Swedish Aerospace Technology Congress 2016

# A review of selective laser melting - Process parameters and its influence on microstructure, defects and strength in superalloy Alloy 718

Authors: Tahira Raza[1], Joel Andersson[1], Lars-Erik Svensson[1] and Magnus Holmquist[2]

[1]*Dept of Engineering Science, University West, SE-46186 Trollhättan, Sweden*
[2]*GKN Aerospace Sweden AB, SE-46181 Trollhättan*

tahira.raza@hv.se



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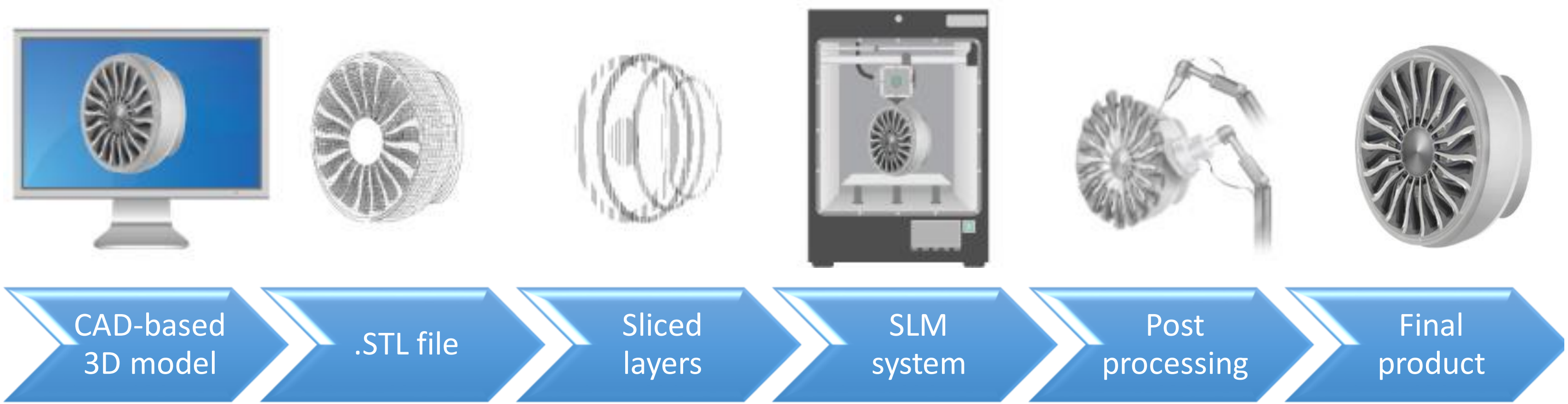
# Selective laser melting (SLM)
# Process chain




[Adapted from: http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-aerospace/. Accessed 2016-10-02]

# SLM process

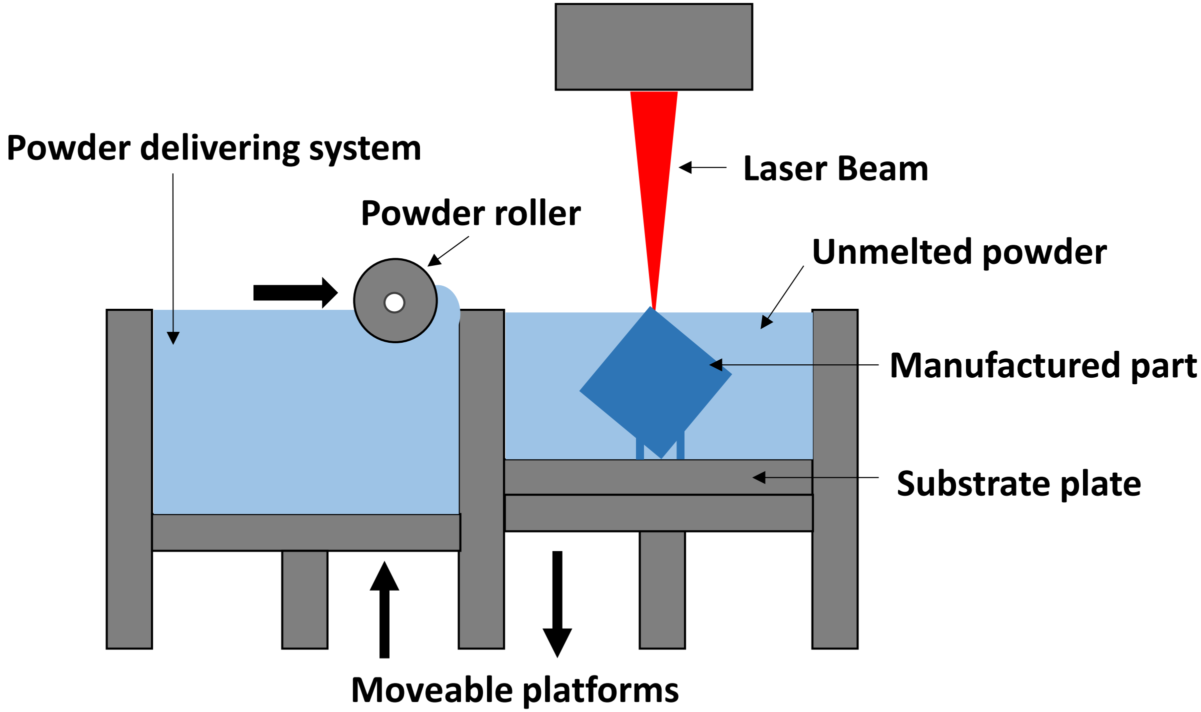
**Advantages**

- ❑ Prototyping
- ❑ Low-volume fabrication of expensive components
- ❑ Individually customized products
- ❑ Possibility of producing geometrically complex components
- ❑ Minimum waste of material

**Challenges**

- ❑ Surface roughness
- ❑ Internal pores
- ❑ Delamination due to residual stresses
- ❑ Long processing time

# SLM process

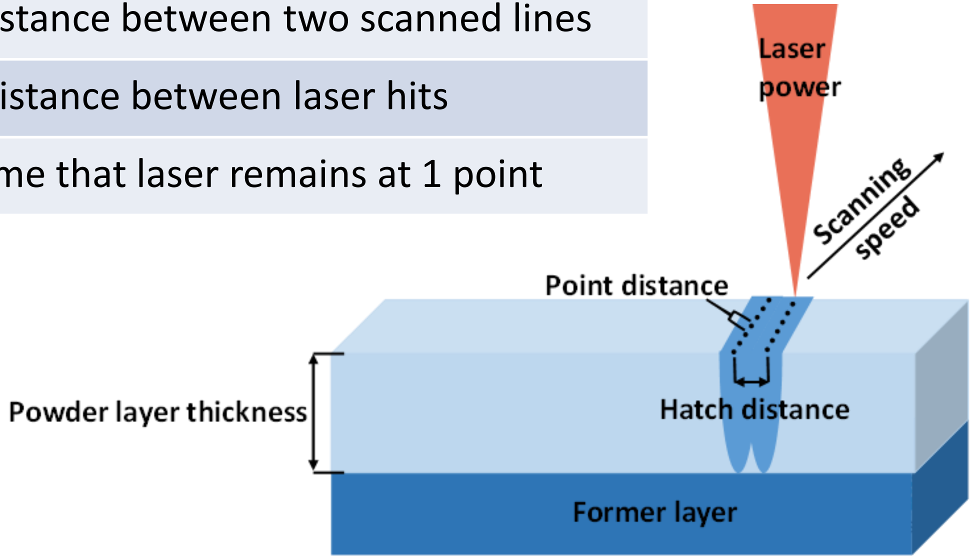

Powder delivering system
Laser Beam
Powder roller
Unmelted powder
Manufactured part
Substrate plate
Moveable platforms

# SLM process parameters

- **Laser related parameters**
  - Laser power, spot size, pulse frequency, pulse duration
- **Scan related parameters**
  - Scanning strategy, scanning speed, hatch distance
- **Powder related parameters**
  - Particle size, shape and distribution, powder bed density, layer thickness, material properties, such as melting temperature, thermal conductivity
- **Temperature related parameters**
  - Powder bed temperature, powder feeder temperature, temperature uniformity

# Process parameters

| Parameter | Unit | Description |
|---|---|---|
| **Laser power** | W | The power of the laser beam which fuses the powder with the substrate |
| **Scanning speed** | mm/s | Travel speed of the laser |
| **Powder layer thickness** | mm | The height of each powder layer |
| **Hatch distance** | mm | The distance between two scanned lines |
| **Point distance** | mm | The distance between laser hits |
| **Exposure time** | ms | The time that laser remains at 1 point |



# Energy density

$$E\rho = \frac{P}{V\,H\,T}$$

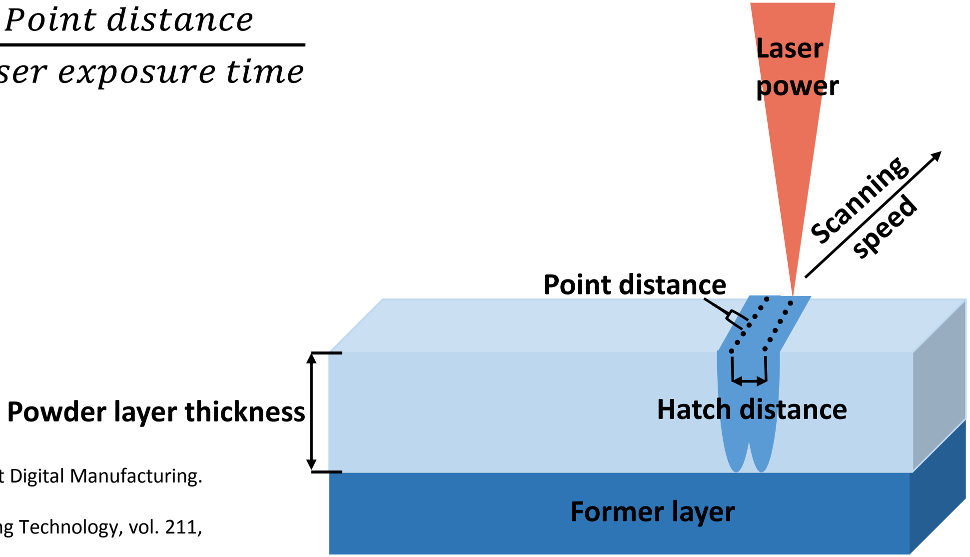
Where $E\rho$ = *Energy density [J/mm³]*

$P$ = *Laser power [W]*

$V$ = *Scanning speed [mm/s]* => $\frac{Point\ distance}{Laser\ exposure\ time}$

$H$ = *Hatch distance [mm]*

$T$ = *Powder layer thickness [mm]*





Gibson et al. Additive manufacturing technologies, 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. Springer, 2015.

Louvis et al. Selective laser melting of aluminium components. Journal of Materials Processing Technology, vol. 211, pp. 275-284. 2011.

# Alloy 718

| Ni | Cr | Fe | Nb | Mo | Ti | Mn | C | Al | Co |
|---|---|---|---|---|---|---|---|---|---|
| Bal. | 19 | 18 | 5 | 3 | 0.90 | 0.04 | 0.05 | 0.48 | 0.08 |
| **Si** | **N** | **Cu** | **B** | **Ca** | **Mg** | **P** | **S** | **Se** | |
| 0.04 | 0.02 | 0.02 | <0.006 (ppm) | <0.010 (ppm) | <0.010 (ppm) | 0.015 (ppm) | <0.010 (ppm) | <0.001 (ppm) | |

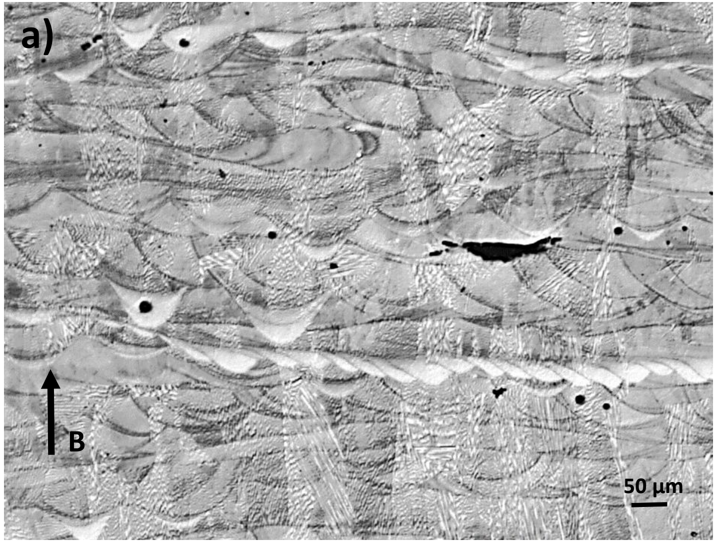
Chemical composition, wt %

- Iron-nickel based superalloy
- Nuclear, aerospace, oil and gas industry
- Excellent creep properties, oxidation resistance and hot corrosion resistance
- Excellent weldability

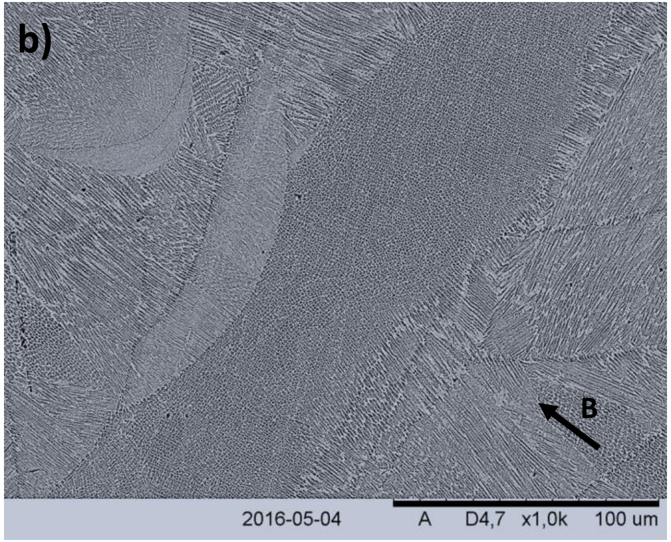


Geddes et al. Superalloys: Alloying and Performance. Materials Park, OH: ASM International. 2010.
R. Reed. The Superalloys, Fundamentals and Applications. Cambridge, UK: Cambridge University Press. 2006.

# Microstructure of SLM-manufactured




OM image of as-manufactured Alloy 718.

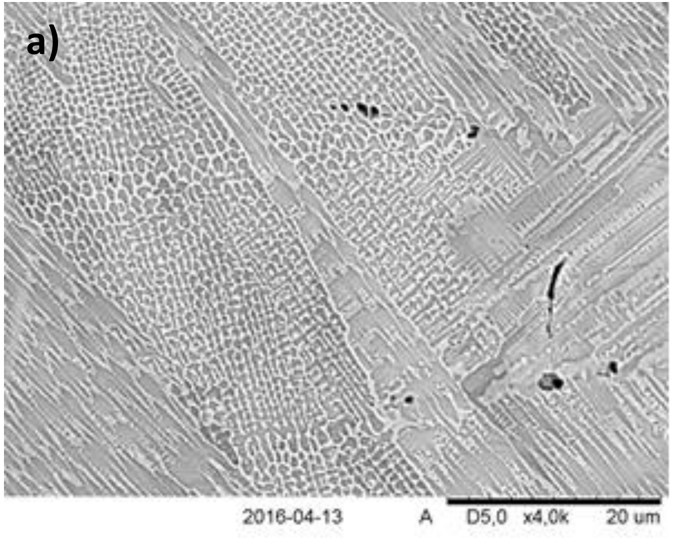


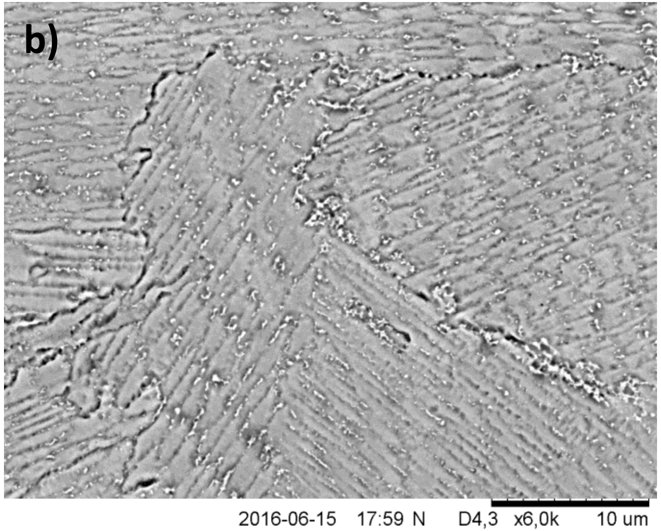

SEM image of layer development.



Raza et al. A review of the effect of selective laser melting process parameters and its influence on microstructure, defects and strength in the iron-nickel based superalloy Alloy 718. 2016

# Microstructure of SLM-manufactured Alloy 718



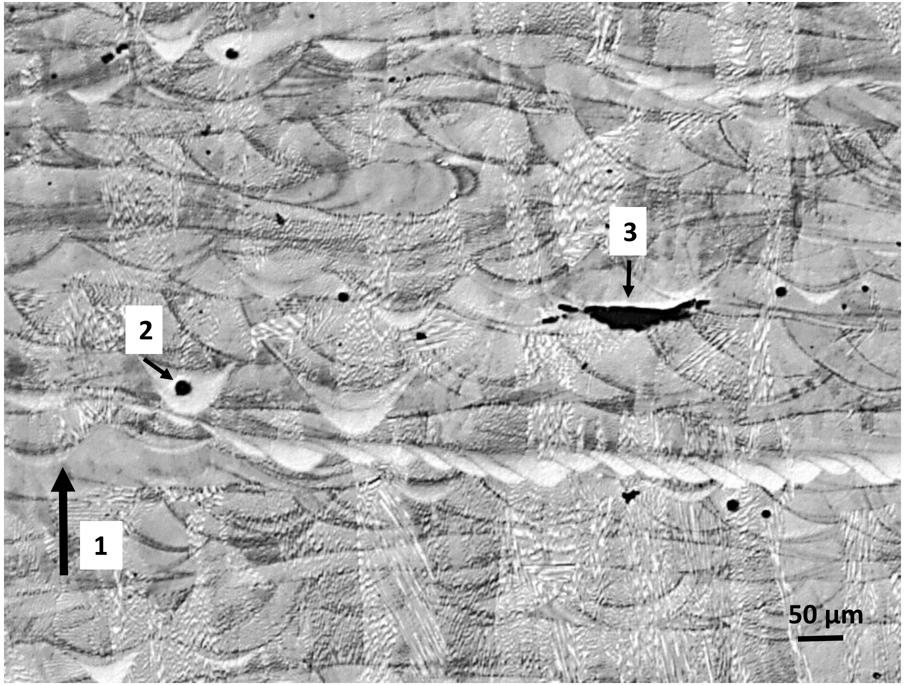

**SEM images showing a) columnar grain structures and b) segregation of Nb and Mo.**

- Columnar dendrite grains
- Segregation of Nb and Mo
  - Laves phase



Raza et al. A review of the effect of selective laser melting process parameters and its influence on microstructure, defects and strength in the iron-nickel based superalloy Alloy 718. 2016

# Process induced defects: porosity



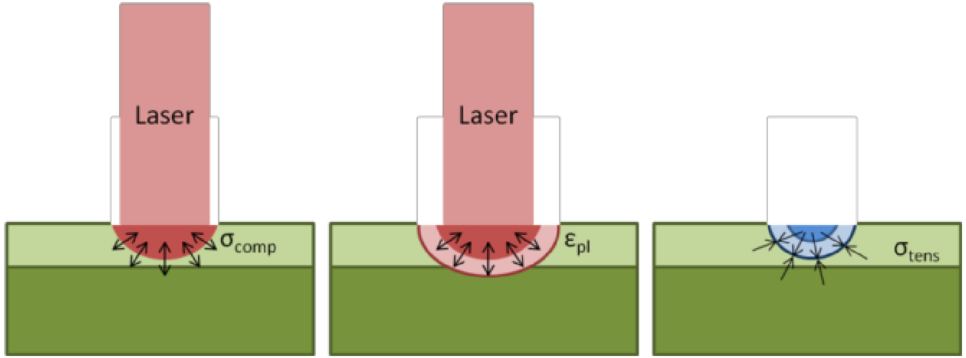

**OM image of as-manufactured Alloy 718, showing (1) build direction, (2) gas porosity, (3) lack of fusion.**

- Gas porosity - entrapped gas in the powder particles.
- Lack of fusion - insufficient heat input to the material.


G.K.L. Ng, A.E.W. Jarfors, G. Bi, H.Y. Zheng. Porosity formation and gas bubble retention in laser metal deposition. Applied Physics A, 97 (2009), 641-649., 2009.
Raza et al. A review of the effect of selective laser melting process parameters and its influence on microstructure, defects and strength in the iron-nickel based superalloy Alloy 718. 2016

# Process induced defects: residual stresses

- ❑ Process parameters:
  - Part height
  - Scanning strategy
  - Heating conditions




- ❑ Mechanism causing residual stresses
  - Temperature gradient
  - Thermal contraction



Kempen et al. Lowering thermal gradients in selective laser melting by pre-heating the baseplate. 2013.
Mercelis et al. Residual stresses in selective laser sintering and selective laser melting. Rapid Prototyping Journal, vol. 12, pp. 254-265. 2006.
Chlebus et al. Effect of heat treatment on the microstructure and mechanical properties of Inconel 718 processed by selective laser melting. Materials Science and Engineering: A, vol. 639, pp. 647-655. 2015.

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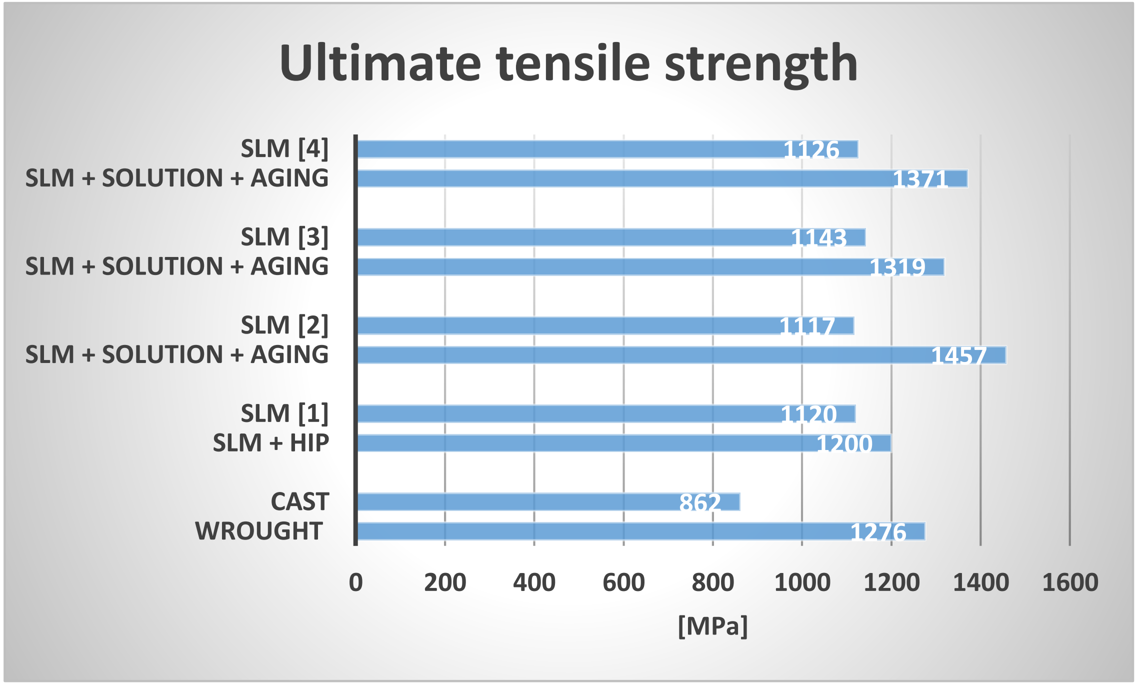
# Mechanical properties of SLM-manufactured Alloy 718





[1] Amato et al. Acta Materialia, vol. 60, pp. 2229-2239. 2012.
[2] Chlebus et al. Materials Science and Engineering: A, vol. 639, pp. 647-655. 2015.
[3] Wang et al. Journal of Alloys and Compounds, vol. 513, pp. 518-523. 2012.
[4] Zhang et al. Materials Science and Engineering: A, vol. 644, pp. 32-40. 2015.

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# Summary

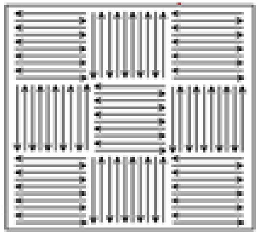
- Laser power, scanning speed, layer thickness and hatch distance.
- Columnar dendrite grains
  - Laves phases
- Strength and hardness of the SLM-manufactured Alloy 718 increases with heat treatments and are comparable with wrought Alloy 718.
- Common voids in SLM-manufactured Alloy 718:
  - Gas porosity
  - Lack of fusion
  - Residual stresses
  - Surface roughness
- Heat treatment necessary to achieve desired properties.

# Thank you

Tahira Raza
tahira.raza@hv.se

# Solutions

- ❑ Residual stresses
  - Heating of substrate plate
  - Scanning  strategy
- ❑ Surface roughness and porosity
  - Re-melting strategies



Island scanning strategy

Kempen et al. Lowering thermal gradients in selective laser melting by pre-heating the baseplate. 2013.
Mercelis et al. Residual stresses in selective laser sintering and selective laser melting. Rapid Prototyping Journal, vol. 12, pp. 254-265. 2006.
Chlebus et al. Effect of heat treatment on the microstructure and mechanical properties of Inconel 718 processed by selective laser melting. Materials Science and Engineering: A, vol. 639, pp. 647-655. 2015.

# Mechanical properties of SLM-manufactured Alloy 718

| Reference | Experiment | Hardness [HV] | Tensile strength [Mpa] | Yield strength [Mpa] |
|---|---|---|---|---|
| Amato et al. [1] | SLM | 398 | 1120 | 830 |
| | SLM + HIP | 571 | 1200 | 930 |
| | SLM + HIP + Solution | 469 | | |
| | | | | |
| Chlebus et al. [2] | SLM | 313 | 1117 | 723 |
| | SLM + Solution + aging | 463 | 1457 | 1241 |
| | | | | |
| Wang et al. [3] | SLM | 365 | 1143 | 903 |
| | SLM + Solution + aging | 470 | 1319 | 1132 |
| | | | | |
| Zhang et al. [4] | SLM | 323 | 1126 | 849 |
| | SLM + Solution + aging | 423 | 1371 | 1084 |
| | SLM + Homogenization + Solution + aging | 417 | 1371 | 1046 |


[1] Amato et al. Microstructures and mechanical behavior of Inconel 718 fabricated by selective laser melting. Acta Materialia, vol. 60, pp. 2229-2239. 2012.
[2] Chlebus et al. Effect of heat treatment on the microstructure and mechanical properties of Inconel 718 processed by selective laser melting. Materials Science and Engineering: A, vol. 639, pp. 647-655. 2015.
[3] Wang et al. The microstructure and mechanical properties of deposited-IN718 by selective laser melting. Journal of Alloys and Compounds, vol. 513, pp. 518-523. 2012.
[4] Zhang et al. Effect of standard heat treatment on the microstructure and mechanical properties of selective laser melting manufactured Inconel 718 superalloy. Materials Science and Engineering: A, vol. 644, pp. 32-40. 2015.

# Mechanical properties of SLM-manufactured Alloy 718