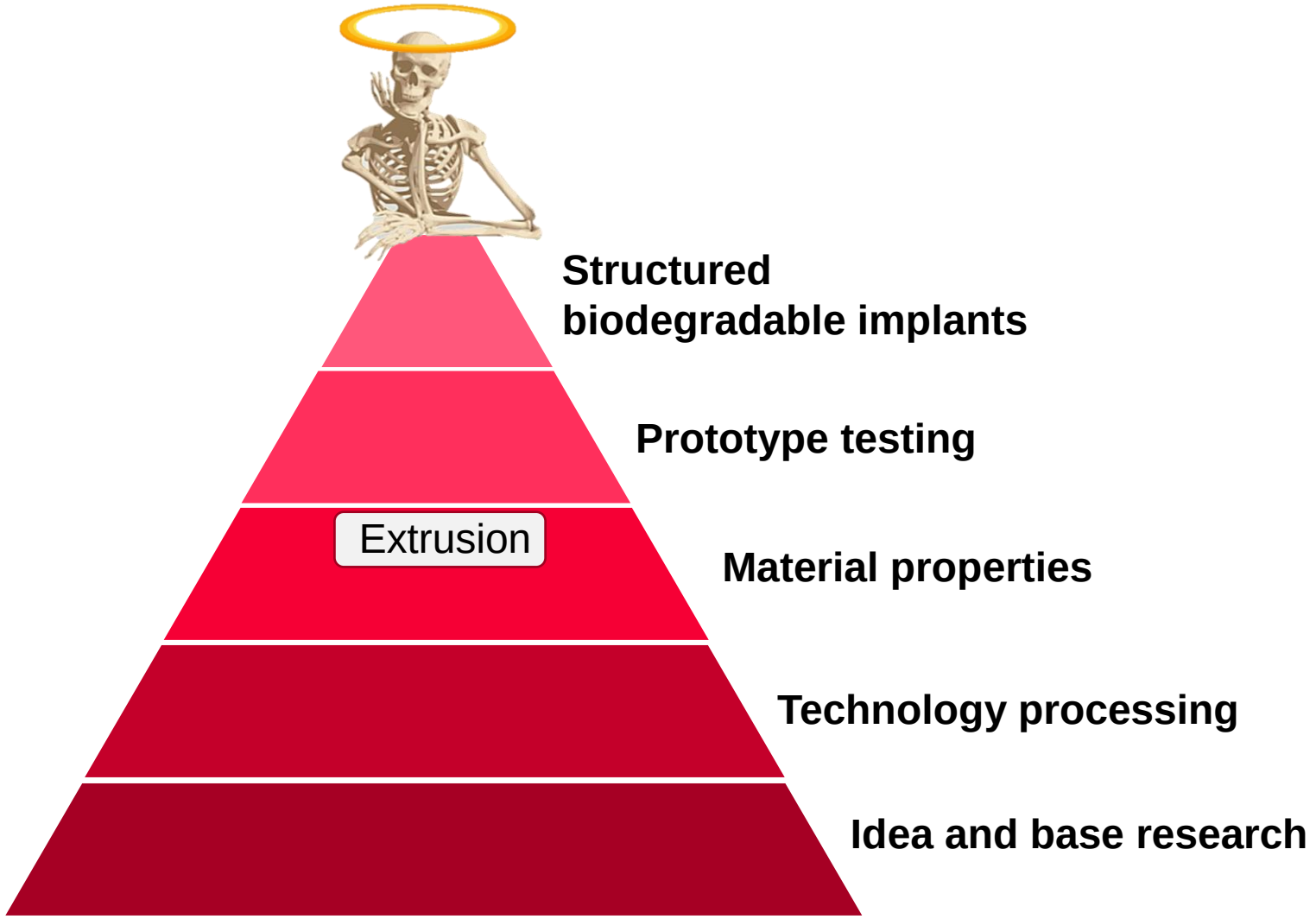


State of Art

Analysis of Blanks

Global problem

- Low corrosion resistance

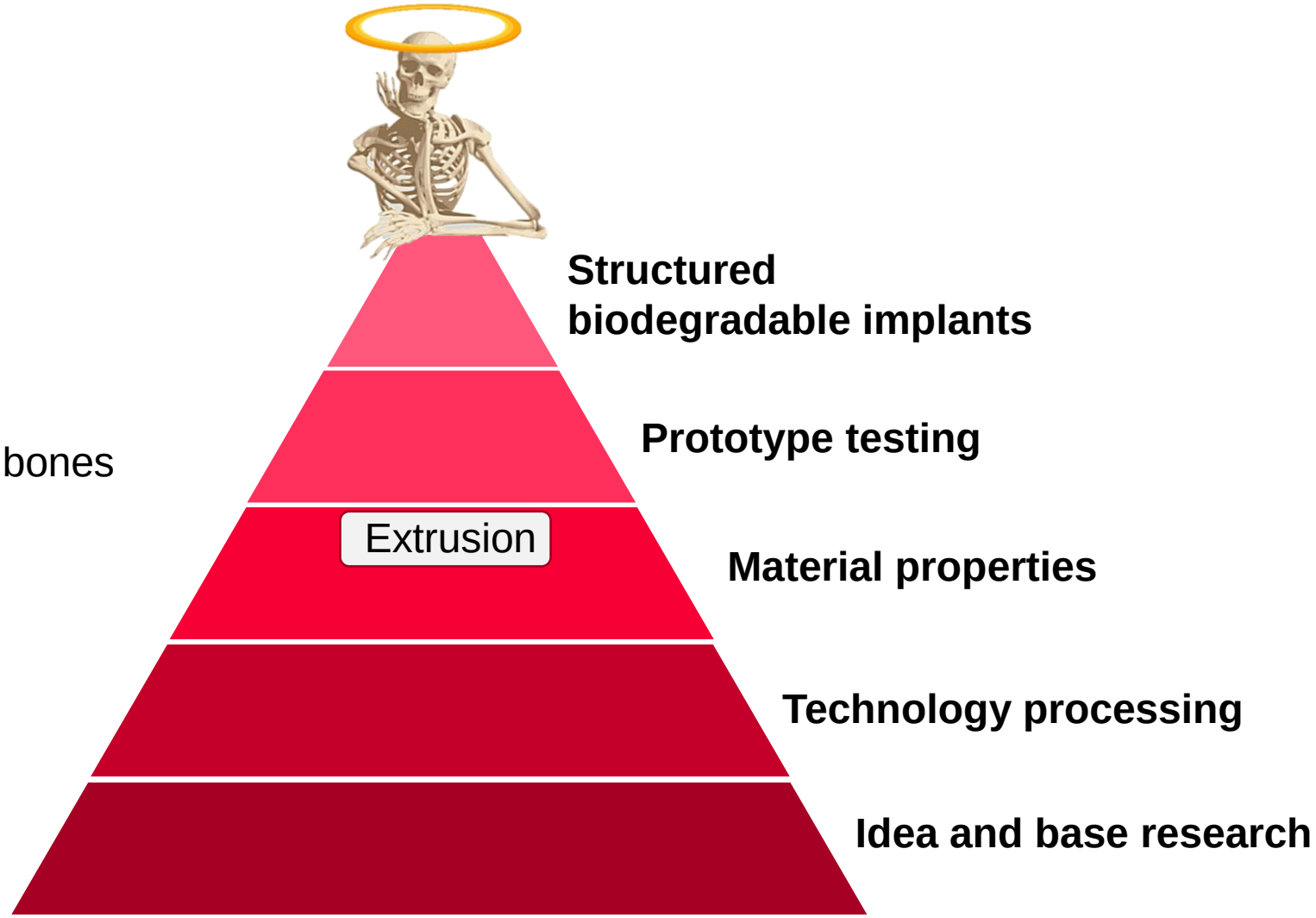


State of Art

Analysis of Blanks

Global problem
- Low corrosion resistance

Material selection **WE43**
- Biocompatible
- Mechanical properties nearness to bones
- Accelerate regeneration
- Higher corrosion resistance



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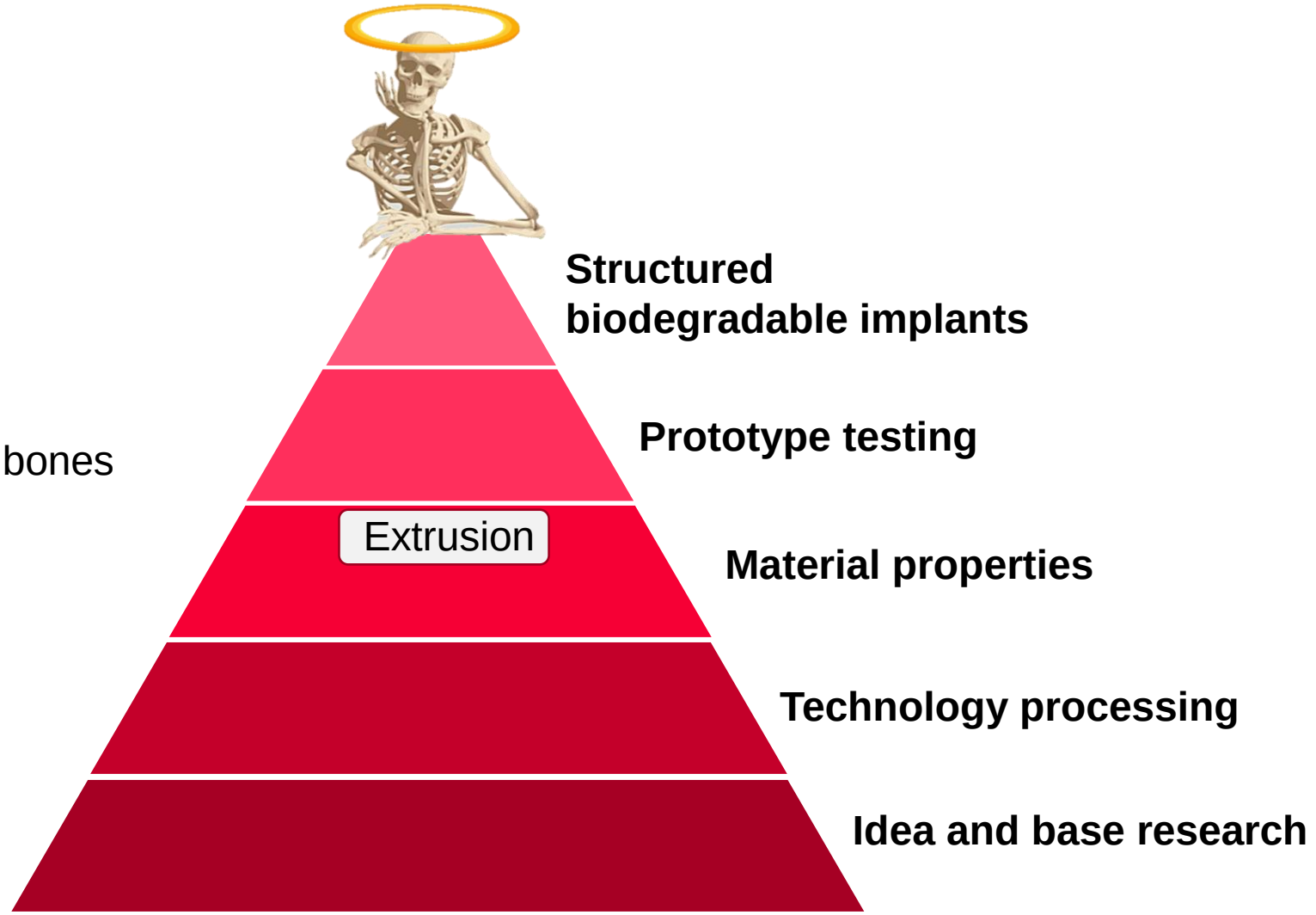
- Increased corrosion resistance
- Customized small implants



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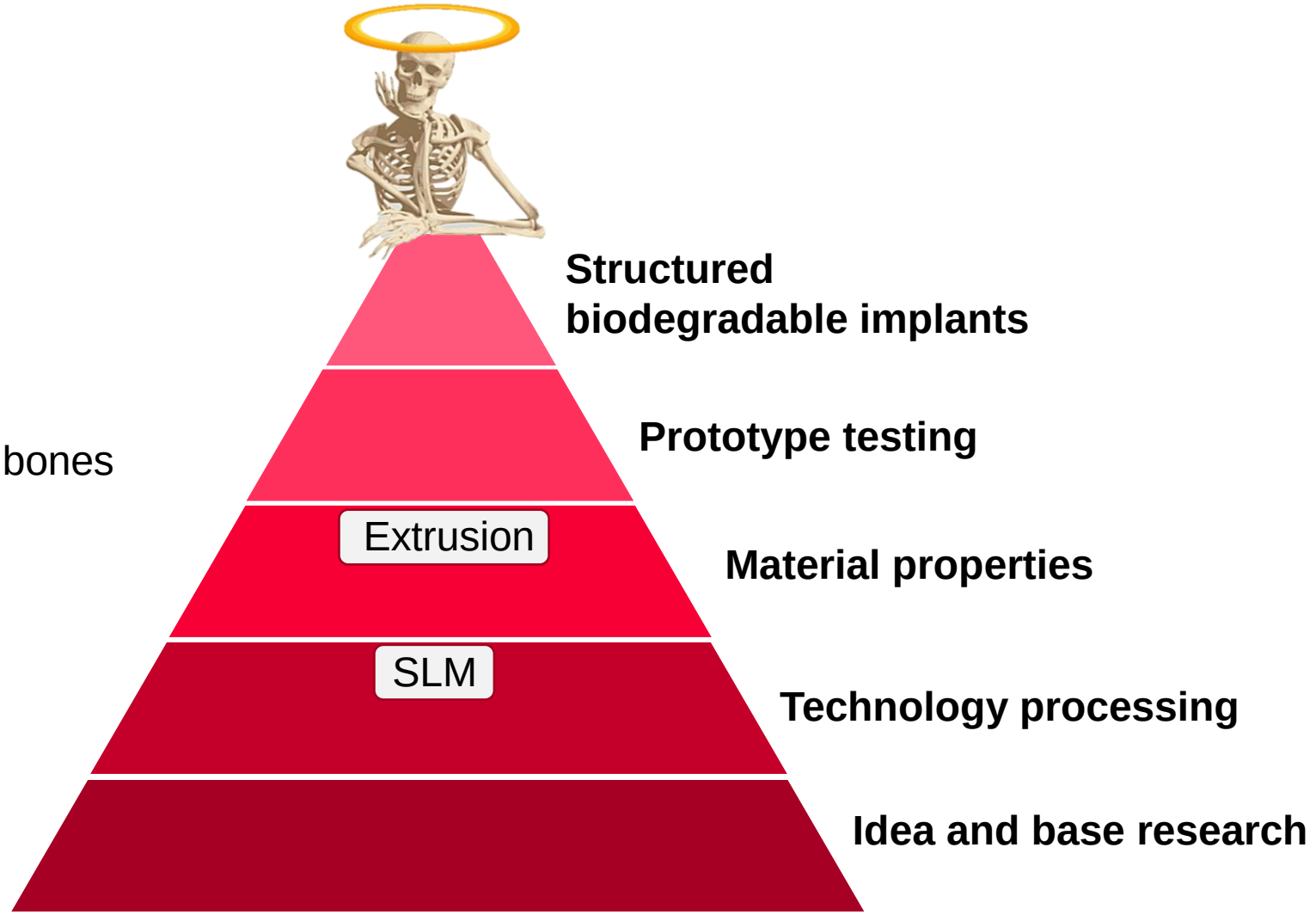


Goals of the thesis

The main goal of the work

- The main goal of the presented doctoral thesis is to clarify the influence of process parameters and technological conditions on the corrosion behavior of WE43 magnesium alloy produced by the SLM method.

Sub-goals

- The printing process setting
- Optimization of the printing process
- Determining of the corrosion rate of 3D printed material

Keywords

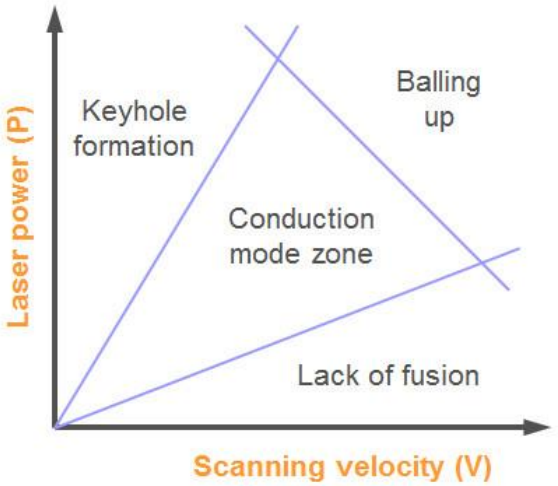
- Selective laser melting, Magnesium alloys, Homogeneous material, Microstructure, Corrosion rate

Scientific questions

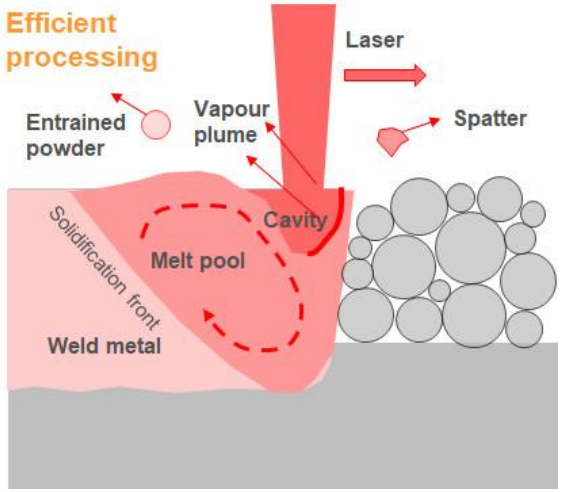
1. Scientific question
What influences most the final value of the relative density of the WE43 magnesium alloy?

1. Hypotheses
- The laser beam is defocused by vapors
- It created non-stable printing conditions
- Vapors can be removed by setting the suitable combination of process parameters

Process mapping



Optimization

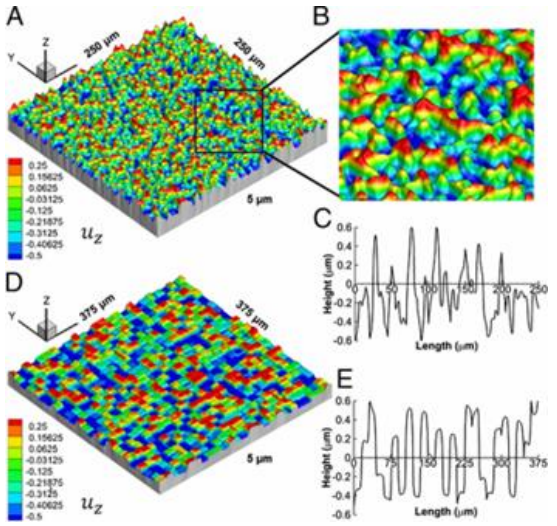


Scientific questions

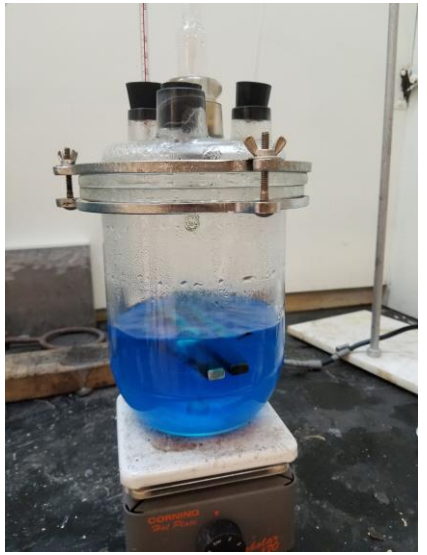
2. Scientific question
Is it possible to control the corrosion rate of the WE43 alloy processed by the SLM method by adjusting the process parameters?

2. Hypotheses
- Material properties can be changed by process parameters
- Especially the surface roughness and microstructure
- Its change can lead to improving the corrosion rate of the 3D printed material

Influence of parameters



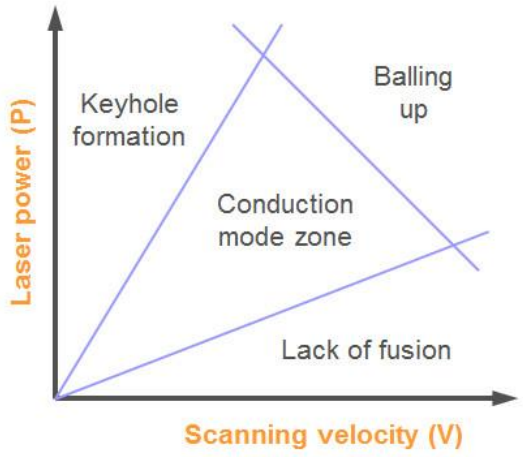
Immersion testing

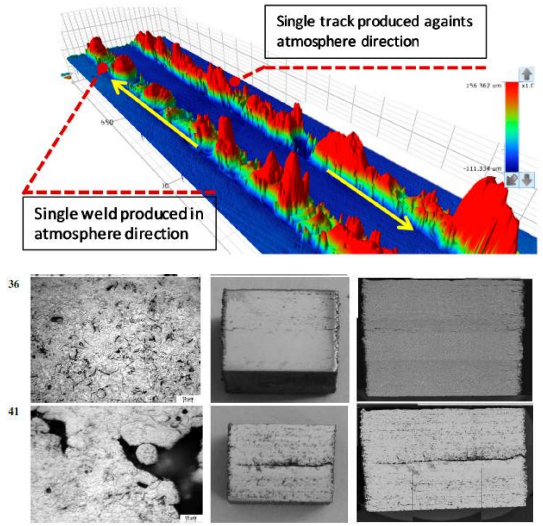


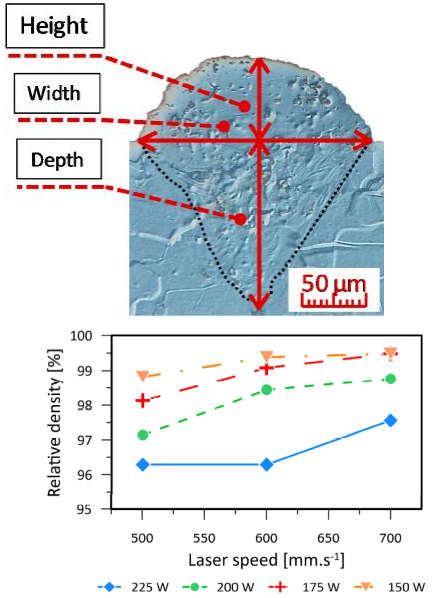
Methodology

Scientific question 1

What?	On what?	How?	By what?
• Influence of process parameters	• Weld deposit • Volume samples	• Weld deposit geometry • Porosity	• Profilometer • Optodigital microscope
• 3D printing strategy	• Cube samples made by different strategies	• Porosity	• Optodigital microscope







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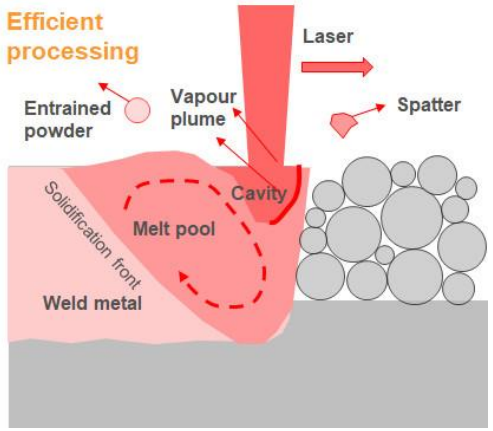
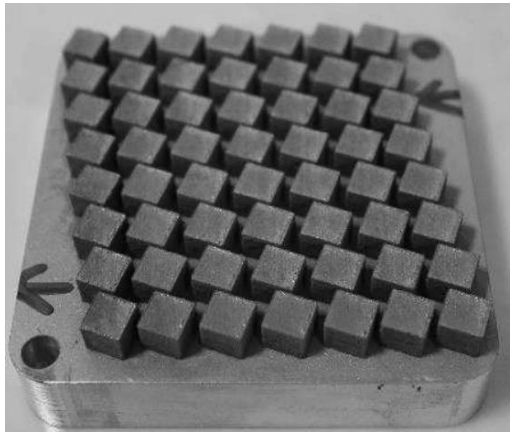
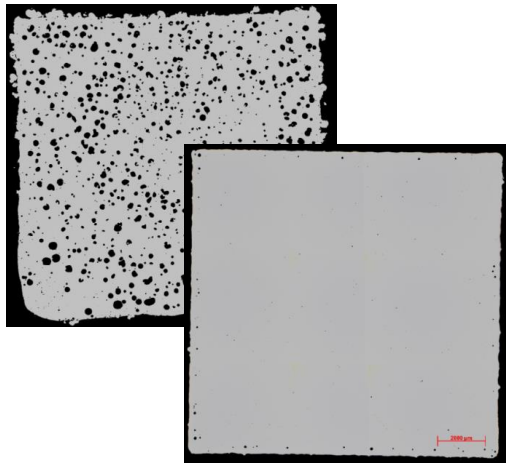


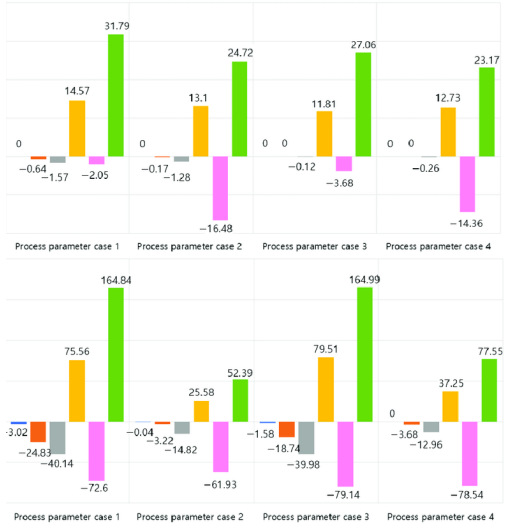


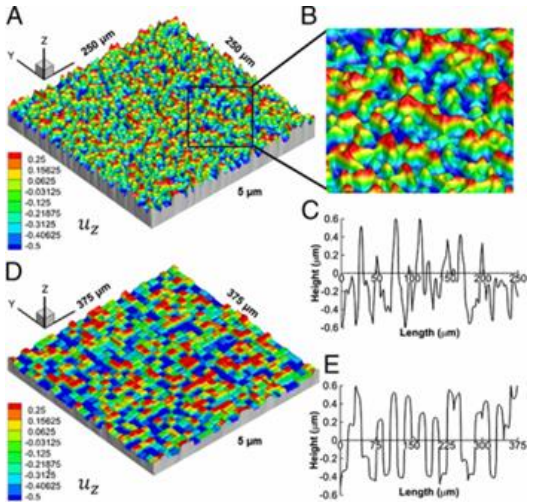


Methodology

Scientific question 2

What?	On what?	How?	By what?
• Sensitivity on the change of process parameters	• Thin-wall samples • Volume samples	• Surface roughness • Microstructure	• Profilometer • Optodigital microscope
• The trend of corrosion rate	• Cube samples with a different parameters	• Weight loss on time	• Laboratory weighting machine





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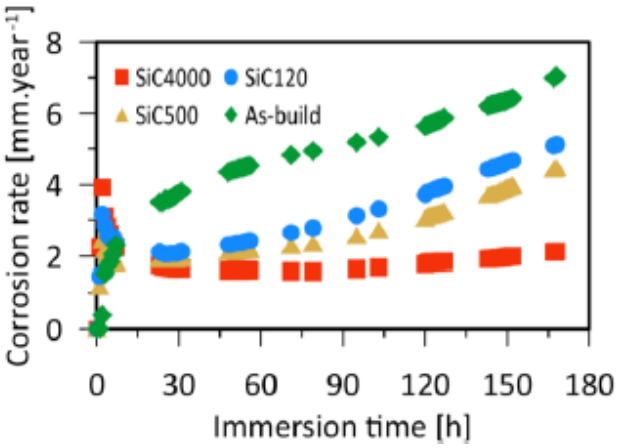
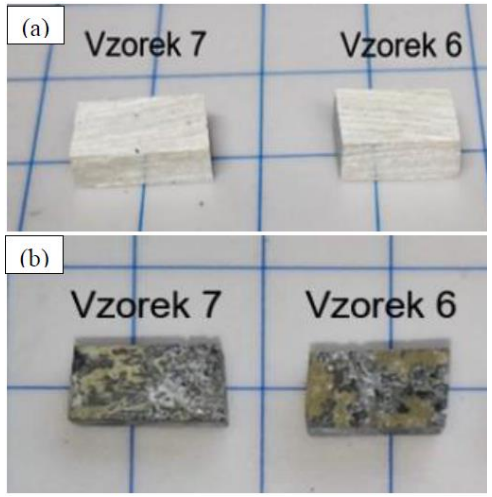
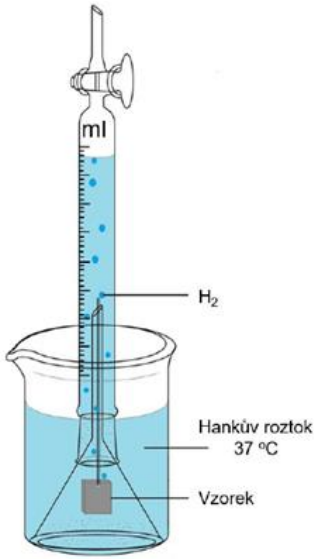
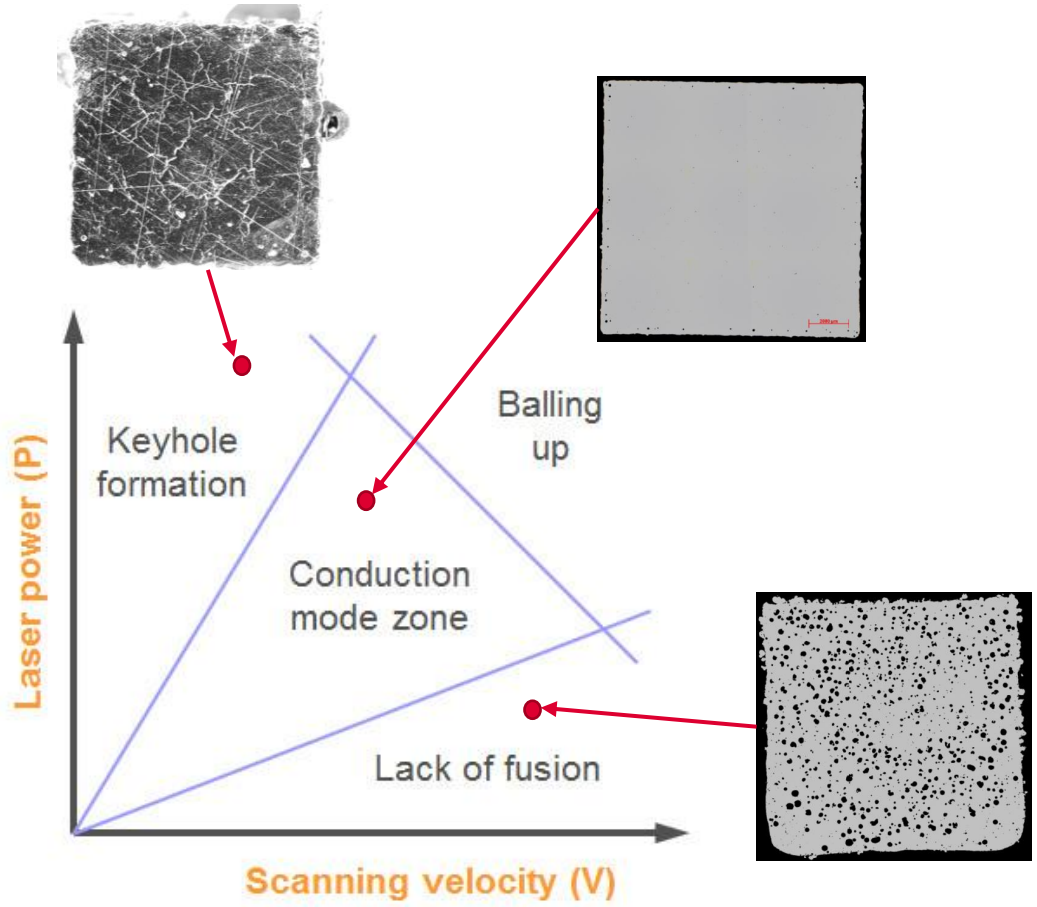




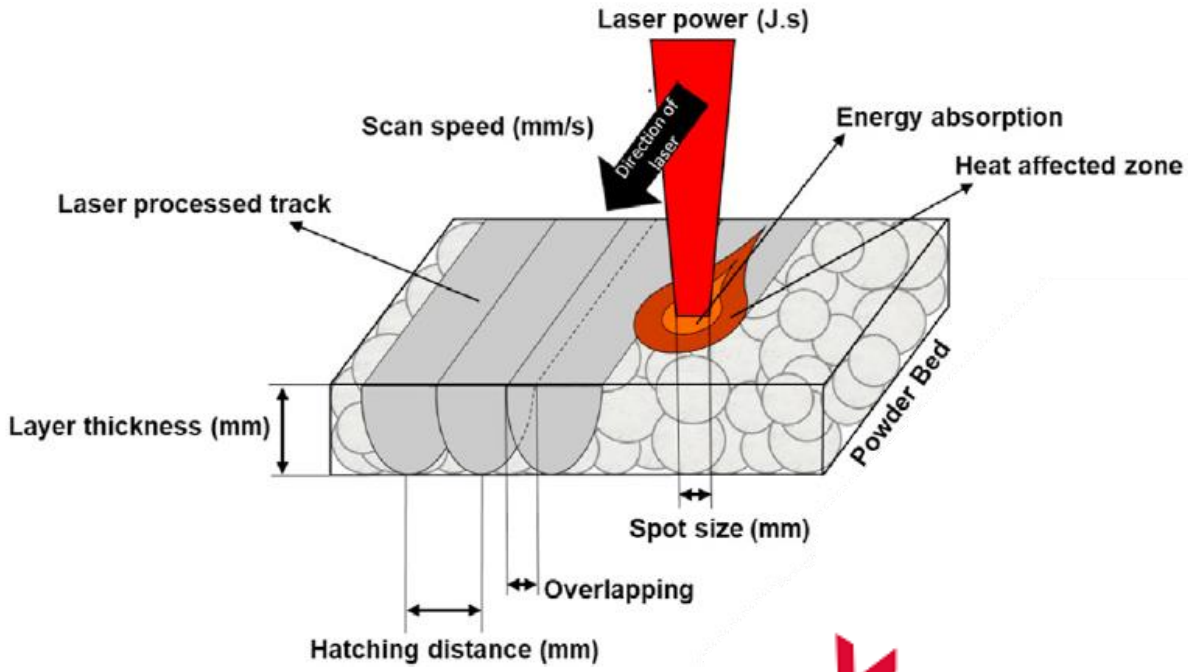


Results and discussion

Scientific question 1 **1/2** **Process mapping**



$$E = \frac{L_p}{L_s \times H_d \times L_t}$$

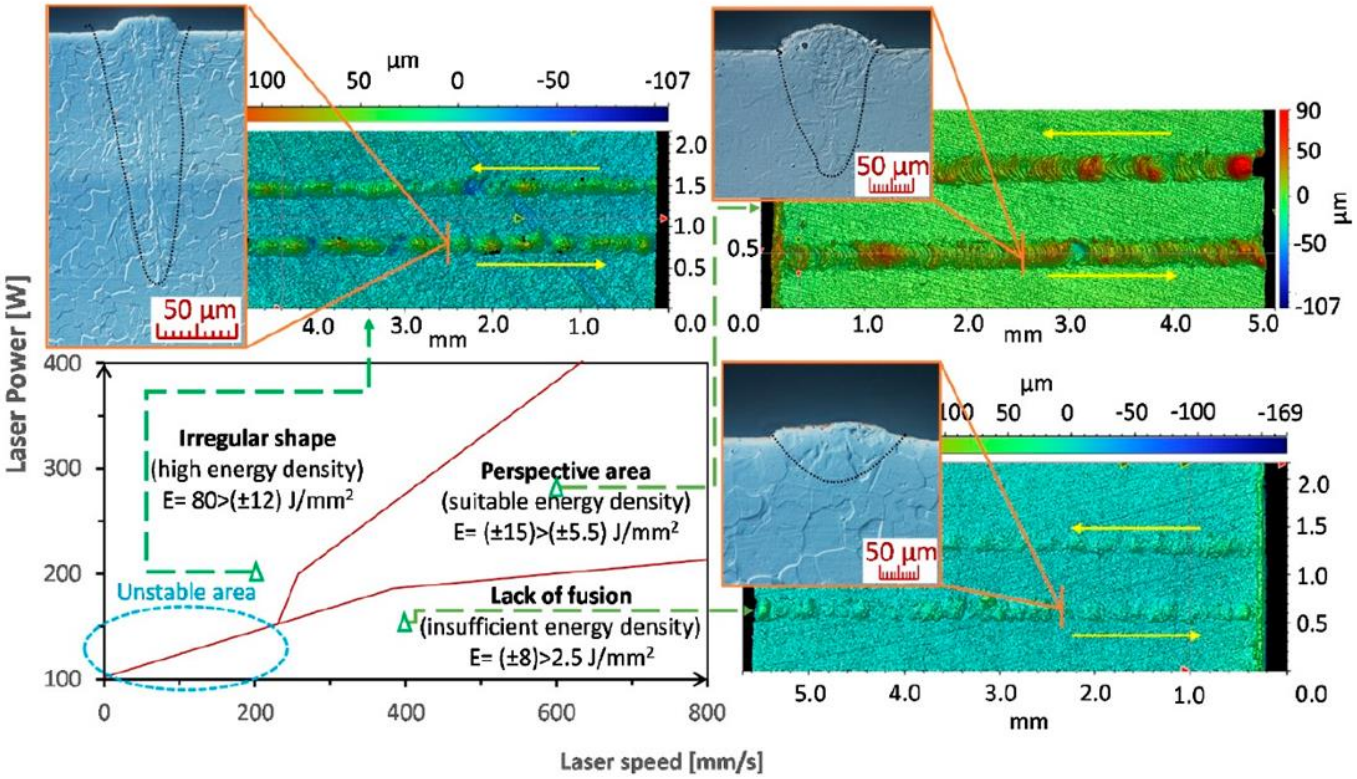


Results and discussion

Scientific question 1 **1/2** **Process mapping**

Major Findings

- Dominant effect of laser power on the shape of weld depositions
- The depth of the weld depositions corresponded to 3-6 deposited layers thickness



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Results and discussion

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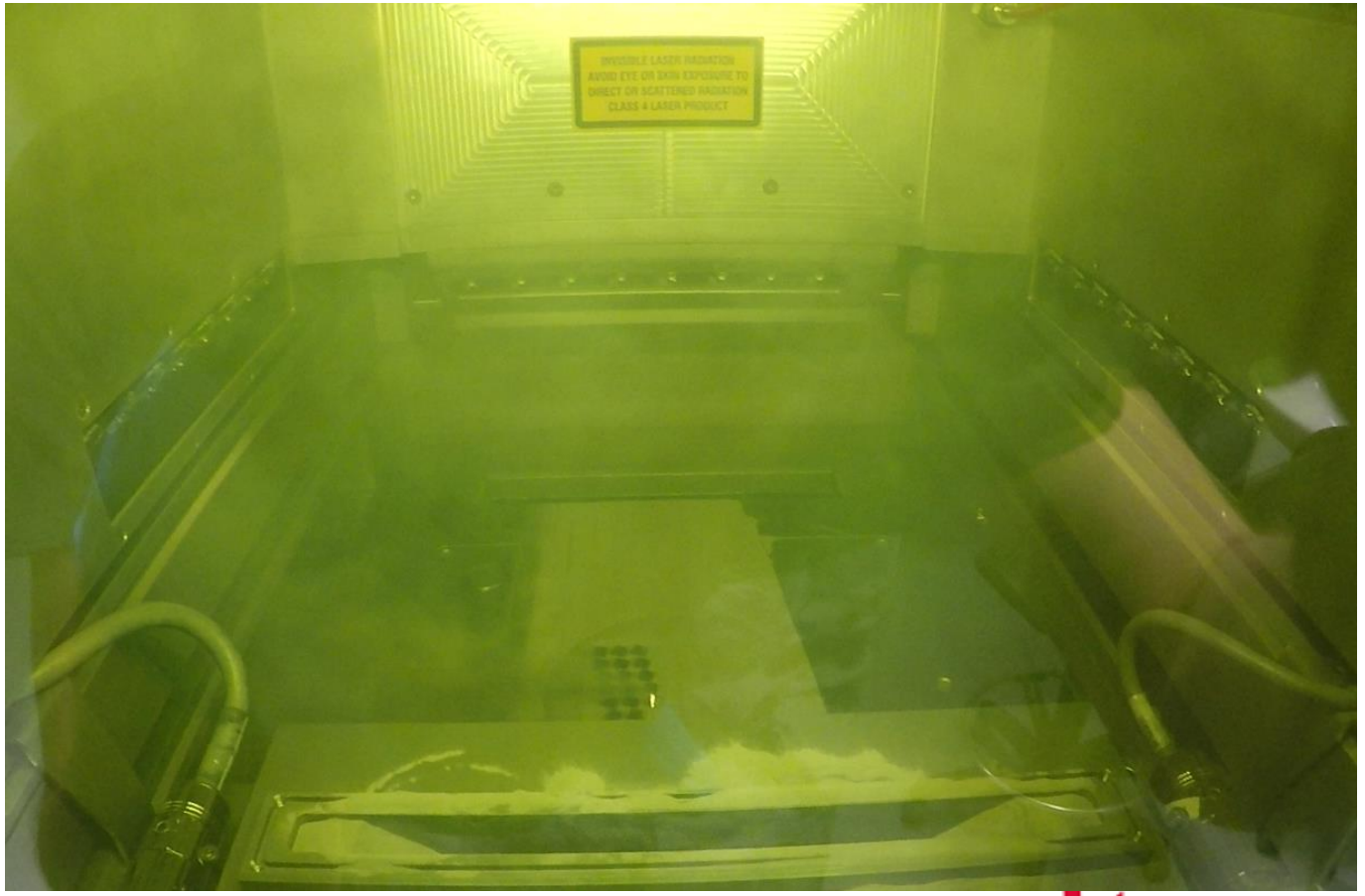

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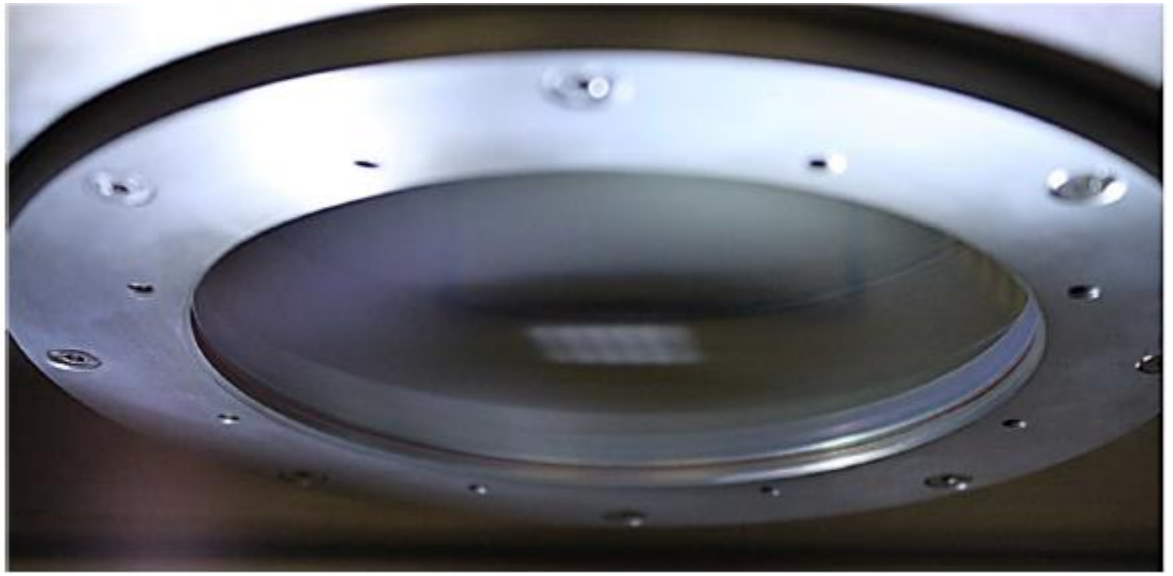

Results and discussion

Scientific question 1 1/2 Process mapping

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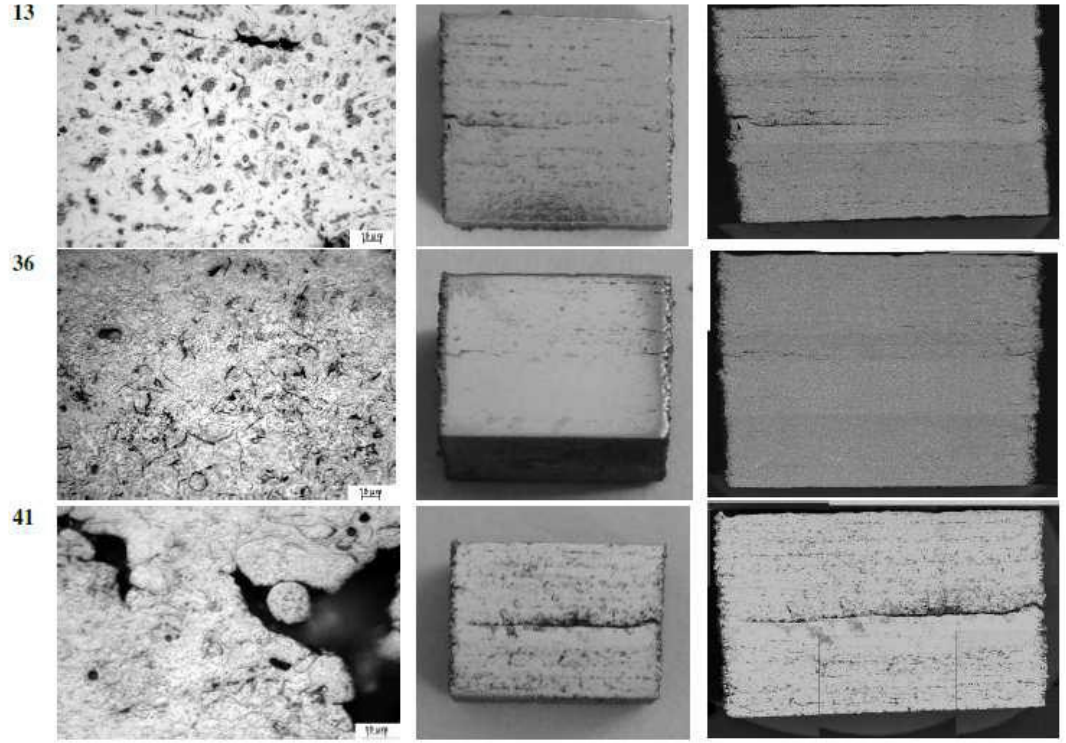
- The increase of input energy lead to massive evaporation of Mg
- The repeatability was too low



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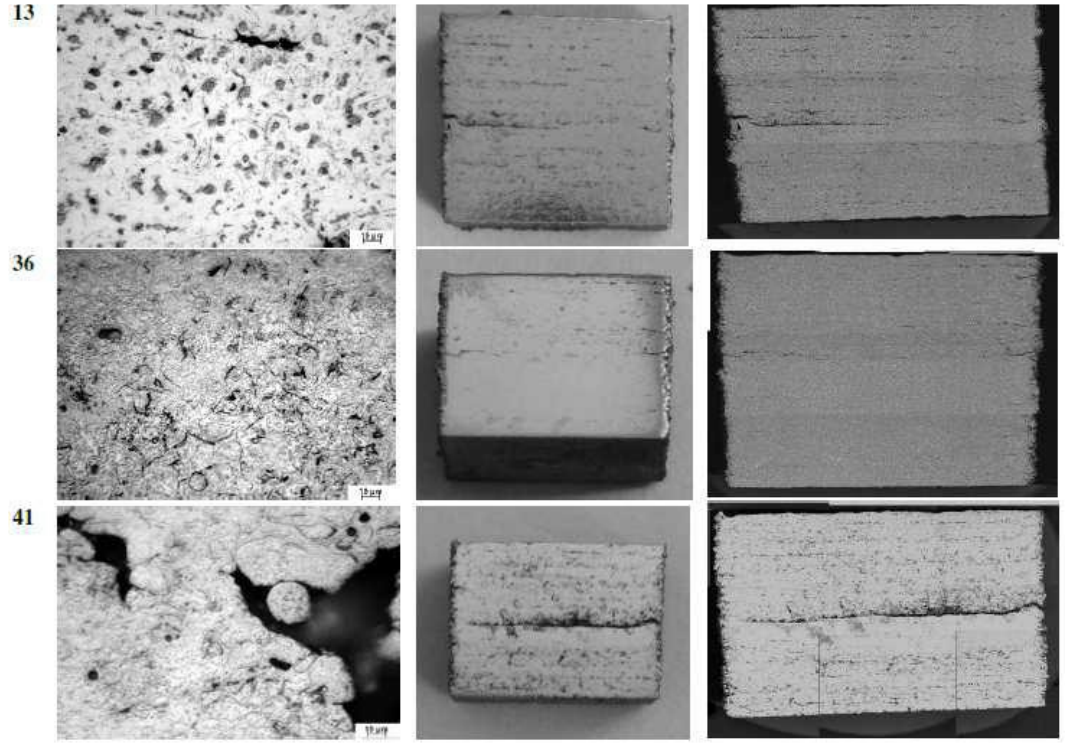


Summary

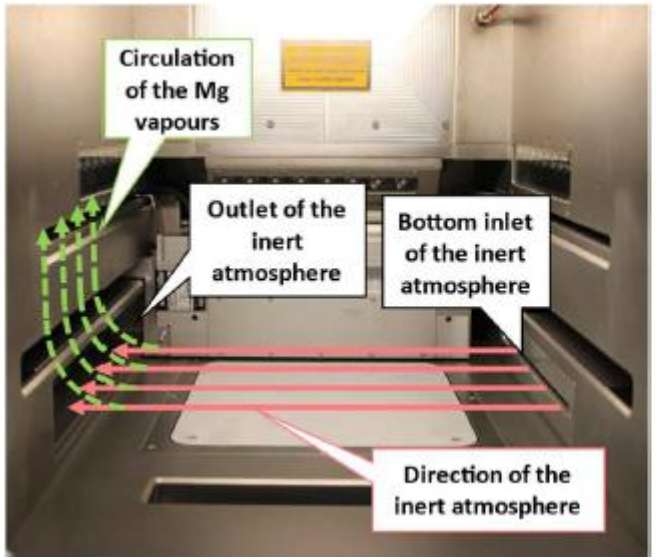
- The laser power has to be decreased
- A satisfactory reduction in the amount of vapor could not be achieved only by changing the process parameters

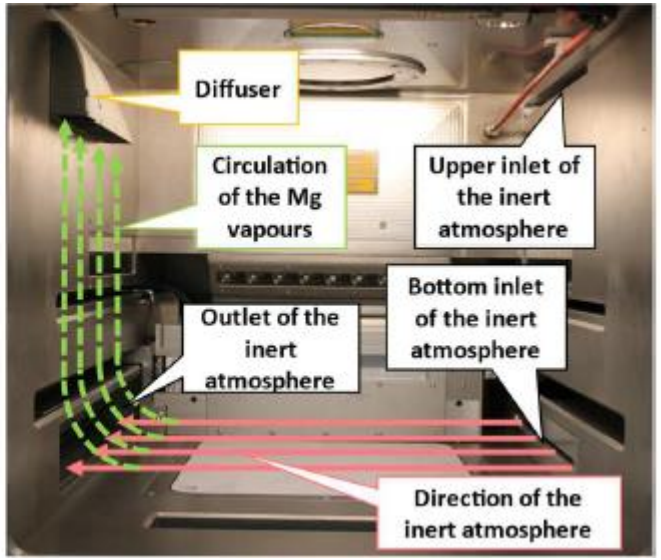
Results and discussion

Scientific question 1 **2/2** **3D printing strategy setting**

Major Findings

- Increased extraction of process emissions from the production chamber





Results and discussion

Scientific question 1 2/2 3D printing strategy setting

Major Findings

- Increased extraction of process emissions from the production chamber

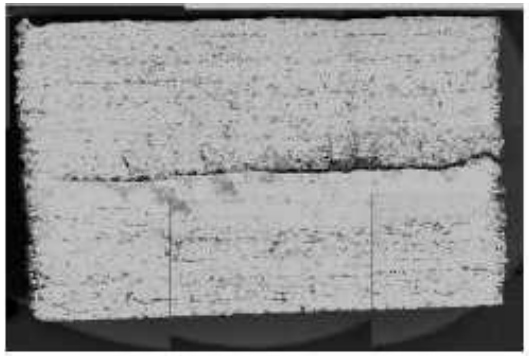
Results and discussion

Scientific question 1 **2/2** **3D printing strategy setting**

Major Findings

- Increased extraction of process emissions from the production chamber

Phase	Input energy	Output energy	Porosity
Original strategy	Low	Low	Homogeneous
After reduction of vapors			
Adding time delay			



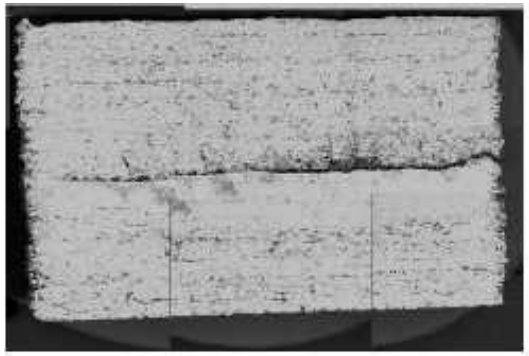
Results and discussion

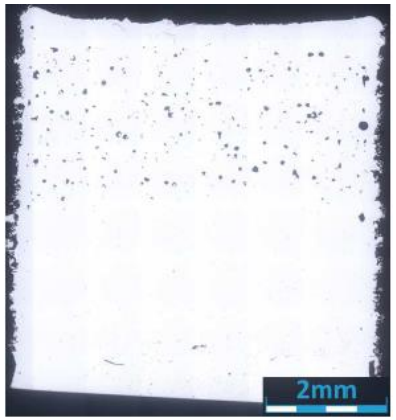
Scientific question 1 **2/2** **3D printing strategy setting**

Major Findings

- Increased extraction of process emissions from the production chamber

Phase	Input energy	Output energy	Porosity
Original strategy	Low	Low	Homogeneous
After reduction of vapors	High	Low	Non-uniform
Adding time delay			





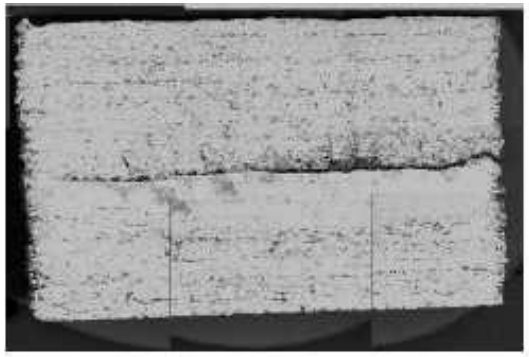
Results and discussion

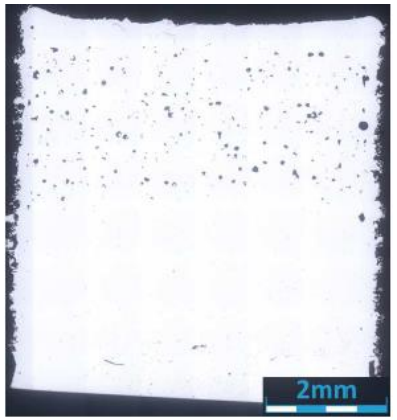
Scientific question 1 **2/2** **3D printing strategy setting**

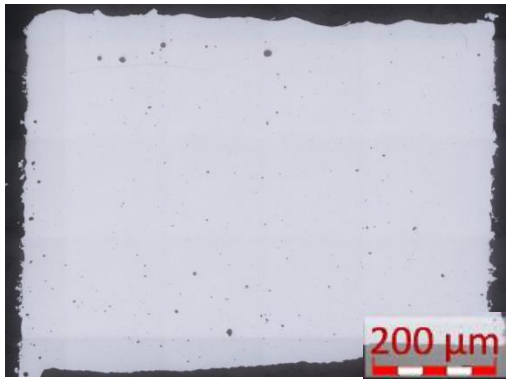
Major Findings

- Increased extraction of process emissions from the production chamber
- Print repeatability is ensured

Phase	Input energy	Output energy	Porosity
Original strategy	Low	Low	Homogeneous
After reduction of vapors	High	Low	Non-uniform
Adding time delay	High	Compensated	Homogeneous





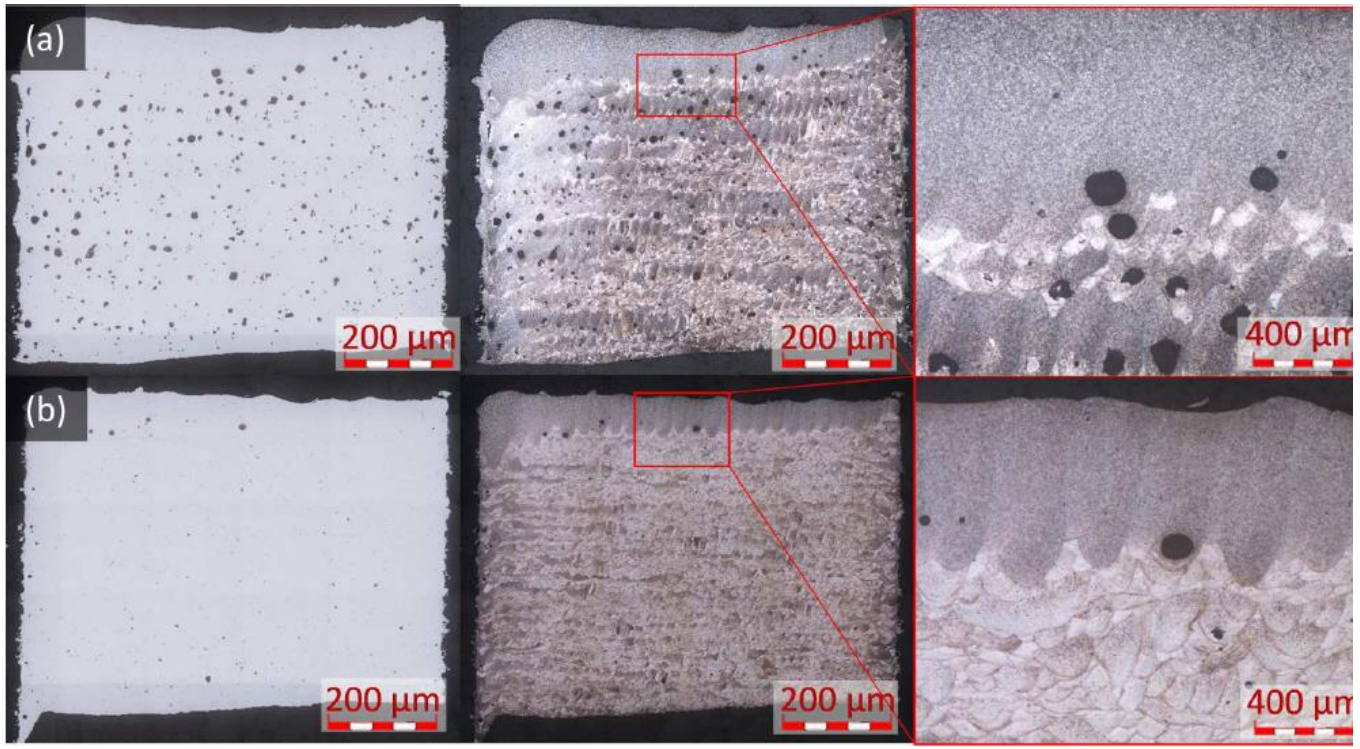


Results and discussion

Scientific question 1 **2/2** **3D printing strategy setting**

Major Findings

- Increased extraction of process emissions from the production chamber
- Print repeatability is ensured
- Relative density of material achieved of 99.5 %



Results and discussion

Scientific question 1 **2/2** **3D printing strategy setting**

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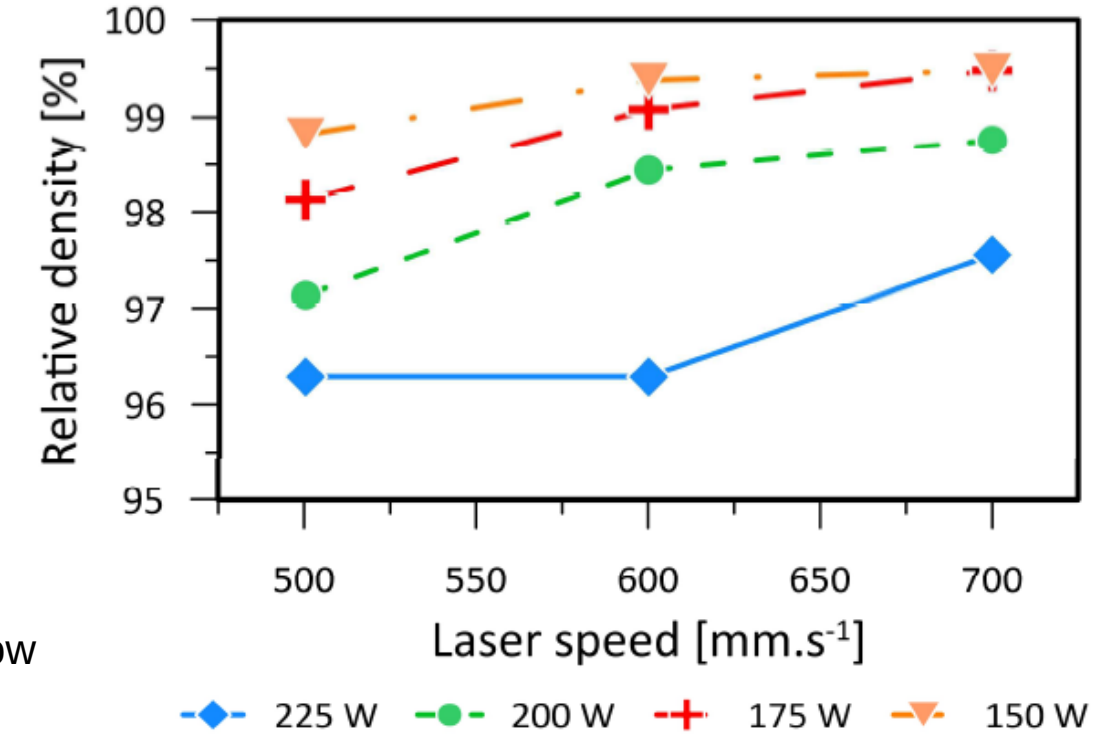


Summary

- The ability to print repeatedly volume samples with a low level of porosity

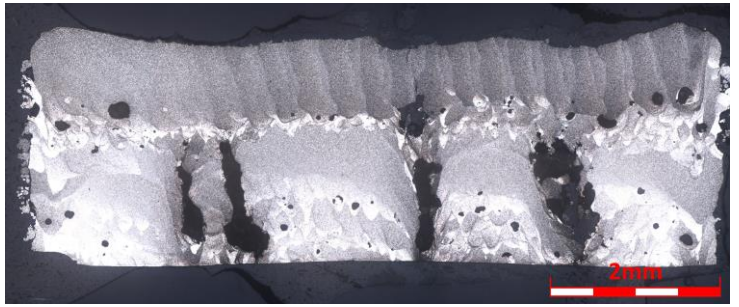
Results and discussion

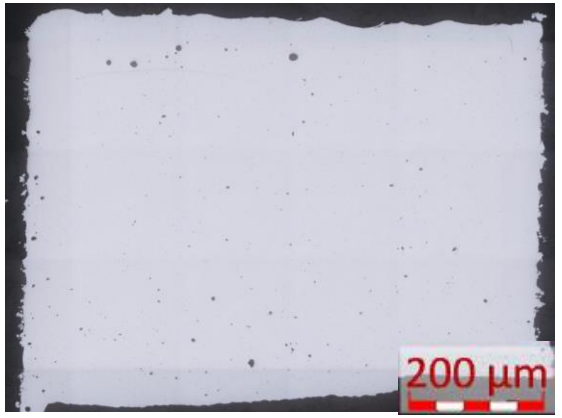
Scientific question 1

3D printing strategy setting

Scientific question
What influences most the final value of the relative density of the WE43 magnesium alloy?

Hypotheses
- The laser beam is defocused by vapors
- It created non-stable printing conditions
- Vapors can be removed by setting the suitable combination of process parameters



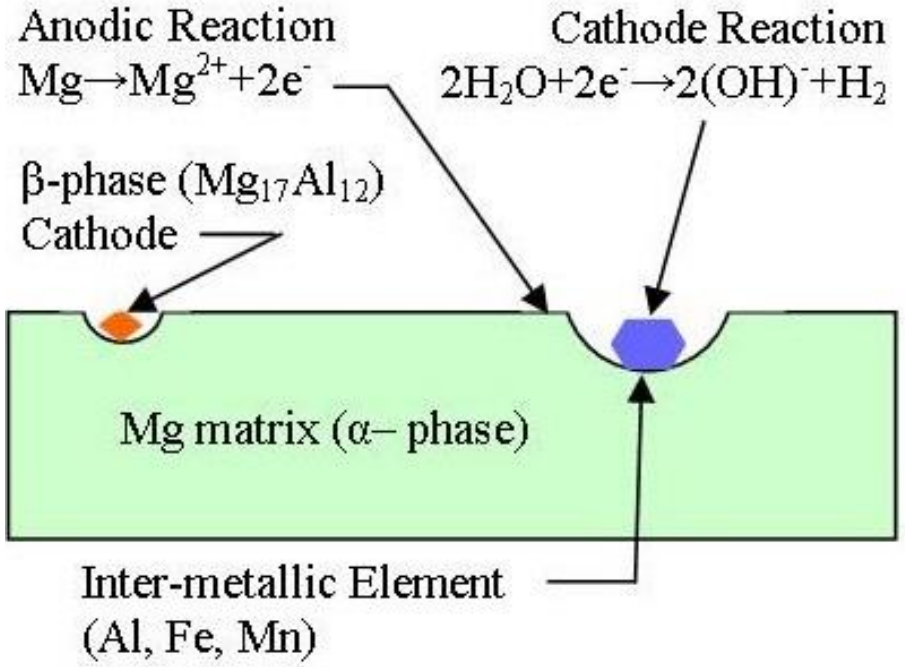


The hypothesis was particularly confirmed

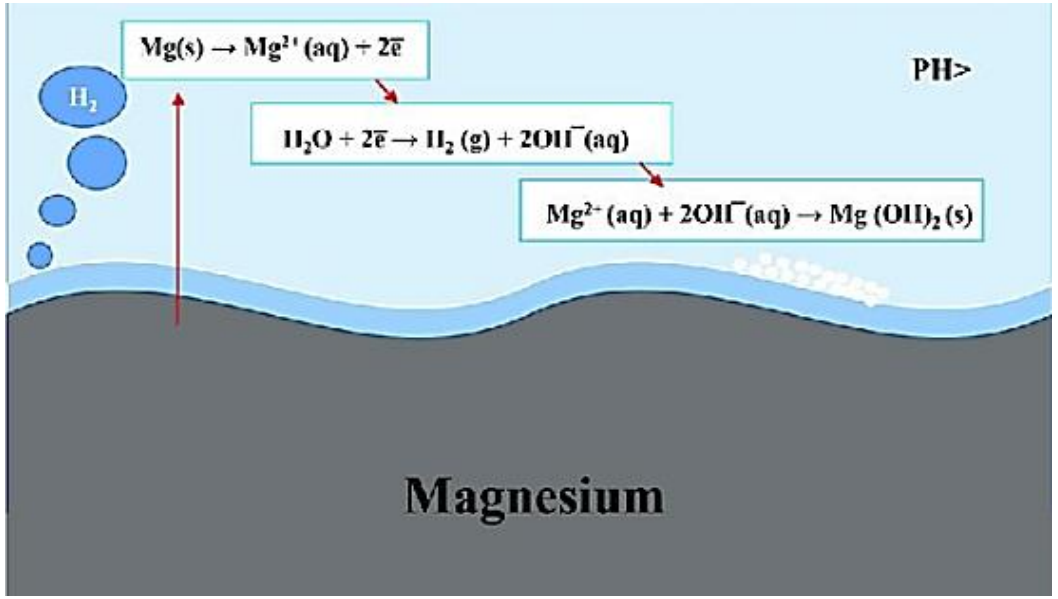
Results and discussion

Scientific question 2 **1/2** **Influence of process parameters**

Galvanic corrosion
Microstructure



Atmospheric corrosion
Surface roughness

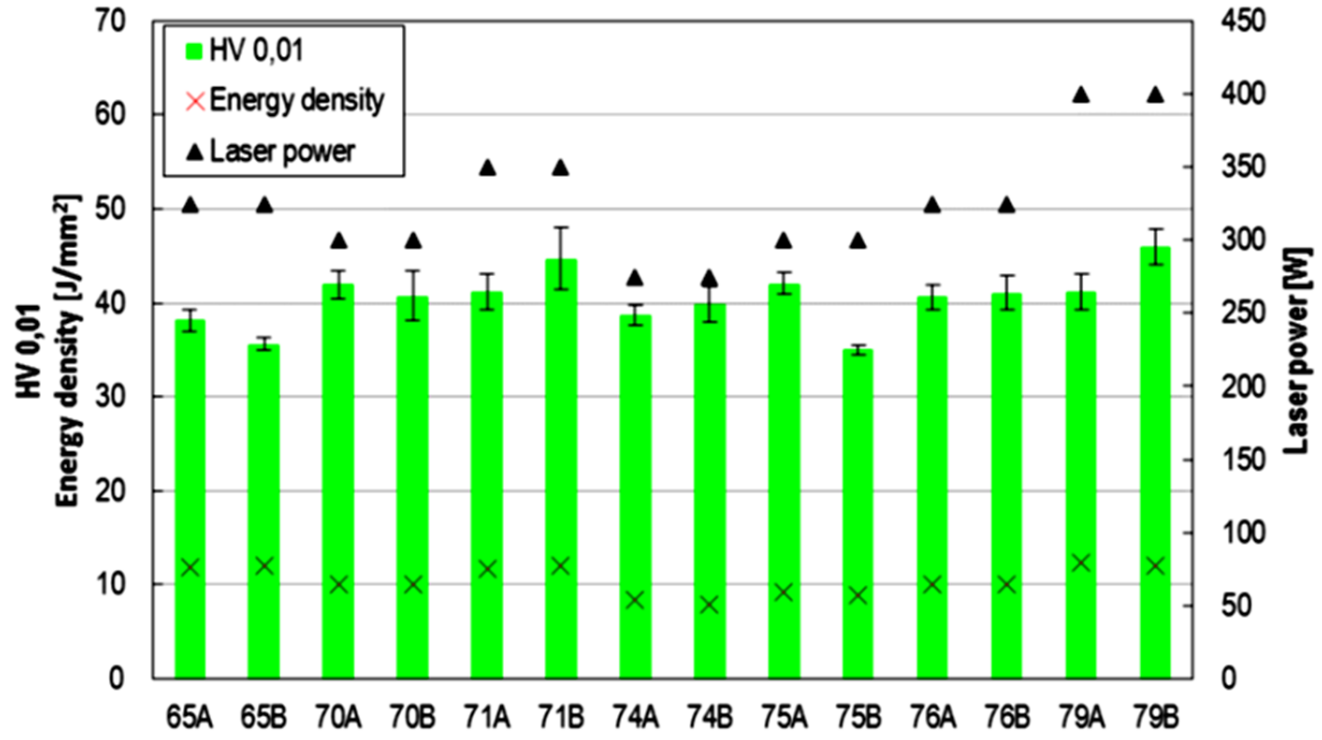


Results and discussion

Scientific question 2 **1/2** **Influence of process parameters**

Major Findings

- No change in the microhardness

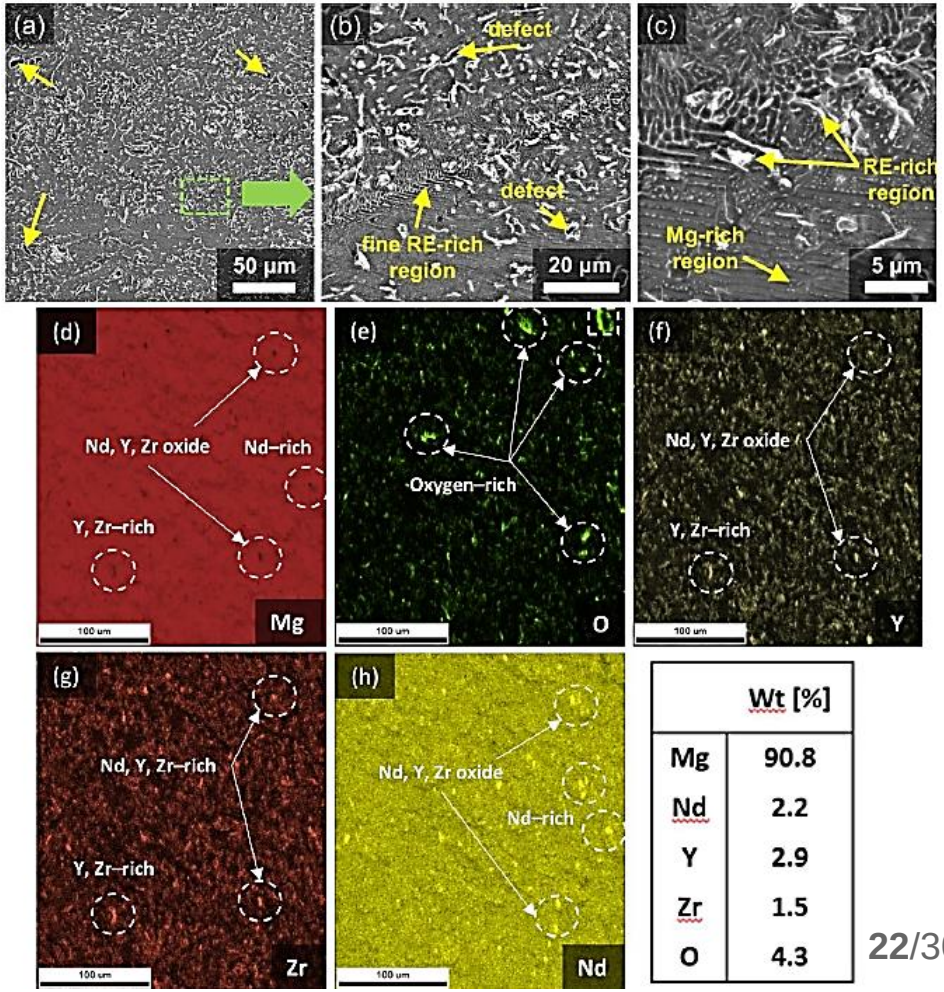


Results and discussion

Scientific question 2 1/2 Influence of process parameters

Major Findings

- No change in the microhardness
- No change in the distribution or chemical compositions of phases



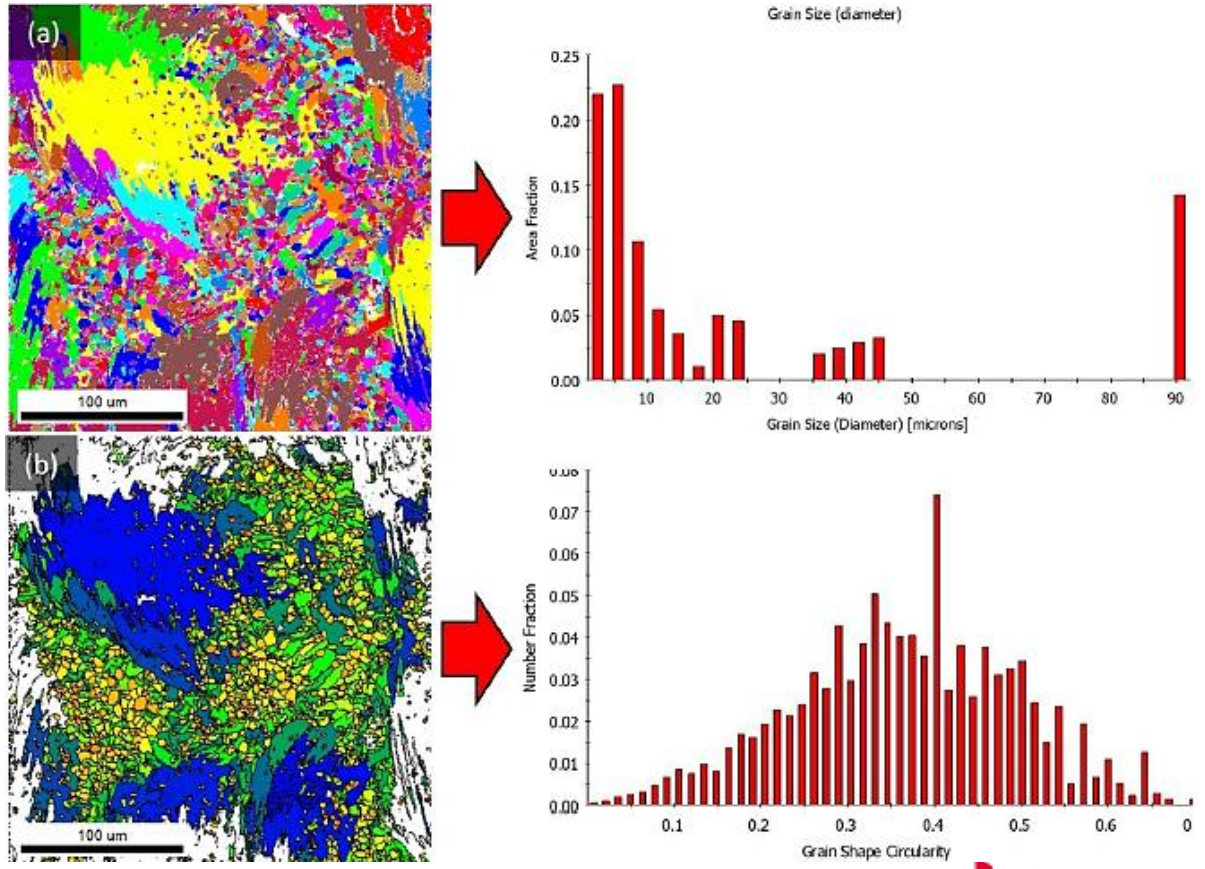
	Wt [%]
Mg	90.8
Nd	2.2
Y	2.9
Zr	1.5
O	4.3

Results and discussion

Scientific question 2 1/2 Influence of process parameters

Major Findings

- No change in the microhardness
- No change in the distribution or chemical compositions of phases
- No change in the shape or size of grains



Results and discussion

Scientific question 2 **1/2** **Influence of process parameters**

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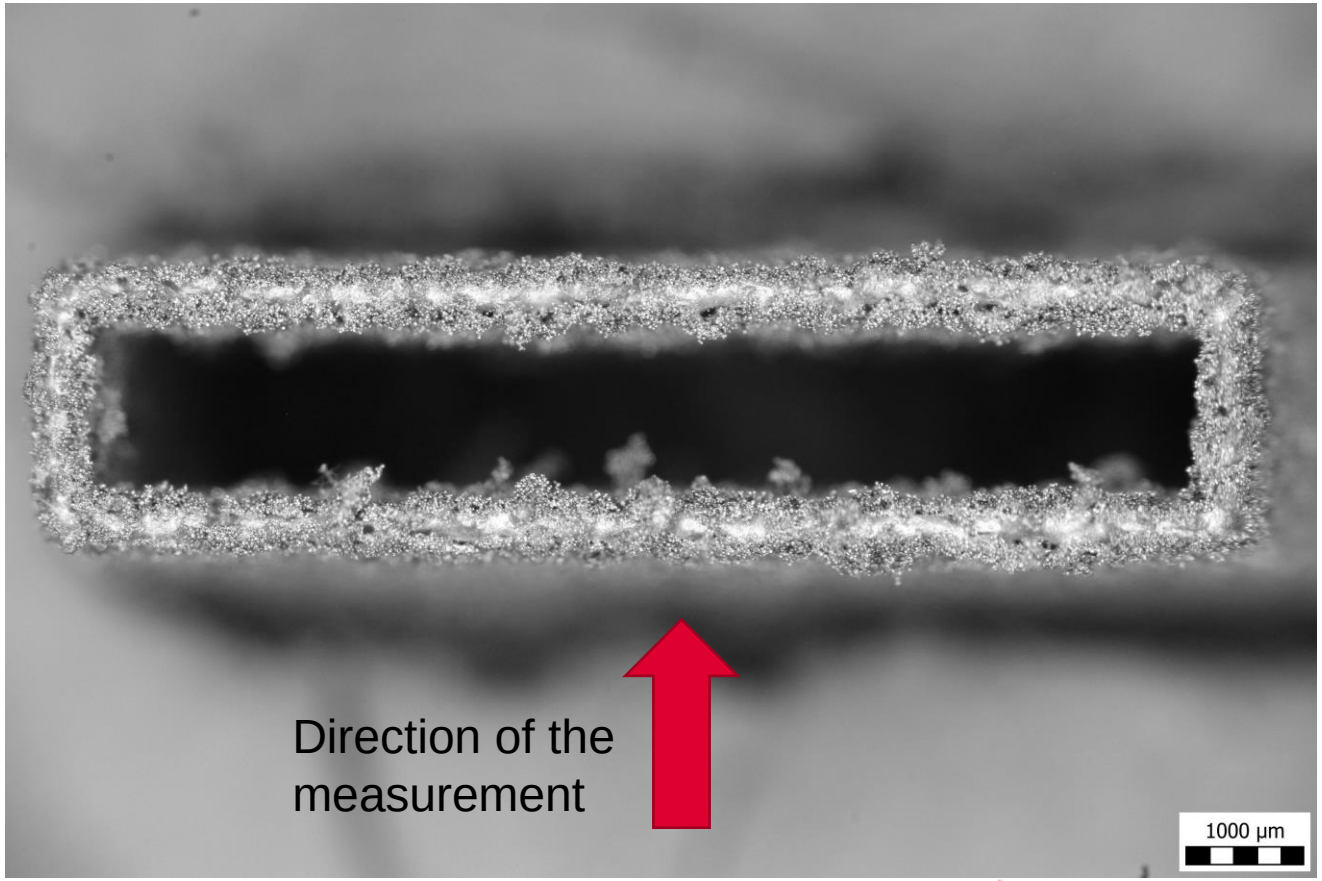
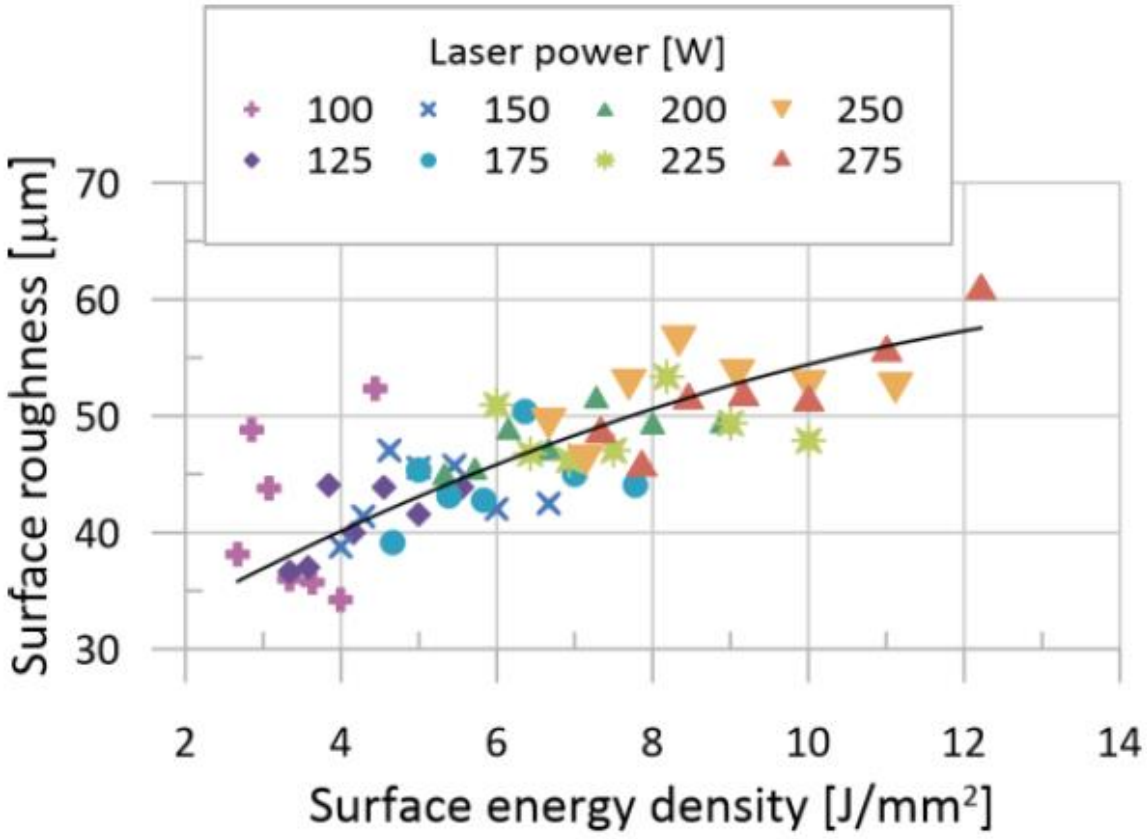


Results and discussion

Scientific question 2 1/2 Influence of process parameters

Major Findings

- No change in the microhardness
- No change in the distribution or chemical compositions of phases
- No change in the shape or size of grains
- The laser power has the biggest influence on the surface quality
- The value of Ra was changed up to 50 %



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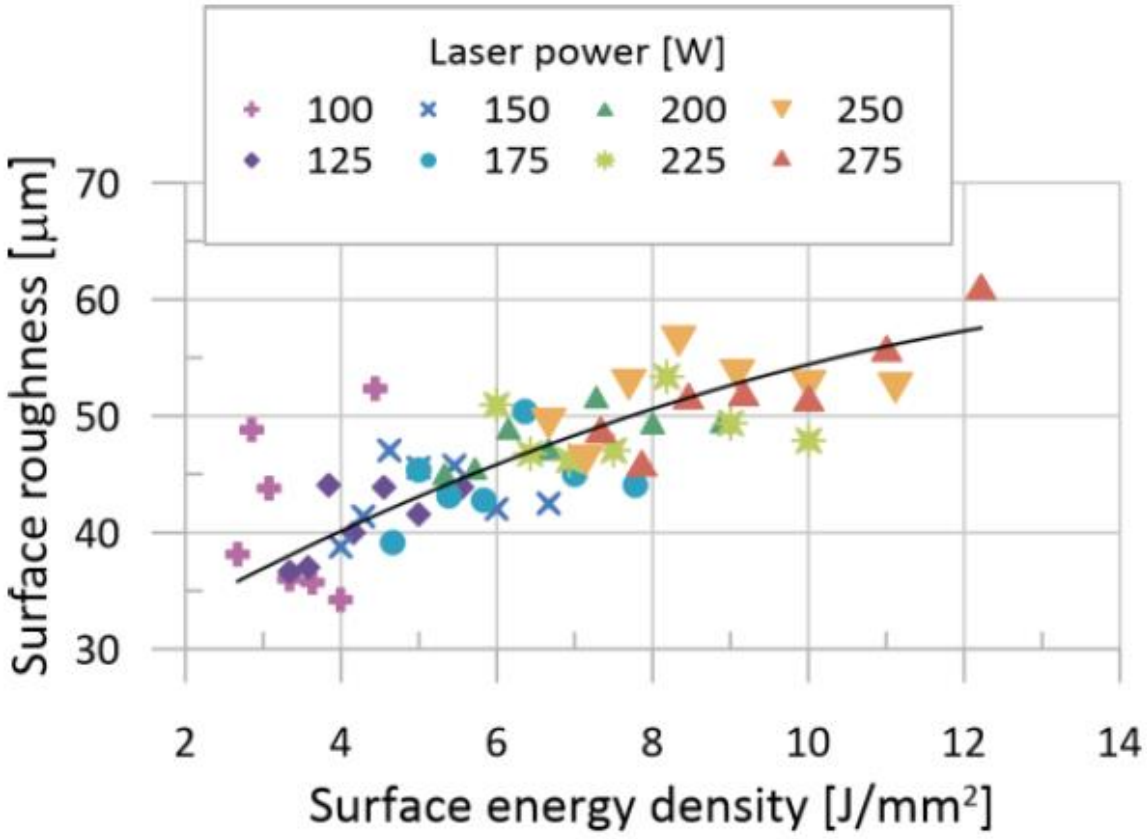


Summary

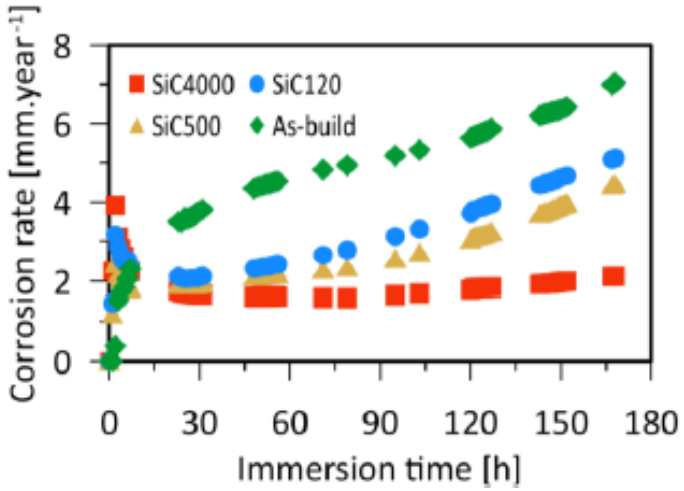
- The surface roughness can be significantly changed by process parameters in comparison to microstructure

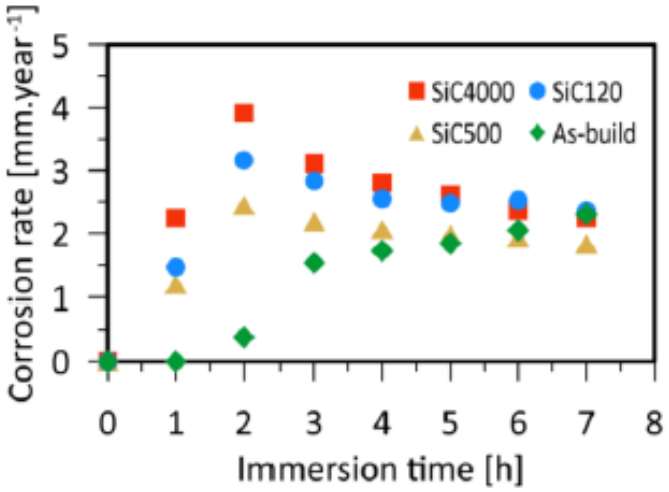
Results and discussion

Scientific question 2 2/2 Corrosion behavior

Major Findings

- Decrease of Ra from 51 to 34 led to an improvement in corrosion rate by 10 %
- The sintered powder removal can lead to reducing about 30 %





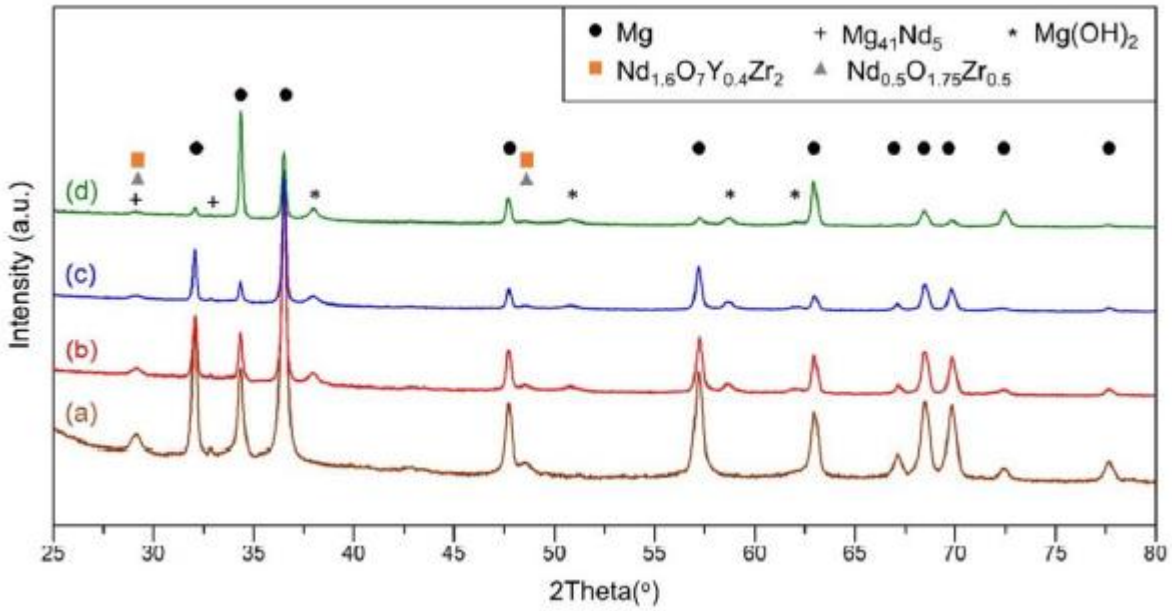
- As- build Ra 51.02 i_g= 7.04 mm·year^{-1}
- SiC120 Ra 3.84 i_g= 5.12 mm·year^{-1}
- SiC500 Ra 1.02 i_g= 4.48 mm·year^{-1}
- SiC4000 Ra 0.11 i_g= 2.11 mm·year^{-1}

Results and discussion

Scientific question 2 **2/2** **Corrosion behavior**

Major Findings

- Decrease of Ra from 51 to 34 led to an improvement in corrosion rate by 10 %
- The sintered powder removal can lead to reducing about 30 %
- Zr-rich phases were consumed really quickly



Results and discussion

Scientific question 2 — 2/2 — Corrosion behavior

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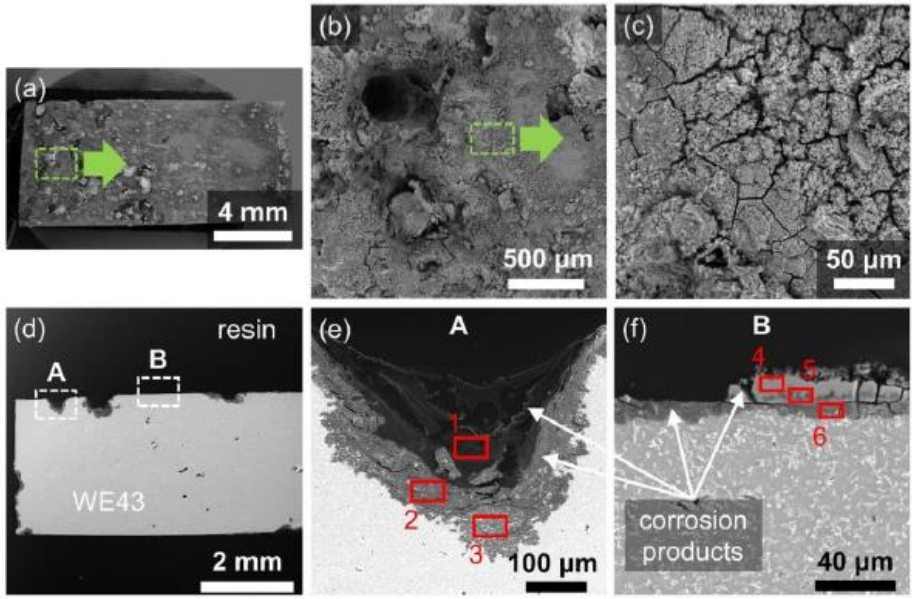


(g)

Position	Element (wt.%)								
	Mg	O	Y	Nd	Si	P	Cl	Na	Ca
1	47.8	45.1	-	-	1.2	1.0	4.4	-	0.5
2	46.0	50.5	2.3	1.2	-	-	-	-	
3	43.3	49.6	4.2	1.7	0.5	-	-	-	0.7
4	5.5	50.1	-	-	-	17.3	-	0.6	26.5
5	12.9	51.8	-	1.4	-	15.2	-	1.0	17.7
6	34.6	51.1	4.8	3.5	-	2.7	1.2	0.7	1.4

Summary

- The corrosion resistance of the printed material is possible significantly controlled by the process parameters like laser power or scanning speed

Results and discussion

Scientific question 2

Corrosion behavior

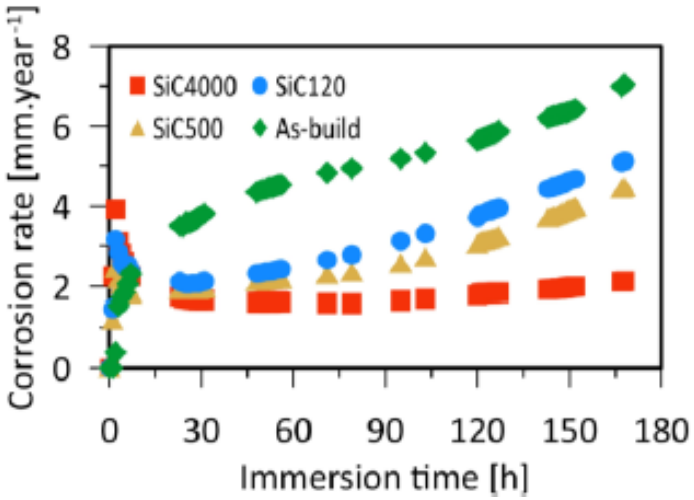
Scientific question

Is it possible to control the corrosion rate of the WE43 alloy processed by the SLM method by adjusting the process parameters?

Hypotheses

- Material properties can be changed by process parameters ✓
- Especially the surface roughness can be improved ✓
- It will have effect on the corrosion rate of the 3D printed material ✓

The hypothesis was confirmed



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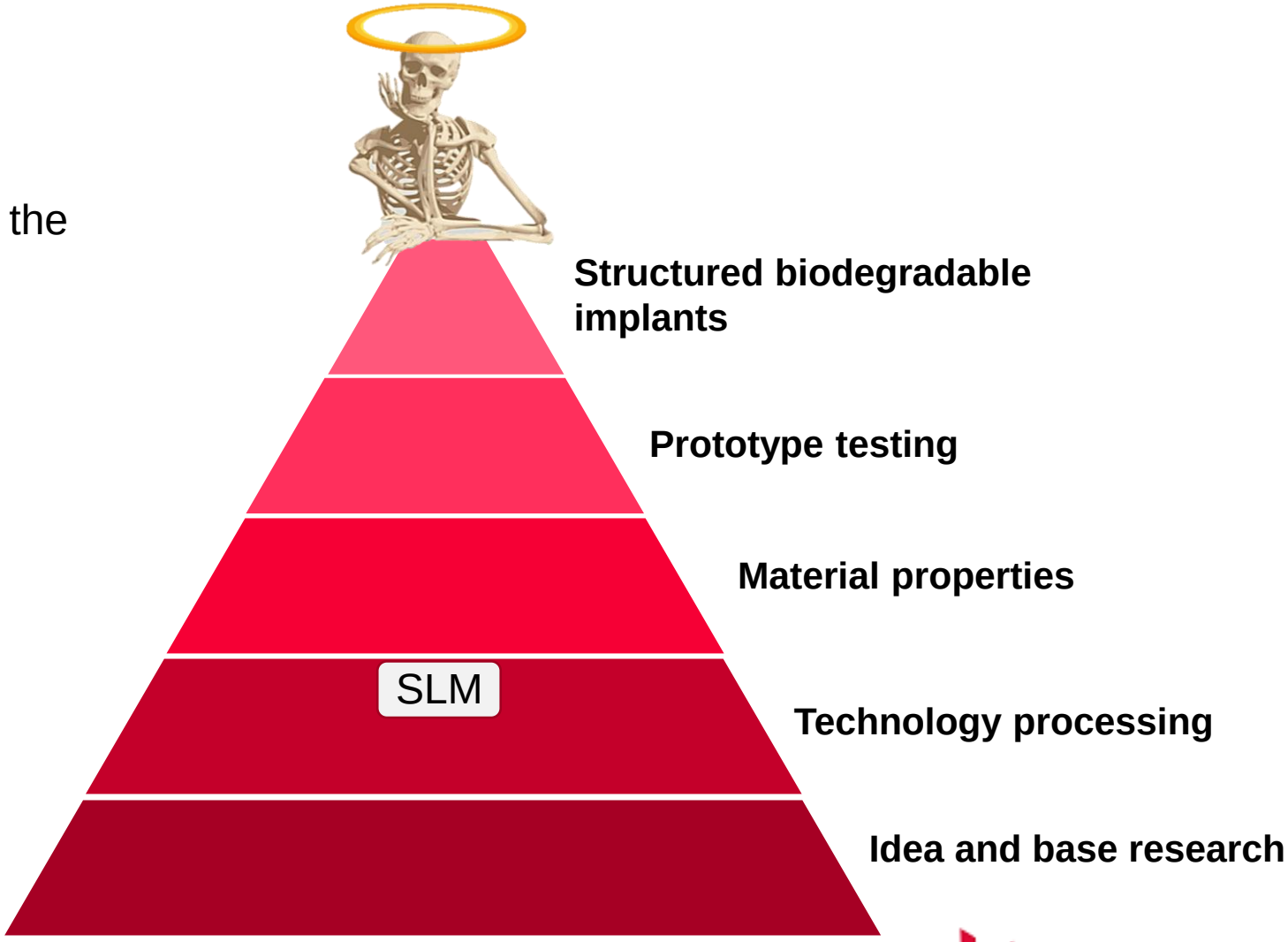
Summary

Main achievement

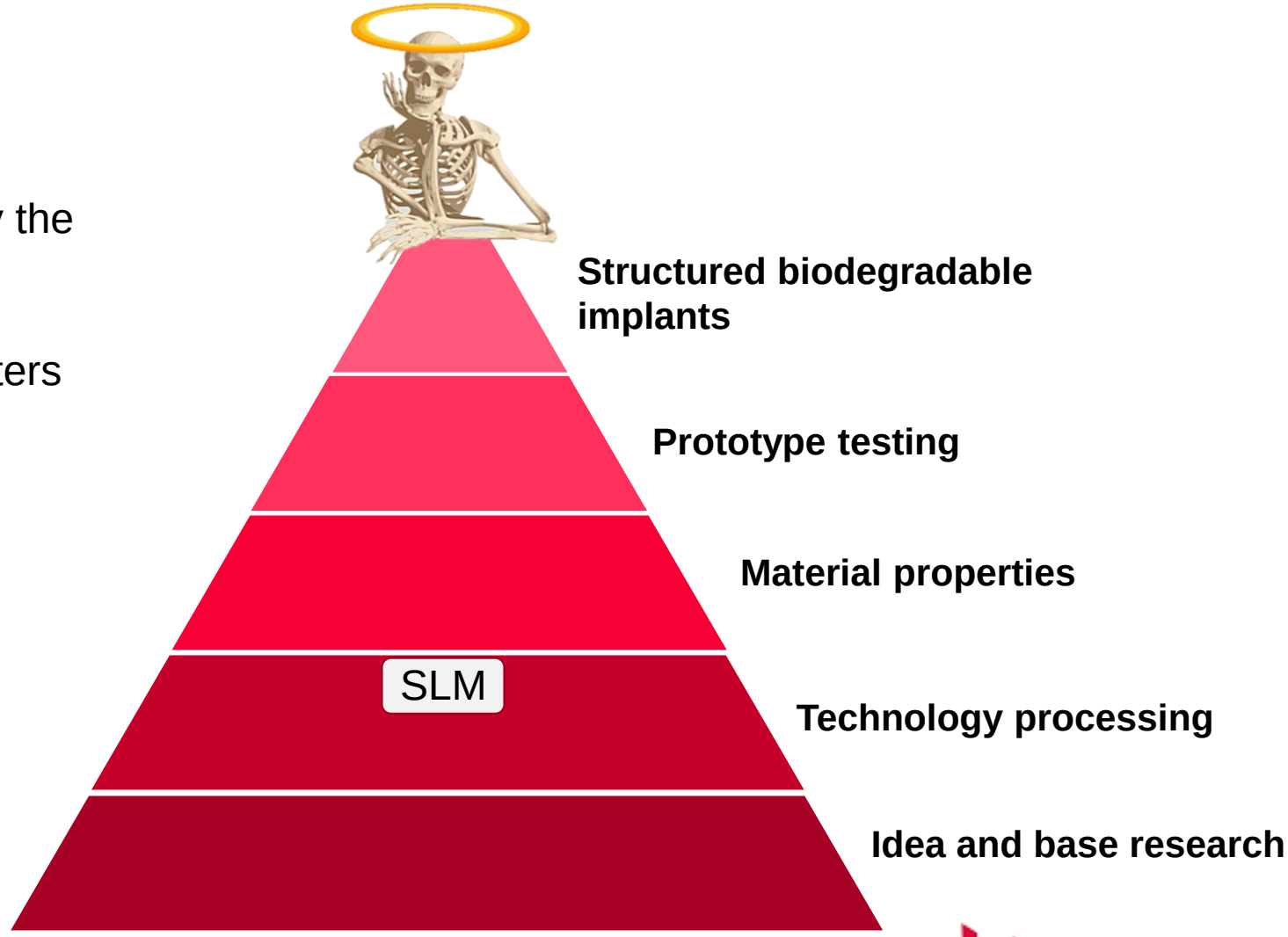
- Clarified the way how to process WE43 by the SLM method



Summary

Main achievement

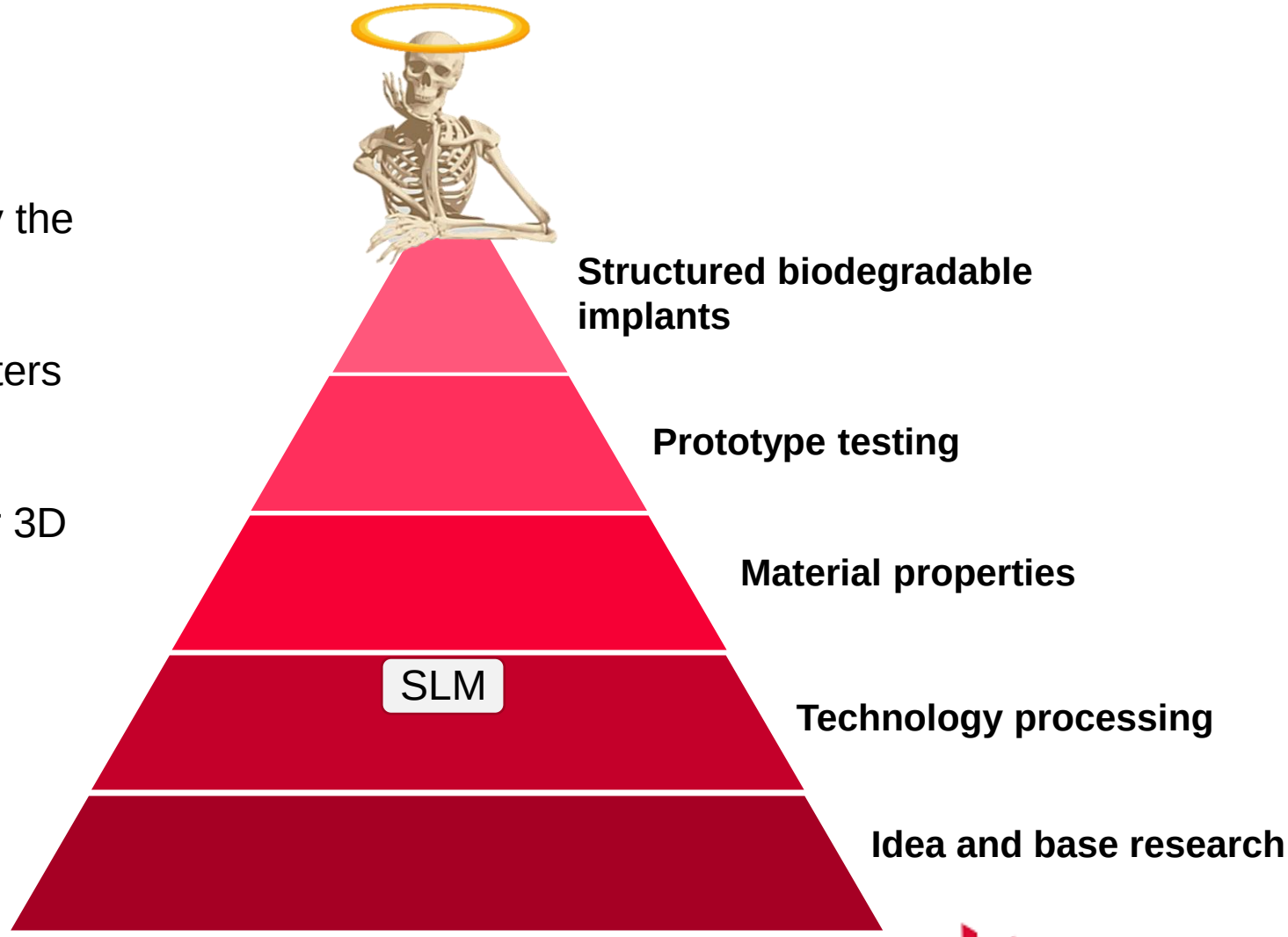
- Clarified the way how to process WE43 by the SLM method
- Describe the influence of process parameters on the printing process



Summary

Main achievement

- Clarified the way how to process WE43 by the SLM method
- Describe the influence of process parameters on the printing process
- Determining the value of corrosion rate for 3D printed material
- The corrosion resistance of 3D printed material was improved



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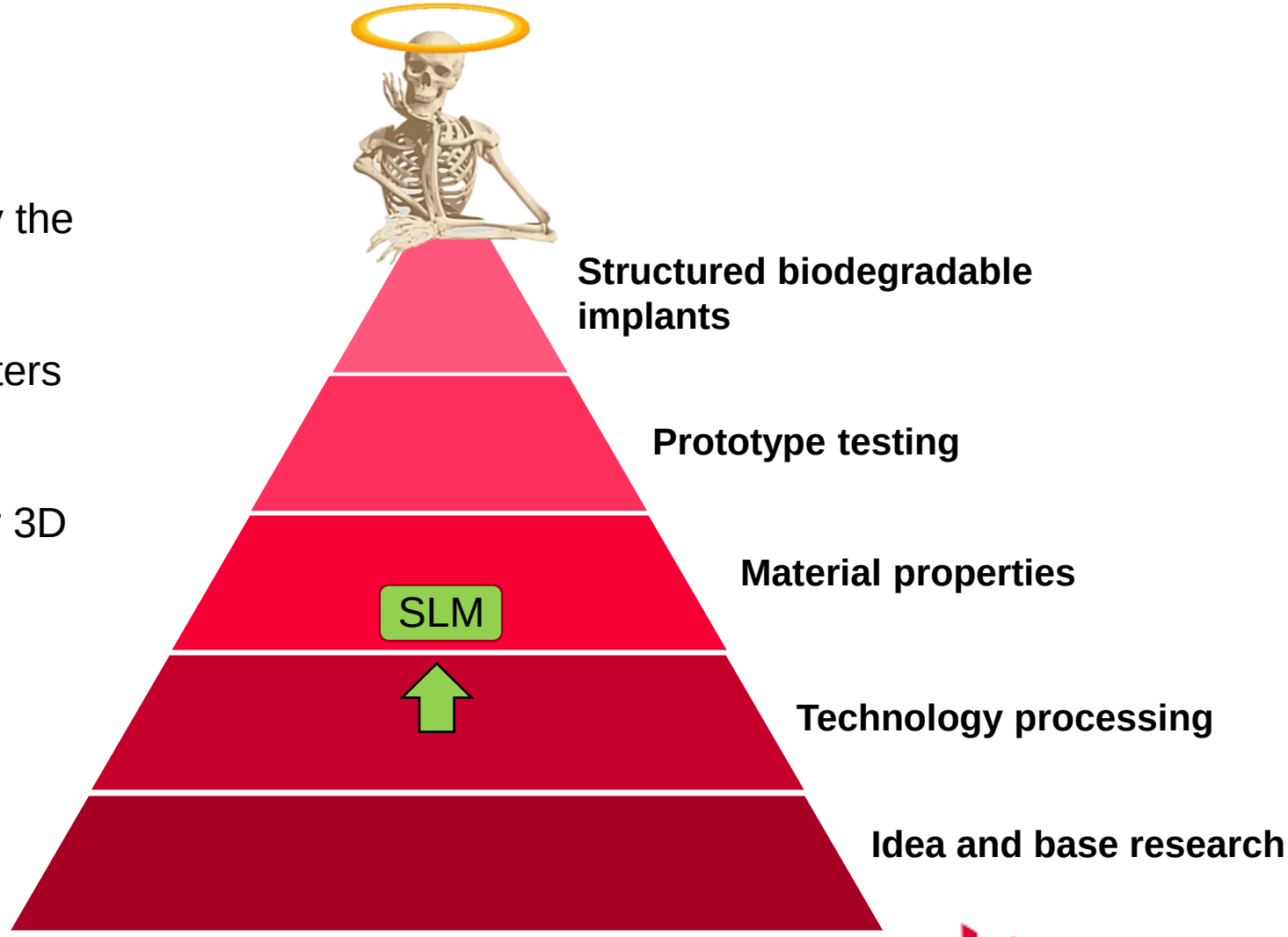

Summary

1. **SUCHY, Jan**, Miroslava HORYNOVÁ, Lenka KLAKURKOVÁ, David PALOUSEK, Daniel KOUTNY a Ladislav CELKO. Effect of laser parameters on processing of biodegradable magnesium alloy WE43 via selective laser melting method. Materials [online]. 2020, 13(11). ISSN 19961944. Dostupné z: doi:10.3390/ma13112623

2. **Jan Suchý**, Lenka Klakurková, Ondřej Man, Michaela Remešová, Miroslava Horynová, David Paloušek, Daniel Koutný, Patrícia Krištofová, Dalibor Vojtěch, Ladislav Čelko. Corrosion behaviour of WE43 magnesium alloy printed using selective laser melting in simulation body fluid solution, Journal of Manufacturing Processes, Volume 69, 2021, Pages 556-566, ISSN 1526-6125, https://doi.org/10.1016/j.jmapro.2021.08.006.

3. KRIŠTOFOVÁ, Patrícia, Michaela ROUDNICKÁ, Jiří KUBÁSEK, David PALOUŠEK, **Jan SUCHÝ** a Dalibor VOJTĚCH. Influence of Production Parameters on the Properties of 3D Printed Magnesium Alloy Mg-4Y-3RE-Zr (WE43). Manufacturing Technology [online]. 2019, 19, 613–618. Dostupné z: doi:10.21062/ujep/343.2019/a/1213-2489/MT/19/4/6013

4. KRIŠTOFOVÁ, Patrícia, Jiří KUBÁSEK, Michaela ROUDNICKÁ, Alena MICHALCOVÁ, **Jan SUCHÝ**, David PALOUŠEK a Dalibor VOJTĚCH. Structure and properties of additively manufactured WE43 magnesium alloy. In: 28th International conference on Metallurgy and Materials [online]. 2019, s. 1578–1582. Dostupné z: doi:10.37904/metal.2019.936

5. KRIŠTOFOVÁ, P.; KUBÁSEK, J.; VOJTĚCH, D.; PALOUŠEK, D.; **SUCHÝ, J.** Microstructure of the Mg-4Y-3RE-Zr (WE43) Magnesium Alloy Produced by 3D Printing. Manufacturing TECHNOLOGY, 2019, roč. 19., č. 1., s. 89-94. ISSN: 1213-2489.

6. Lovašiová, P.; Lovaši, T.; Kubásek, J.; Jablonská, E.; Msallamová, Š.; Michalcová, A.; Vojtěch, D.; **Suchý, J.**; Koutný, D.; Ghassan Hamed Alzubi, E. Biodegradable WE43 Magnesium Alloy Produced by Selective Laser Melting: Mechanical Properties, Corrosion Behavior, and In-Vitro Cytotoxicity. Metals 2022, 12, 469. https://doi.org/10.3390/met12030469

7. **SUCHY, Jan**, Libor PANTELEJEV, David PALOUSEK, Daniel KOUTNY a Jozef KAISER. Processing of AlSi9Cu3 alloy by selective laser melting. Powder Metallurgy [online]. 2020, 63(3), 197–211. ISSN 17430901. Dostupné z: doi:10.1080/00305899.2020.1792675

8. SKŘIVÁNKOVÁ, V.; VLAŠIC, F.; **SUCHÝ, J.**; PALOUŠEK, D.; MAZAL, P. STUDY OF FATIGUE LOADING OF THE SLM AND CAST MATERIAL BY ACOUSTIC EMISSION METHOD. In Metal 2018 - 27th Internation Conference on Metallurgy and Materials, Conference Proceedings. Ostrava-Zabreh: TANGER LTD., 2019. s. 1345-1350. ISBN: 9788087294840.

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