Me3DI

Fatigue Properties of 3D Printed Metals

- Project Metal 3D Innovations (Me3DI)– Forming industrial knowhow cluster of metallic 3D printing to South Karelia.

- Metallien 3D-tulostuksen ajankohtaisseminaari LUT-yliopisto 3.12.2019

Shahriar Afkhami

03.12.2019

ETELÄ-KARJALAN LIITTO

LUT Lappeenranta University of Technology

Programme for Sustainable Growth and Jobs

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Project Me3DI

General view of the project:

- Aim: forming an industrial knowhow cluster on 3D printing of metals throughout the South Karelia region to encourage and enhance the application of additive manufacturing of metals.
- Funding: The project is funded by European Regional Development Fund
- Resources: Required resources and equipment are provided by Lappeenranta-Lahti University of Technology (LUT).
- Schedule: The project has started in 01.09.2018 and is going to be finished by 31.12.2020.

Outcomes:

- Identifying the needs of local industries and companies.
- Enabling the designers to understand and recognize the advantages and limitations of 3D printing.
- Providing manufacturers and designers with inspirations to use additive manufacturing as case studies to evaluate its potential for design, optimization, and production.

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Project Me3DI

Our research at LUT:

- A collaboration between the *Laboratory of Steel Structures* and *Laboratory of Laser Materials Processing*.
- Aim: Analyze and evaluate the effective parameters on the microstructure and mechanical properties of additively manufactured metals.
- Scope of our research includes (but is not limited to):

    1- Microstructures

    2- Mechanical properties of metals under static loadings

    3- Mechanical properties of metals under cyclic loadings

    4- Fracture behaviour of metals

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Our research at LUT:

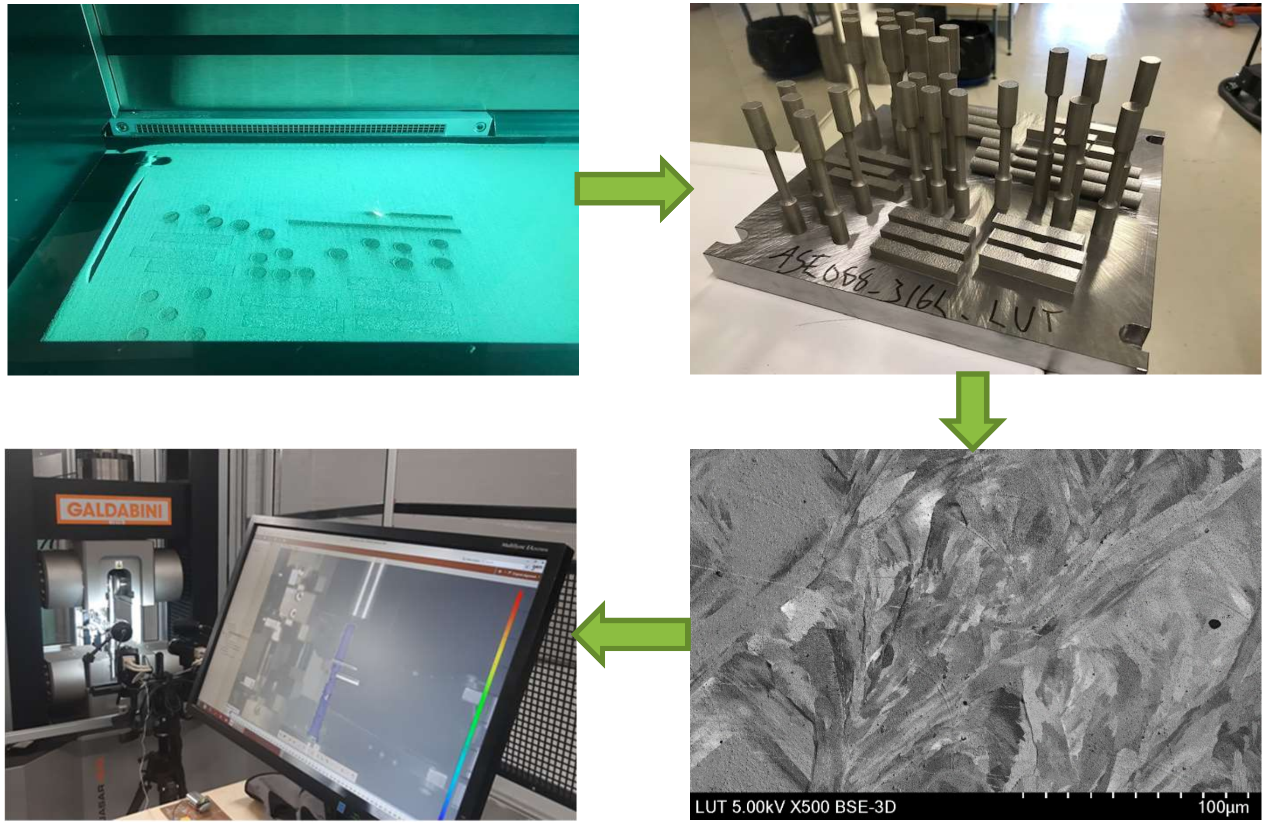

Fig.1. Workflow of the studies associated with 3D printing of metals as a collaboration between the two laboratories at LUT University[1].

[1]Courtesy of *Laboratory of Steel Structures* and *Laboratory of Laser Materials Processing*.

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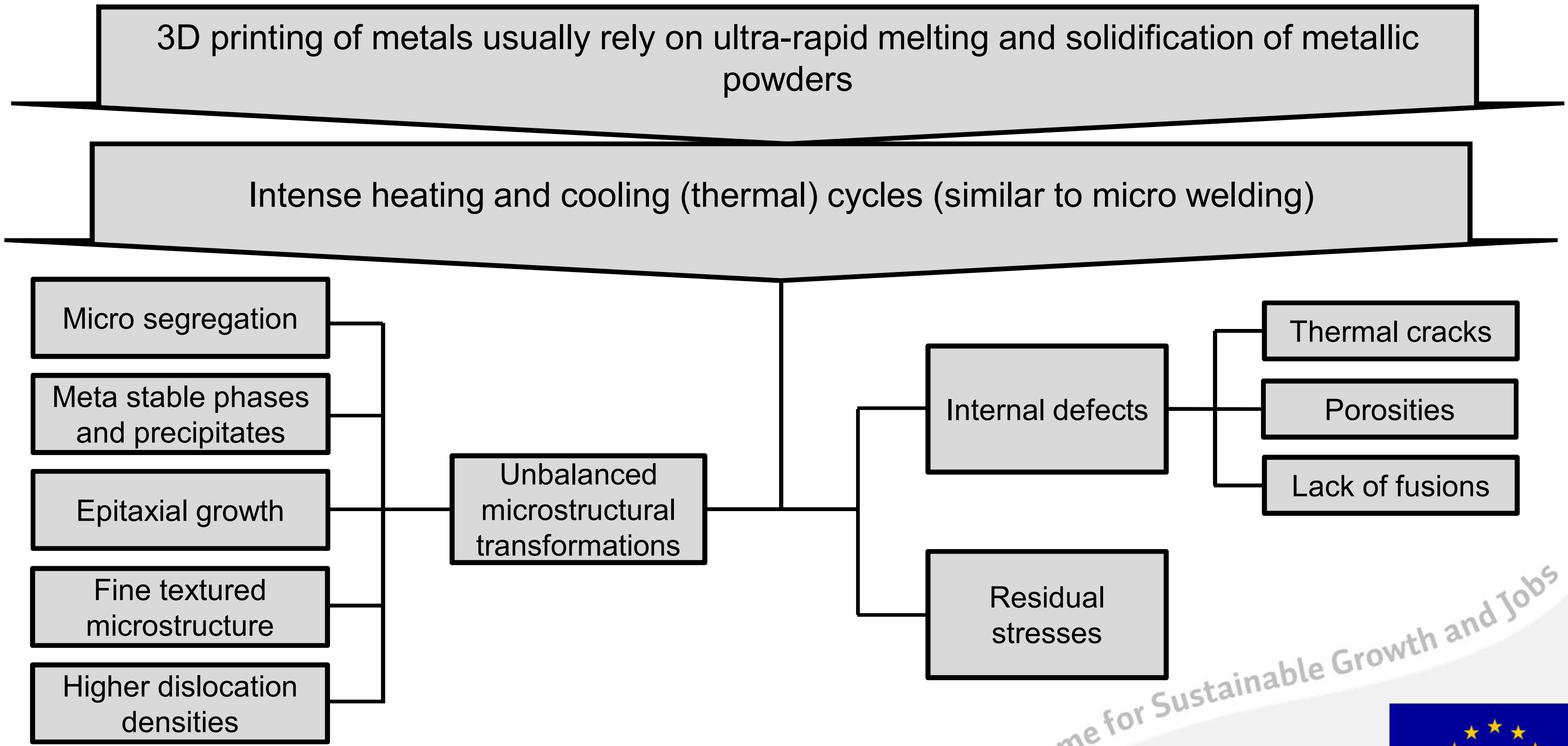
3D Printing and Metals

Why do we need to study additively manufactured metals while we already know the properties of their wrought, cast, or rolled counterparts?



3D Printing and Metals

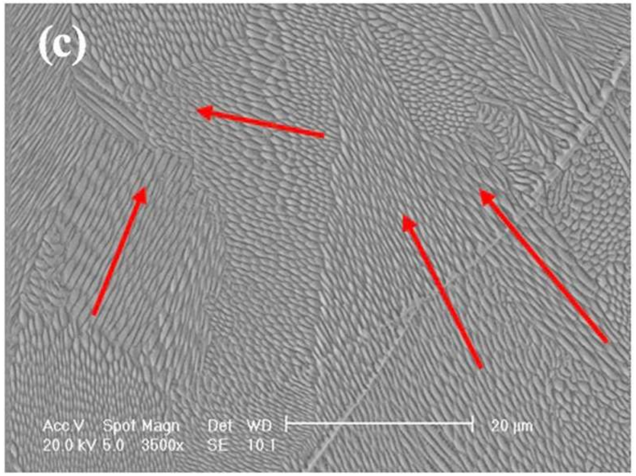


Fig.2. Ultra-fine microstructure of stainless steel 316L processed by 3D printing (Qiu et al. ,2018).

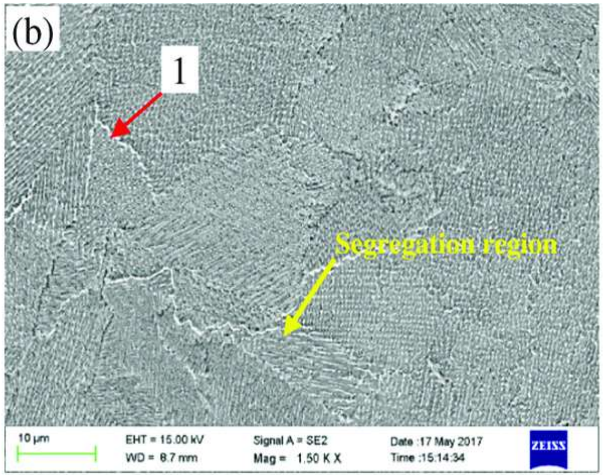


Fig.3. Formation of a segregated region in as as-built Inconel 718 processed by 3D printing (Liu et al., 2018).

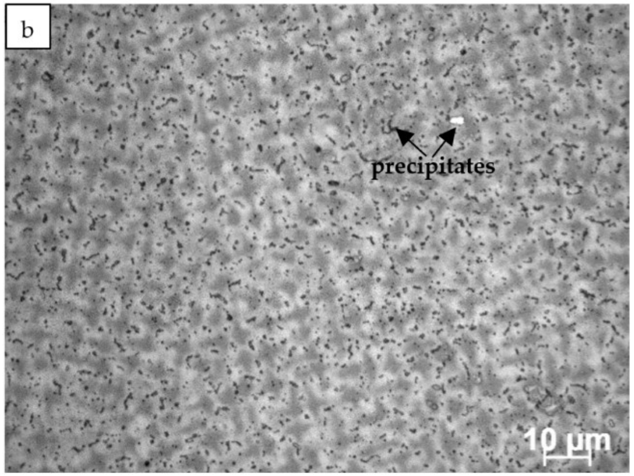


Fig.4. Nb-rich precipitates in the microstructure of Inconel 625 processed by 3D printing (Dubiel & Sieniawski, 2019)

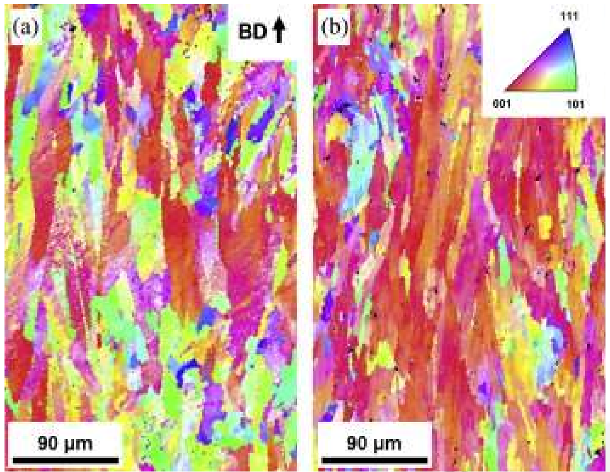


Fig.5. Directional solidification and microstructure of 3D printed 316L (a) as-built (b) annealed at 650°C. (Afkhami et al., 2019; reprint from Riemer et al., 2014).

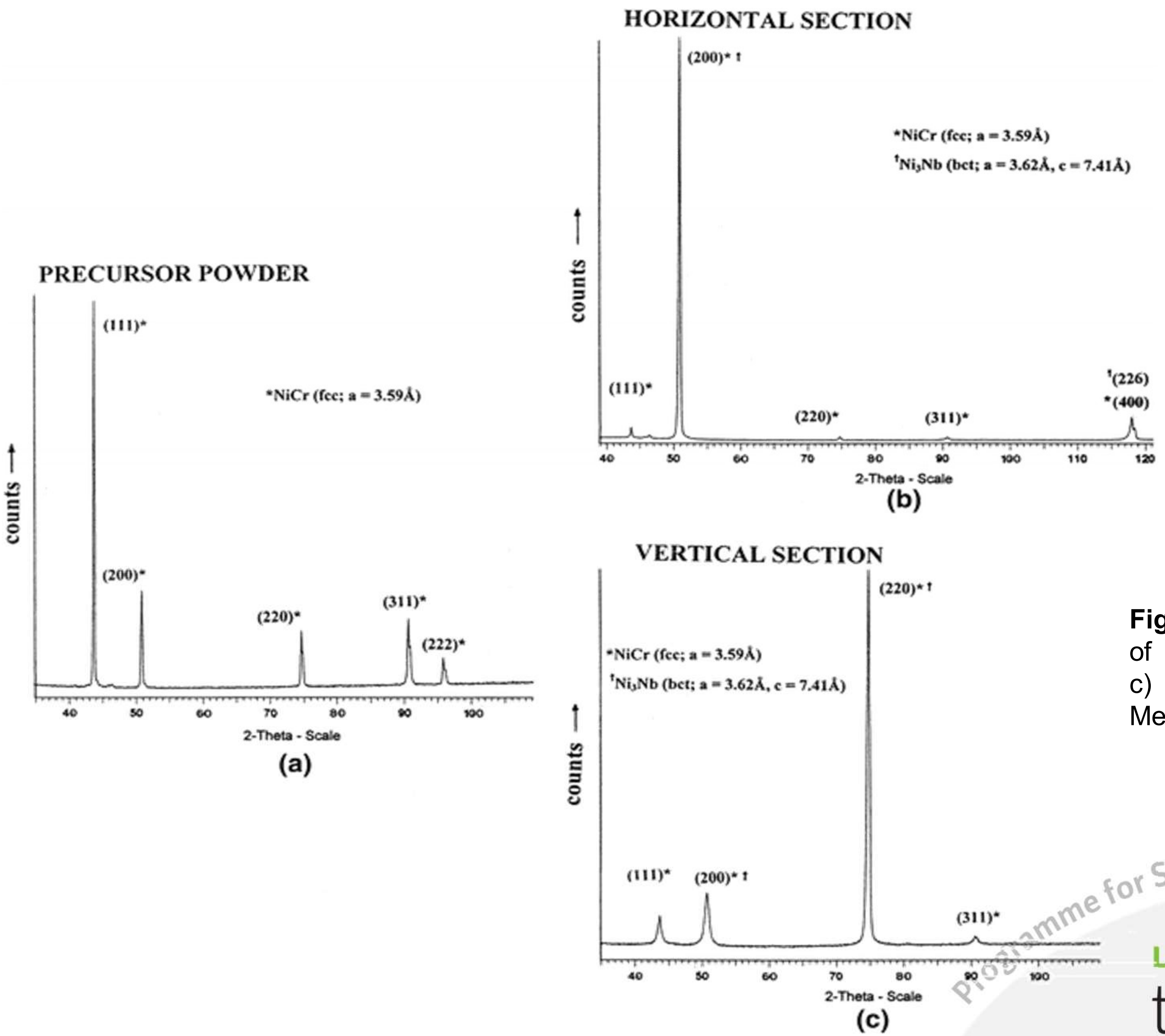


Figure 6. XRD spectroscopy results of Inconel 625 (a) raw powder (b & c) processed by Electron Beam Melting (Murr et al., 2011).

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3D Printing and Metals

Hardness and Tensile Strength:

Fine-textured microstructure
+
Higher dislocation densities and microstructural defects
+
Precipitations associated with 3D printing thermal cycles

- Acceptable Hardness values
- Acceptable yield and tensile strength

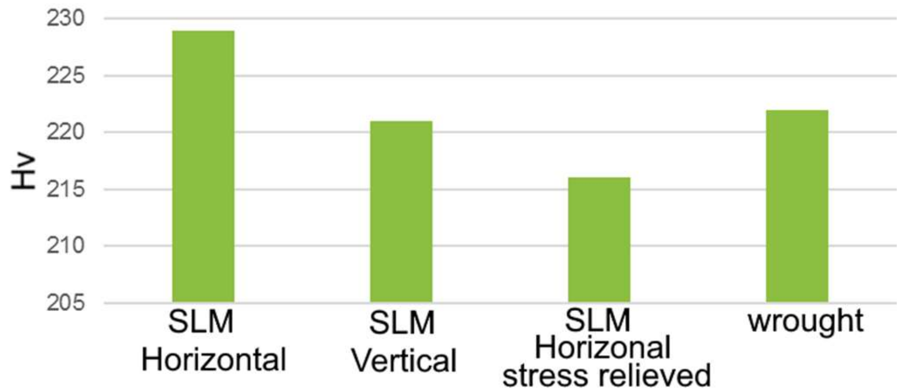

Figure 7. Hardness values of stainless steel 316L processed via different techniques (data from Kurzynowski et al. (2018) and Azom).

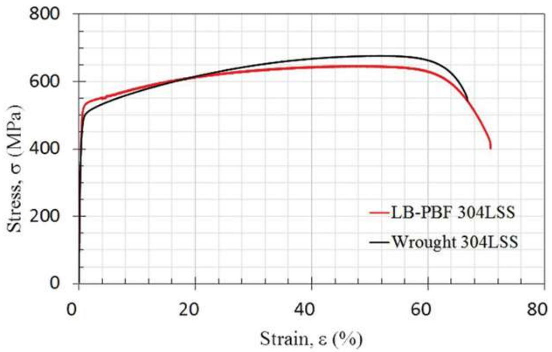

Figure 8. Stress-Strain curve of 3D printed 304L stainless steel against the quasi-static tensile behaviour of its wrought counter part (Pegues, Roach & Shamsaei, 2019).

3D Printing and Metals

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Hardness and Tensile Strength:

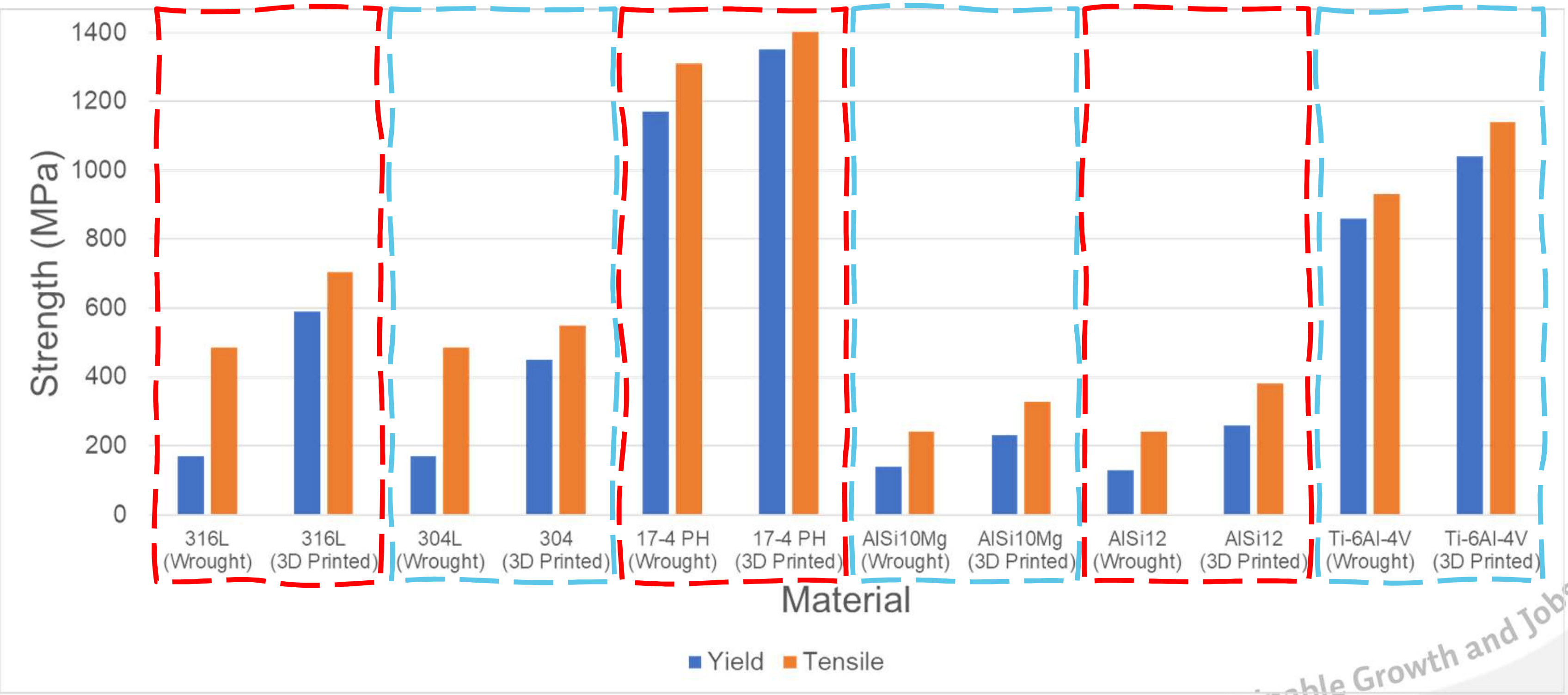

Figure 9. Yield and tensile strength of metals processed by 3D printing in comparison to their conventionally manufactured counterparts (data from Herzog et al., 2016).

3D Printing and Metals

Fatigue strength:

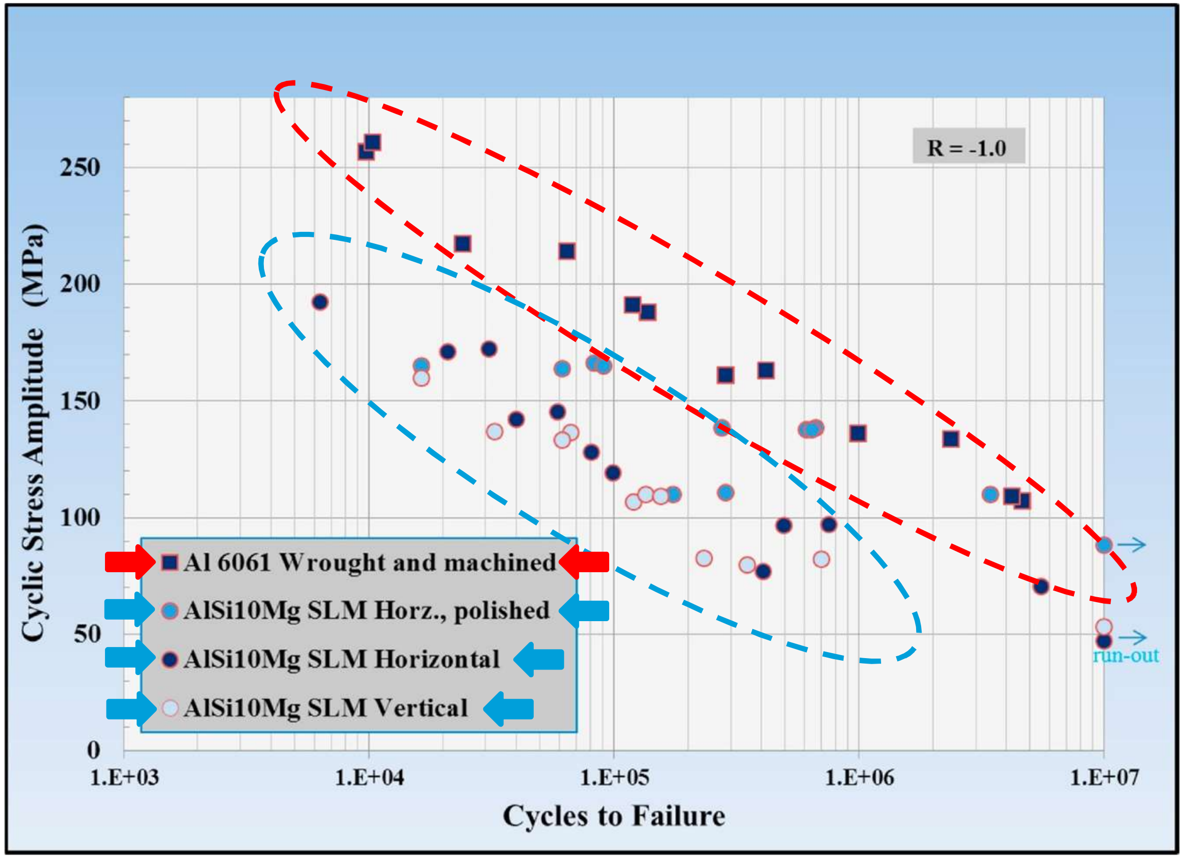

Fig. 10. Fatigue strength of Aluminum alloy AlSi10Mg processed by 3D printing in comparison to its conventionally manufactured counterpart, Al 6062 (data from Mower & Long, 2016).

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Fatigue performance of 3D printed metals

Regardless of their good quasi-static strength and hardness values, Fatigue strength of 3D printed metals is usually inferior to their conventionally manufactured counter parts! but, why?

In fatigue tests and cyclic loadings:

metals go through repetitive loads with smaller stress values, in comparison to quasi-static tests.

Most of the materials' deformations belong to elastic strains, and plastic deformations are small.

- Microstructural inhomogeneities
- Defects

are more prominent as stress risers

- Residual stresses → can have stress values closer to ,or sometimes even higher than, applied stresses.

Fatigue performance of 3D printed metals

3D printing of metals is inevitably accompanied with:

- Intense thermal cycles
- Rapid solidifications
- Processing a powder material

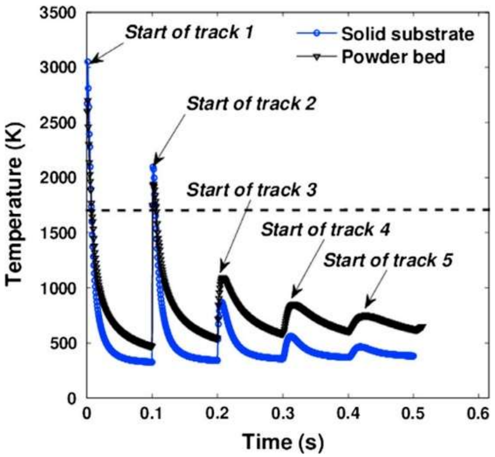


Fig. 11. Simulated thermal cycles and gradients from 3D printing of 316L metal powder processed by a 100 W laser and 100 mm/s scanning speed (Afkhami et al. 2019; reprint from Hussein et al. 2013).

Under cyclic loading, behavior of a 3D printed metal is more governed by:

- Residual stresses
- Microstructural inhomogeneities
- Defects
- Non-equilibrium phases
- Directionality of the microstructure
- Relatively rough surface

Fatigue performance of 3D printed metals

Common applications of 3D printed metals:

- Medical
- Automobile
- Aeronautics
- Aerospace
- Maritime

Cyclic loading

!!! The reliability of the final product depends on its fatigue performance. !!!

Conclusions so far:

- We must know the fatigue performance of our 3D printed metal to evaluate its reliability.
- We cannot use available fatigue data from conventionally manufactured metals.

Important questions:

- How many cycles?
- Is it better, as good as, or worse than its conventionally manufactured counterpart?
- How to improve its performance?
- What are the most effective parameters on the fatigue performance?

Most effective parameters on the fatigue performance of 3D printed metals

- Heat input
- Building direction
- Surface finish
- Heat treatment

$$\textit{Volumetric energy density} = \frac{P}{v \times s \times l}$$

$$\textit{Volumetric energy density} = \frac{P}{v \times d \times l}$$

P : Laser power
v : Scanning speed
d : Spot size
s : Hatch spacing
l : Layer thickness

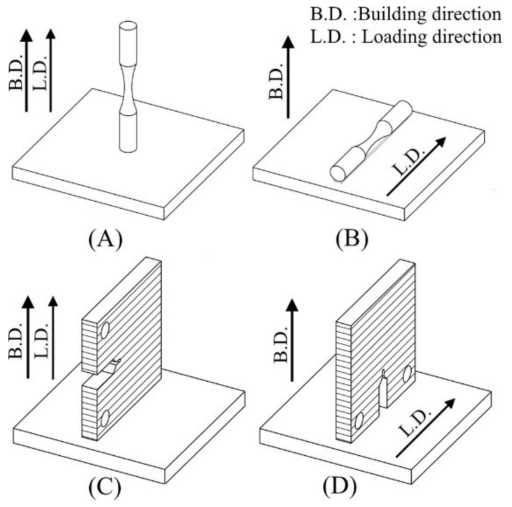


Fig. 12. Different building orientations which are usually used in 3D printnig of metal samples (Afkhami et al., 2019)

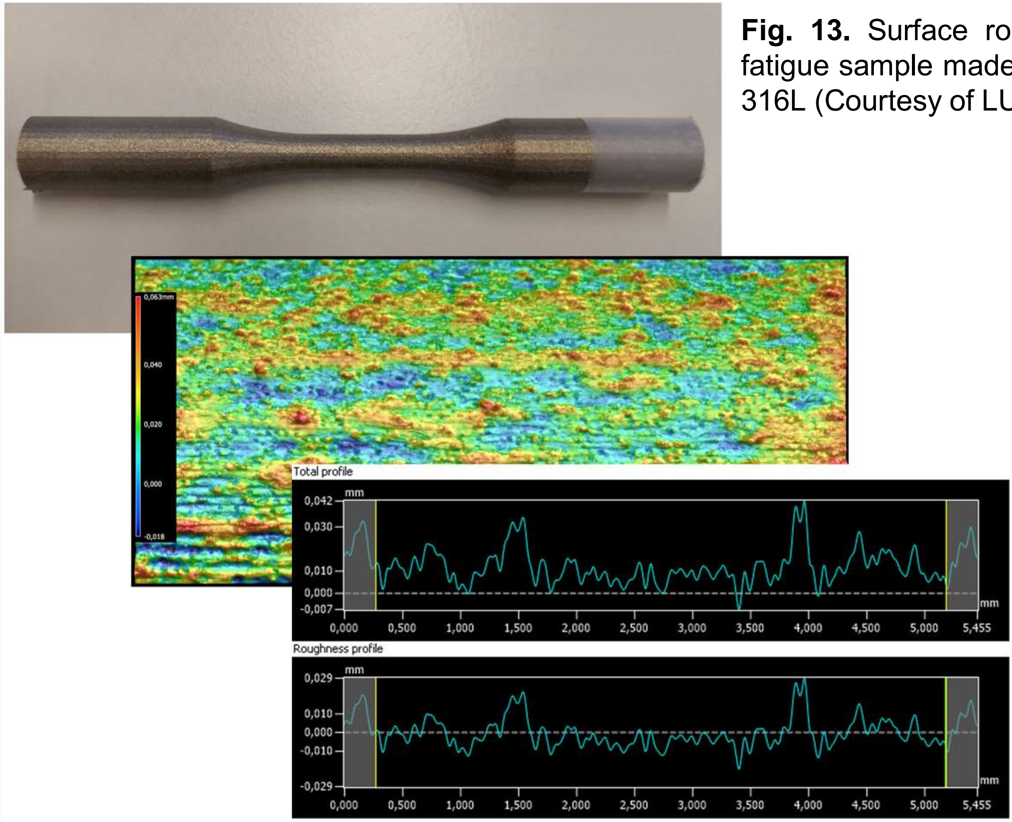


Fig. 13. Surface roughness of a fatigue sample made of 3D printed 316L (Courtesy of LUT University).

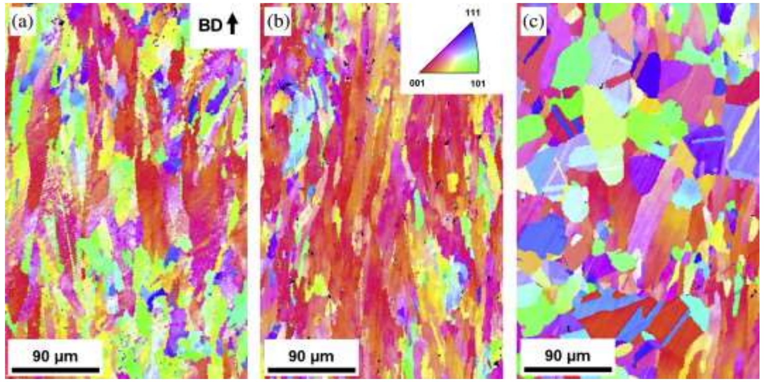
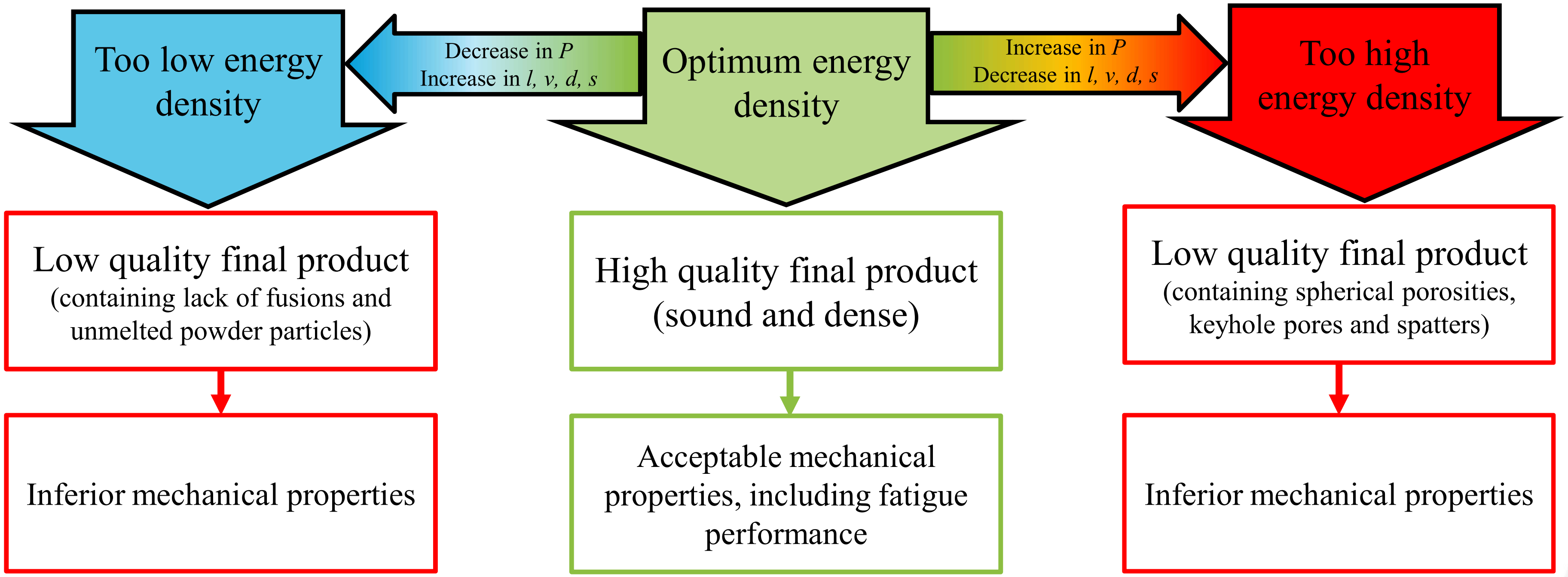


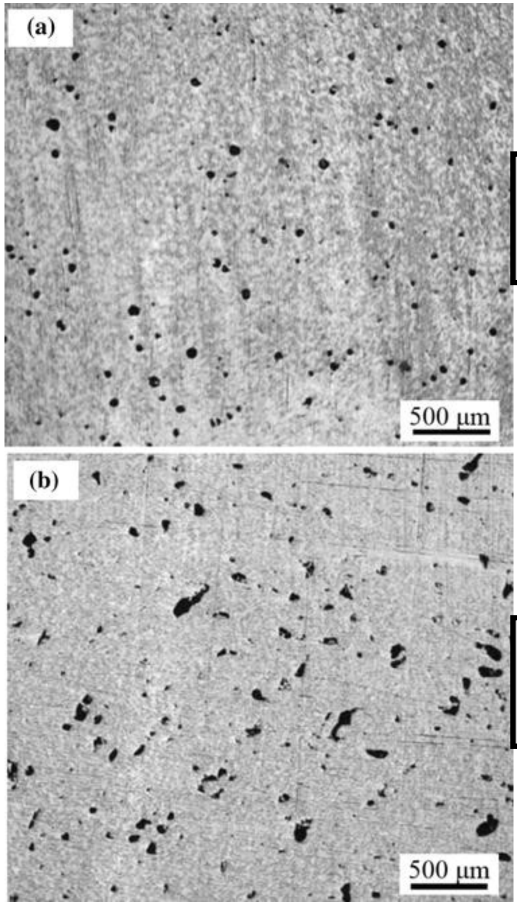
Fig.14. Microstructural evolution of 3D printed stainless steel 316L: (a) as-built; (b) annealed; (c) HIPed (Afkhami et al., 2019; reprint from Riemer et al., 2014)

Heat input:



Too low energy density
Decrease in *P*
Increase in *l, v, d, s*
Optimum energy density
Increase in *P*
Decrease in *l, v, d, s*
Too high energy density
Low quality final product
(containing lack of fusions and unmelted powder particles)
High quality final product (sound and dense)
Low quality final product
(containing spherical porosities, keyhole pores and spatters)
Inferior mechanical properties
Acceptable mechanical properties, including fatigue performance
Inferior mechanical properties

Heat input:



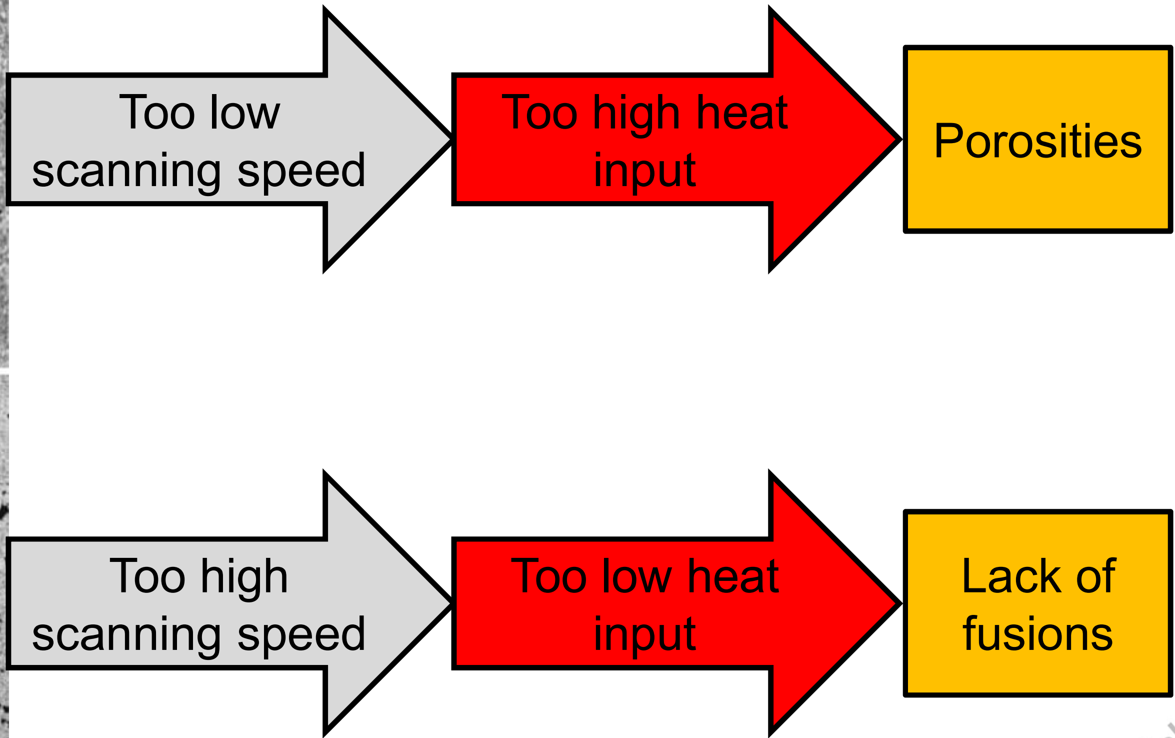
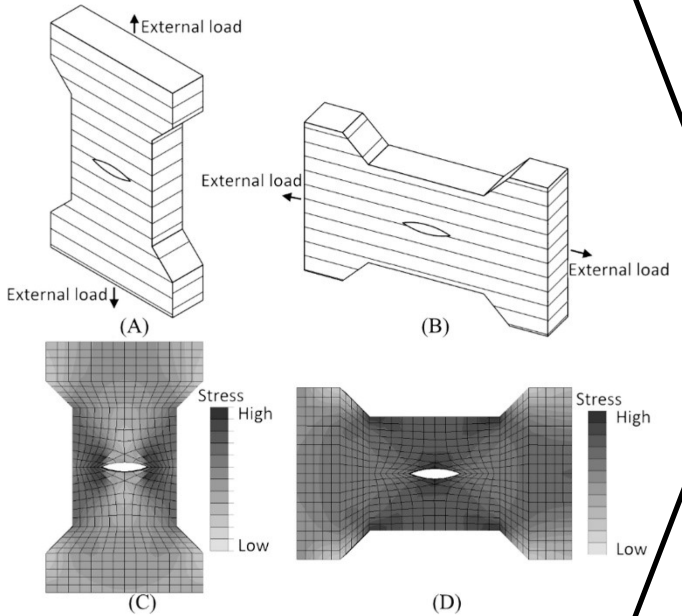


Fig. 15. 3D printed Ti6Al4V samples with (a) 120 W laser and 40 mm/s scanning speed; (b) 120 W laser and 1500 mm/s scanning speed (Zhang et al., 2017).

Built orientation:

Build orientation defines the alignment of defects and weak links against the loading direction

This factor determines the degrees of stress concentrations on the weak spots.



!!! Different fatigue endurances along different directions !!!

Fig. 16. Effects of the building orientations on the stress field and concentration around a planar defect for SLM specimens (Afkhami et al., 2019)

Built orientation:

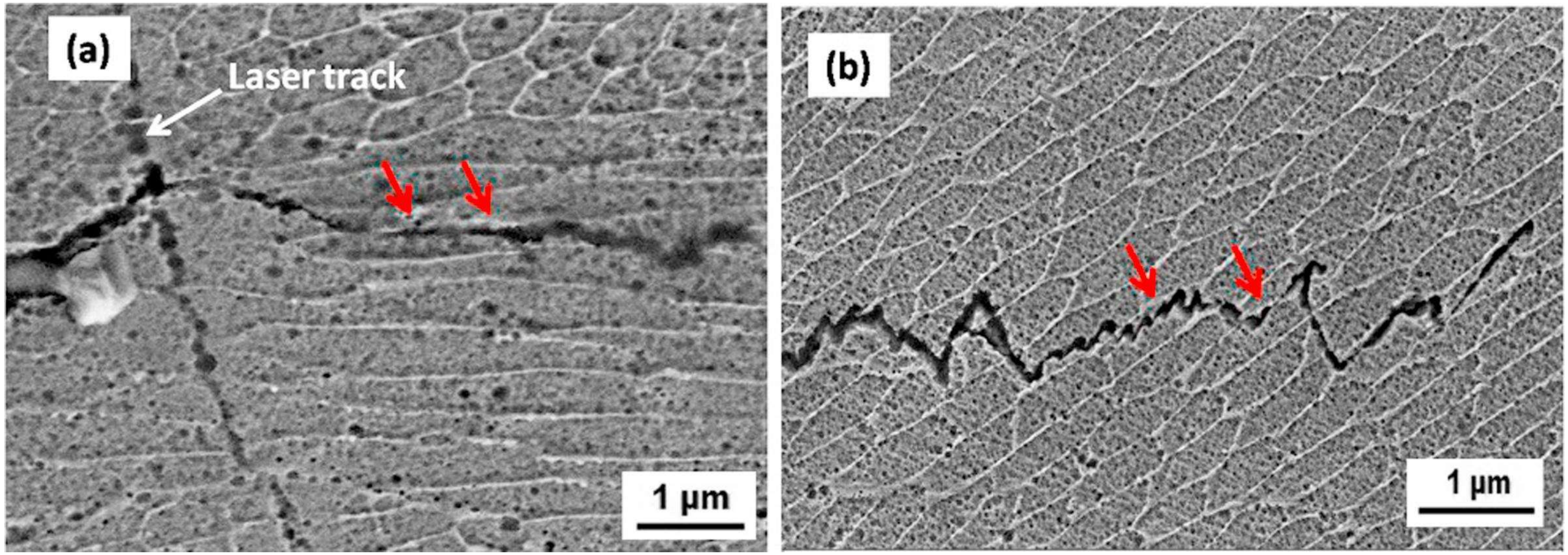


Fig. 17. Interaction between a propagating crack and microstructure in a (a) horizontally made 316L sample; and (b) vertically made 316L sample (Afkhami et al. 2019; reprint from Suryawanshi et al. 2017).

Surface finish:

! In comparison metals processed by subtractive techniques, 3D printed metals have rougher surfaces:

- layer-by-layer deposition mechanism intrinsically yield in a rougher surface
- Application of metal powders as the required raw material
- Staircase effect
- Partially melted particles

!! Surface quality can be improved by:

- Machining
- Polishing
- Surface mechanical treatments (e.g. shot peening, or high frequency mechanical impact (HFMI) treatment)

Surface finish:

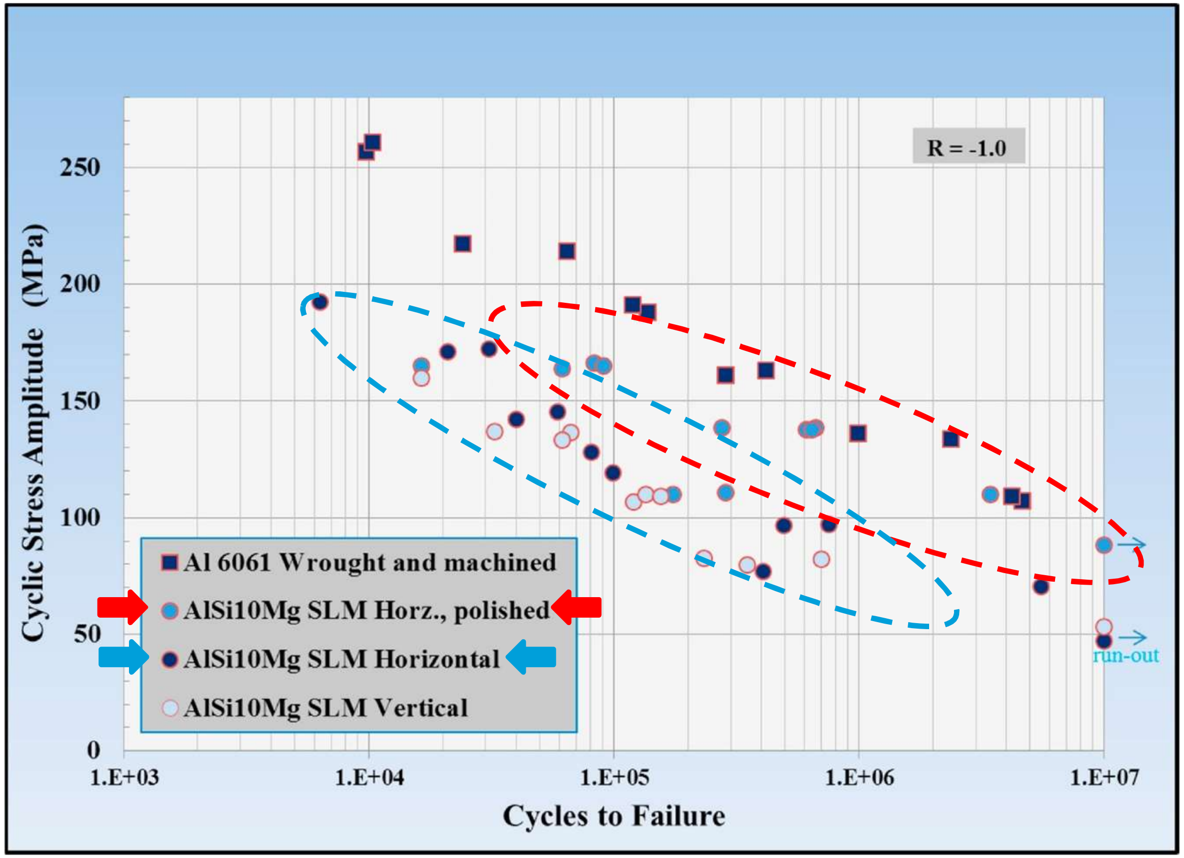


Fig. 10 (from slide No. 9). Fatigue strength of Aluminum alloy AlSi10Mg processed by 3D printing in comparison to its conventionally manufactured counter part, Al 6062 (data from Mower & Long, 2016).

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Heat treatment:

Common heat treatments for 3D printed metals:

- Stress relieving
- Annealing
- Hot isostatic pressing
- Aging

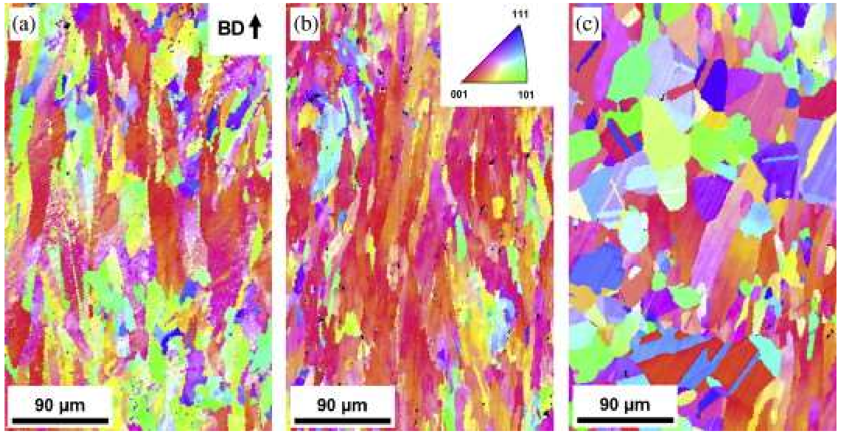

Fig.14 (from slide No. 13). Microstructural evolution of 3D printed stainless steel 316L: (a) as-built; (b) annealed; (c) HIPed (Afkhami et al., 2019 reprint from Riemer et al., 2014)

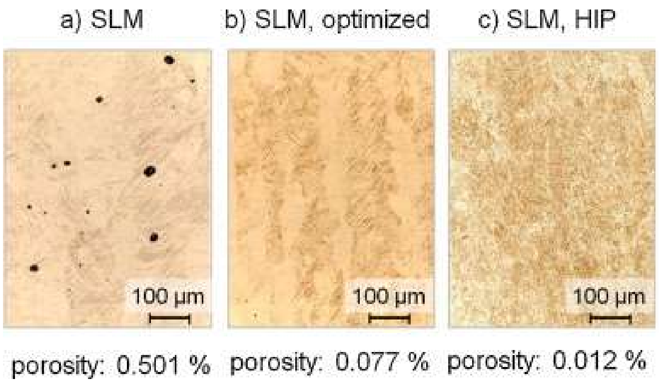

Fig.18. Defect optimization of 3D printed Ti6Al4V: (a) as-built; (b) optimized heat input; (c) processed by HIP (Afkhami et al. 2019b, reprint from Kasperovich & Hausmann, 2015).

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Conclusions:

Table 1. Comparison of the fatigue performance of PBF metals with different building condition (Afkhami et al., 2019b).

Type of PBF metal	Approximate Fatigue limit before processing (Mpa)	Approximate fatigue limit after processing (MPa)	Stress ratio	Type of the processing
Ti6Al4V	200	500	0.1	Polishing
AlSi10Mg	50	90	0.1	Heat treated
316L	200	269	0.1	Polishing
Ti6Al4V	200	500	-1	HIP (at 920 ºC)
Ti6Al4V	300	450	-1	HIP (at 1050 ºC)
17-4 PH	200 (built vertically)	400 (built horizontally)	-1	Building orientation

Bibliography

1- Qiu, C.; Kindi, M., A.; Aladawi, A., S. & Hatmi, I., A.; 2018, "A comprehensive study on microstructure and tensile behaviour of a selectively laser melted stainless steel", Scientific Reports, 8, 7785 (Open access).

2- Dubiel, B. & Sieniawski, J.; 2019, "Precipitates in Additively Manufactured Inconel 625 Superalloy", Metals, Vol. 12, 7, pp. 1-11 (Open access).

3- Liu, P.; Sun, S.; Cao, M.; Gong, J. & Hu, J.; 2018, "Microstructural Evolution and Phase Transformation on the X-Y Surface of Inconel 718 Ni-Based Alloys Fabricated by Selective Laser Melting under Different Heat Treatment", High Temperature Materials and Processes, Vol. 28, pp. 229-236 (Open access).

4- Afkhami, S.; Dabiri, M.; Alavi, S., H.; Björk, T. & Salminen, A.; 2019, "Fatigue characteristics of steels manufactured by selective laser melting", International Journal of Fatigue, 122, pp. 72-83 (Open access).

5- Murr, L., E.; Martinez, E.; Gaytan, S., M.; Ramirez, D., A.; Machado, B., I.; Shindo, P., W.; Martinez, J., L.; Medina, F.; Wooten, J.; Ciscel, D.; Ackelid, U.; 2011, "Microstructural architecture, microstructures, and mechanical properties for a nickel-base superalloy fabricated by electron beam melting", Metallurgical and Materials Transactions A, Vol. 42, 11, pp. 3491-508 (Open access).

6- Pegues, W.; Roach, M., D. & Shamsaei, N.; 2019, "Additive manufacturing of fatigue resistant austenitic stainless steels by understanding process-structure–property relationships", Materials Research Letters, Vol. 8, 1, pp. 7-15 (Open access).

7- Kurzynowski, T.; Gruber, K.; Stopyra, W.; Kuźnicka, B. & Chlebus, E.; 2018, "Correlation between process parameters, microstructure and properties of 316 L stainless steel processed by selective laser melting", Materials Science and Engineering: A, Vol. 718, pp. 64-73.

8- Herzog, D.; Seyda, V.; Wycisk, E.; Emmelmann, C.; 2016, "Additive Manufacturing of Metals", Acta Materialia, pp. 371-392.

9- Mower, T., M. & Long, M., J.; 2016, "Mechanical behavior of additive manufactured, powder-bed laser-fused materials", Materials Science & Engineering A, Vol. 651, pp. 198-213 (Open Access).

10- Afkhami, S.; Piili, H.; Salminen, A. & Björk, T.; 2019b, "Effective parameters on the fatigue life of metals processed by powder bed fusion technique: A short review", Procedia Manufacturing, Vol. 36, pp. 3-10 (Open Access).

11- Kasperovich, G. & Hausmann, J.; 2015, "Improvement of fatigue resistance and ductility of TiAl6V4 processed by selective laser melting", Journal of Materials Processing Technology, Vol. 220, pp. 202-214.

12- Riemer, A.; Leuders, S.; Thöne, M.; Richard, H., A.; Tröster, T. & Niendorf, T.; 2014, "On the fatigue crack growth behavior in 316L stainless steel manufactured by selective laser melting", Engineering Fracture Mechanics, Vol. 120, pp. 15-25.

13- Hussein, A.; Hao, L.; Yan, C. & Everson, R.; 2013, "Finite element simulation of the temperature and stress fields in single layers built without-support in selective laser melting", Materials & Design, Vol. 52, pp. 638-647.

14- Zhang, B.; Li, Y. & Bai, Q.; 2017, "Defect formation mechanisms in selective laser melting: a review", Chinese Journal of Mechanical Engineering, Vol. 30, 3, pp. 515-527 (Open Access).

15- Suryawanshi, J.; Prashanth, K., G. & Ramamurty, U; 2017, "Mechanical behavior of selective laser melted 316L stainless steel", Materials Science and Engineering: A, Vol. 696, pp. 113-121.

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Thank you for your attention!

Any questions?

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