Influence of process parameters on the final 316L stainless steel properties manufactured by selective laser melting (SLM)

A. Chniouel, F. Lomello, P. F. Giroux, P. Aubry, H. Maskrot

DE LA RECHERCHE À L'INDUSTRIE

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INFLUENCE OF PROCESS PARAMETERS ON THE FINAL 316L STAINLESS STEEL PROPERTIES MANUFACTURED BY SELECTIVE LASER MELTING (SLM)

A. CHNIOUEL[a*], Dr F. LOMELLO[a], Dr P.F. GIROUX[b], Dr P. AUBRY[a], Dr H. MASKROT[a]

[a]DEN – Service d'Etudes Analytiques et de Réactivité des Surfaces (SEARS), CEA, Université Paris-Saclay, F-91191, Gif sur Yvette, France.

[b]DEN – Service de Recherches Métallurgiques Appliquées (SRMA), CEA, Université Paris-Saclay, F-91191, Gif sur Yvette, France

*Corresponding author *E-mail adress*: aziz.chniouel@cea.fr

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INTRODUCTION: CONTEXT

Additive Manufacturing: growing technology in the industrial world for different sectors: aeronautics – automotive – medicine.

❖ **Nuclear industry**? Exploring by DOE (U.S.A) since 2012 for different materials: IN600, IN718, IN800, 316L SS, ODS steels.

❖ **Benefits:**

→ Complex manufacturing of geometrical parts for nuclear applications.

→ Components manufacturing which are impossible to process by others traditional processes (cast, forge, rolling,…).

→ Processing steps reduction depending on parts complexity (i.e. GE-SAFRAN Leap-X fuel injector).

→ Waste reduction: powder recyclability.

→ **Rapid prototyping.**

❖ **Question**: Is additive manufacturing adapted for producing nuclear components? (GEN IV – Sodium Fast Cooled Reactor).

→ Material: 316L SS.

→ Mechanical, corrosion and irradiation properties ?

→ **Understand relation between process and microstructure**.

↓

The influence of **substrate temperature** on the **microstructure** and **mechanical properties of 316L SS samples**

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OUTLINE

Raw material properties: 316 SS powder

Experimental details

Influence of the processes parameters on the samples properties

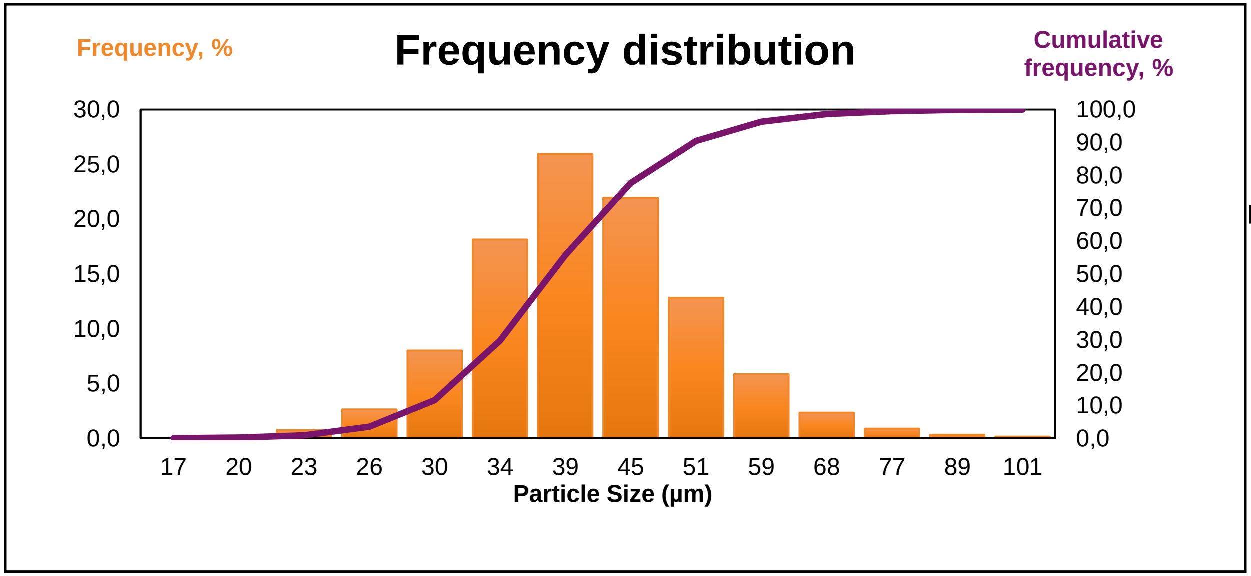
316L SS POWDER PROVIDED BY SLM SOLUTIONS

- Chemical composition

	Majority elements by ICP-OES (% wt) (uncertainly related of 3%)					Minority elements (%wt) By GDOES and LECO (uncertainly related of 5%)				
	Cr	Ni	Mn	Si	Mo	C	N	O	S	P
Standard RCC-MRx	16,5-18,50	10-13	2 max	1 max	2-2,5	300 max	1100 max	-	150 max	300 max
316L SS powder	17,35	11,45	1,06	0,51	2,07	230	982	1876	130	305

- Chemical composition in good agreement with RCC-MRx Code → French Nuclear Standard for Experimental Reactors

- Particles size

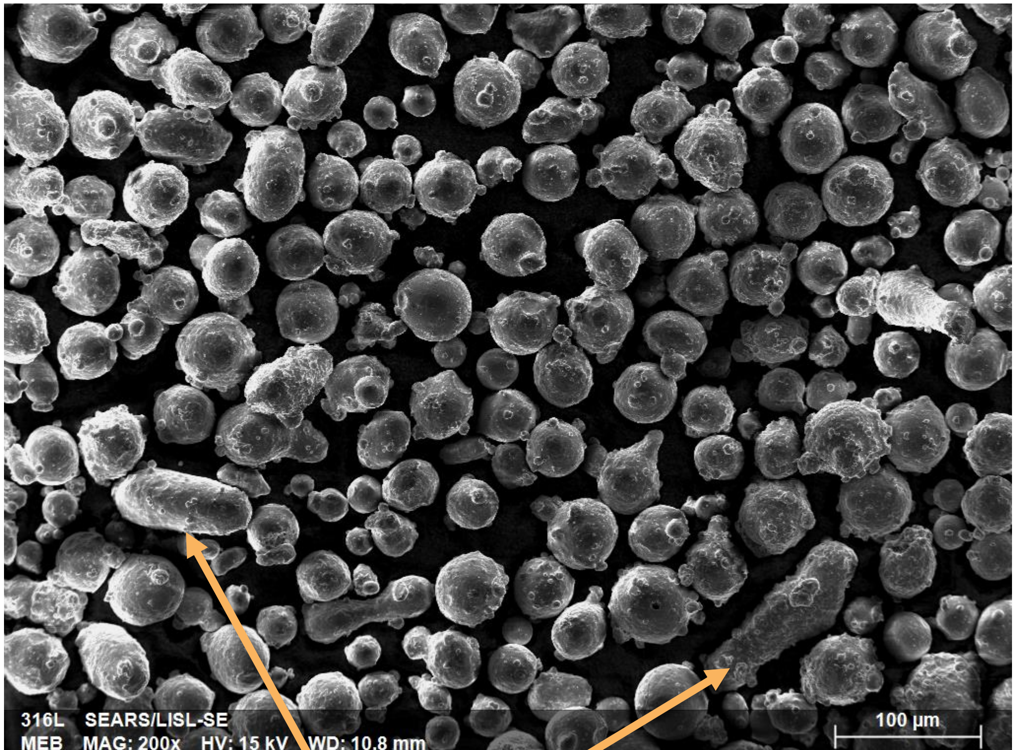


D_{10}	29 µm
D_{50}	38 µm
D_{90}	51 µm

316L SS POWDER PROVIDED BY SLM SOLUTIONS

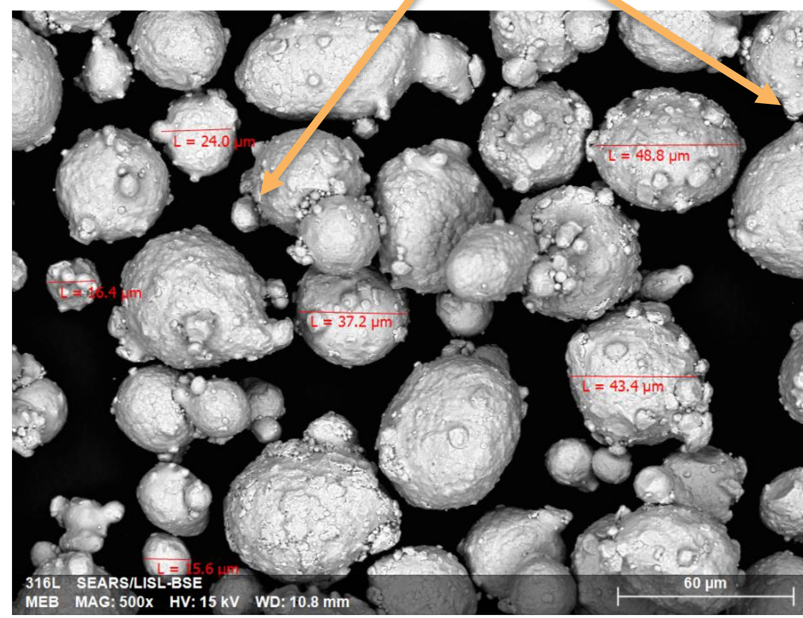
- ❑ Morphology

> - Argon atomized powder.
> - Typical heterogeneous shapes.



- Rod-like particles

- Satellites



OUTLINE

- Raw material properties: 316 SS powder
- Experimental details
- Influence of the processes parameters on the samples properties

EXPERIMENTAL PROCESS: SELECTIVE LASER MELTING

SLM 280^{HL}

- Selective laser melting
- Power max: 400 W
- Ytterbium doped laser fiber.
- Laser's spot size: 75 µm

❖ Fixed process parameters:

→ Power: 175W

→ Layer thickness, e=30 µm

→ Scan speed, v=700 mm/s

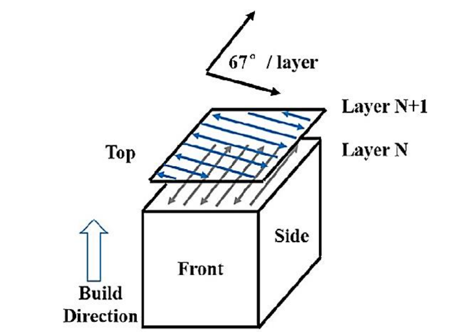
→ Hatching distance, HD: 100 µm

$$E = \frac{P}{e.v.HD} = 84\ J/mm^3$$

→ Argon gas atmosphere.

→ Scan Strategy:

incrementation of 67° between each layer



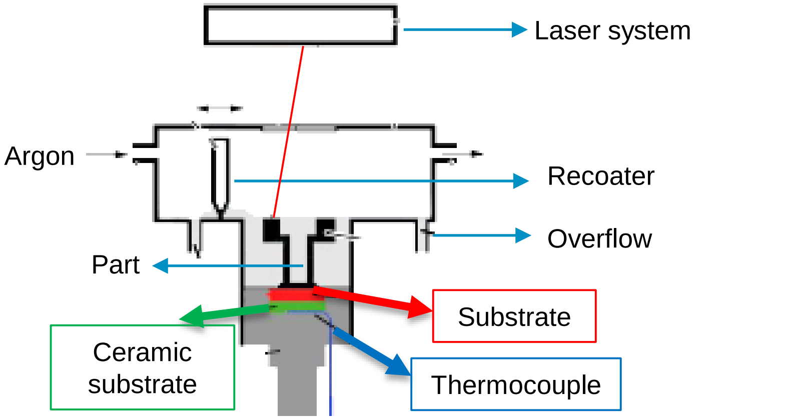
Zhou et al. J. of Mat. Proc. Tech, 2016 , 222: 33-42.

❖ Variable process parameter:

→ Heating Platform

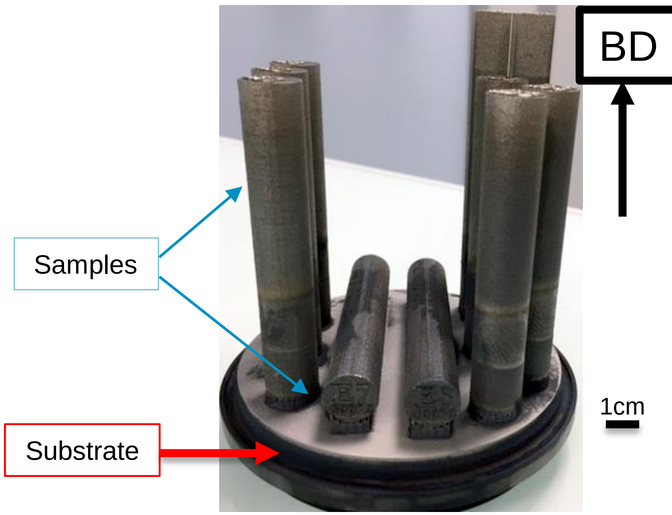
RT=25°C < T < 600°C

EXPERIMENTAL PROCESS: SELECTIVE LASER MELTING



Flow diagram

- Build enveloppe size: Ø=100 mm and height 100 mm.
- Aim: reduce thermal stresses and formation of cracks in the parts.



- Samples manufactured at different temperatures:
  → RT, 100°C, 200°C, 350°C, 500°C and 600°C.
- Cylindrical and Beam-like samples (X, Y, Z and 45° from XY plane).

Aim of In situ heat:

→Decrease internal thermal stresses.
→Grain sizes modification.
→**"In situ" heat treatment in order to reduce post process steps.**

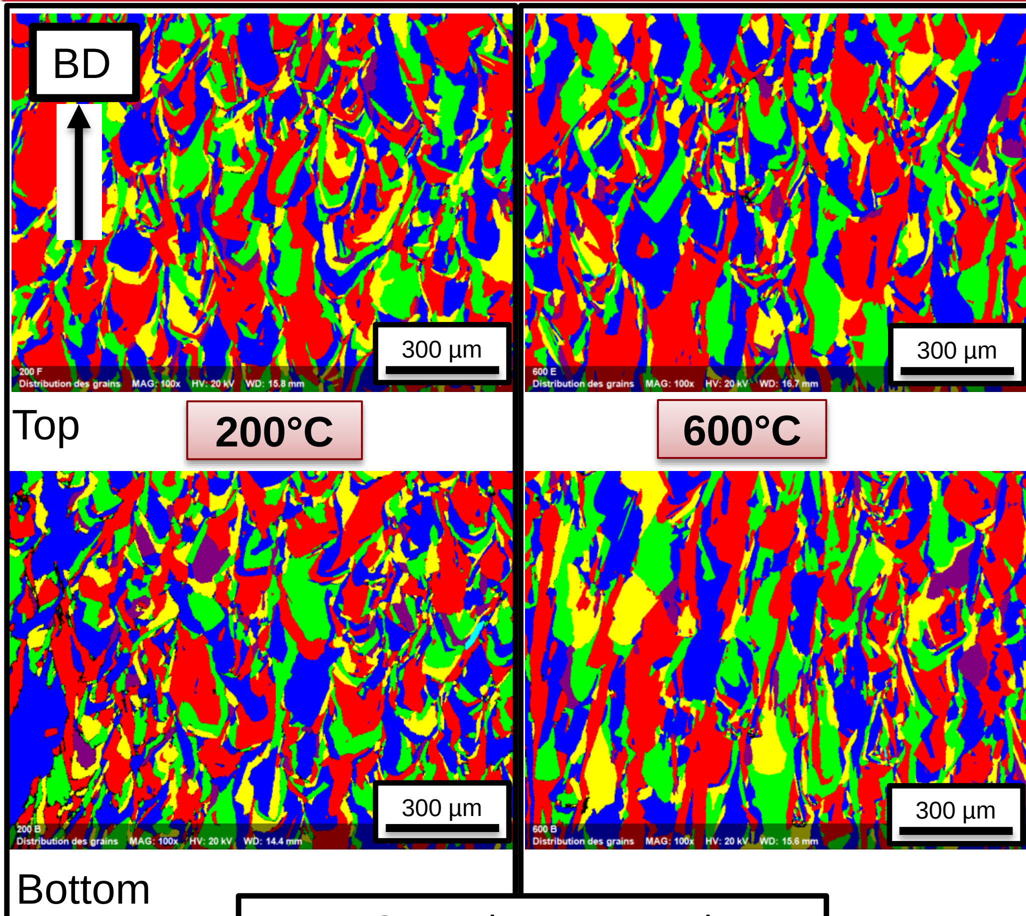
OUTLINE

Experimental details

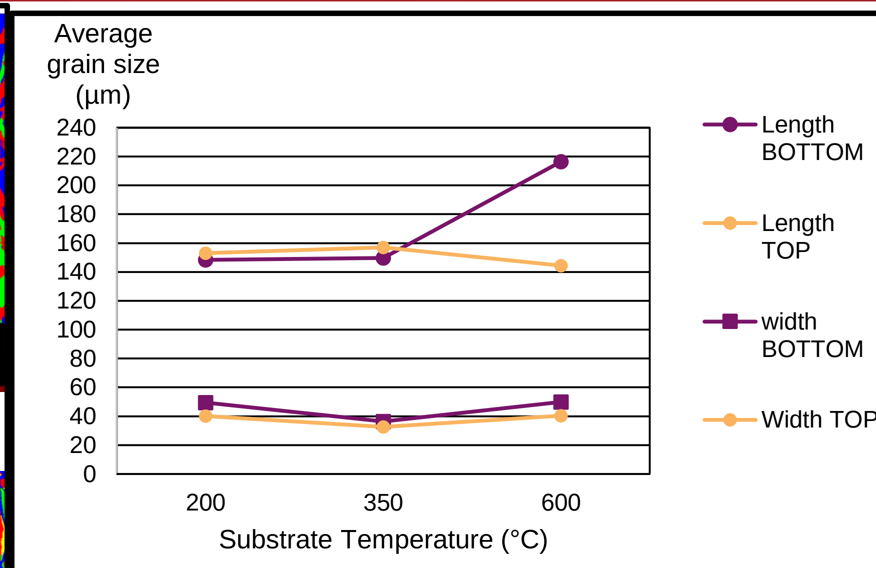
Raw material properties: 316 SS powder

Influence of processes parameters on the samples properties

Micro scale: Grains

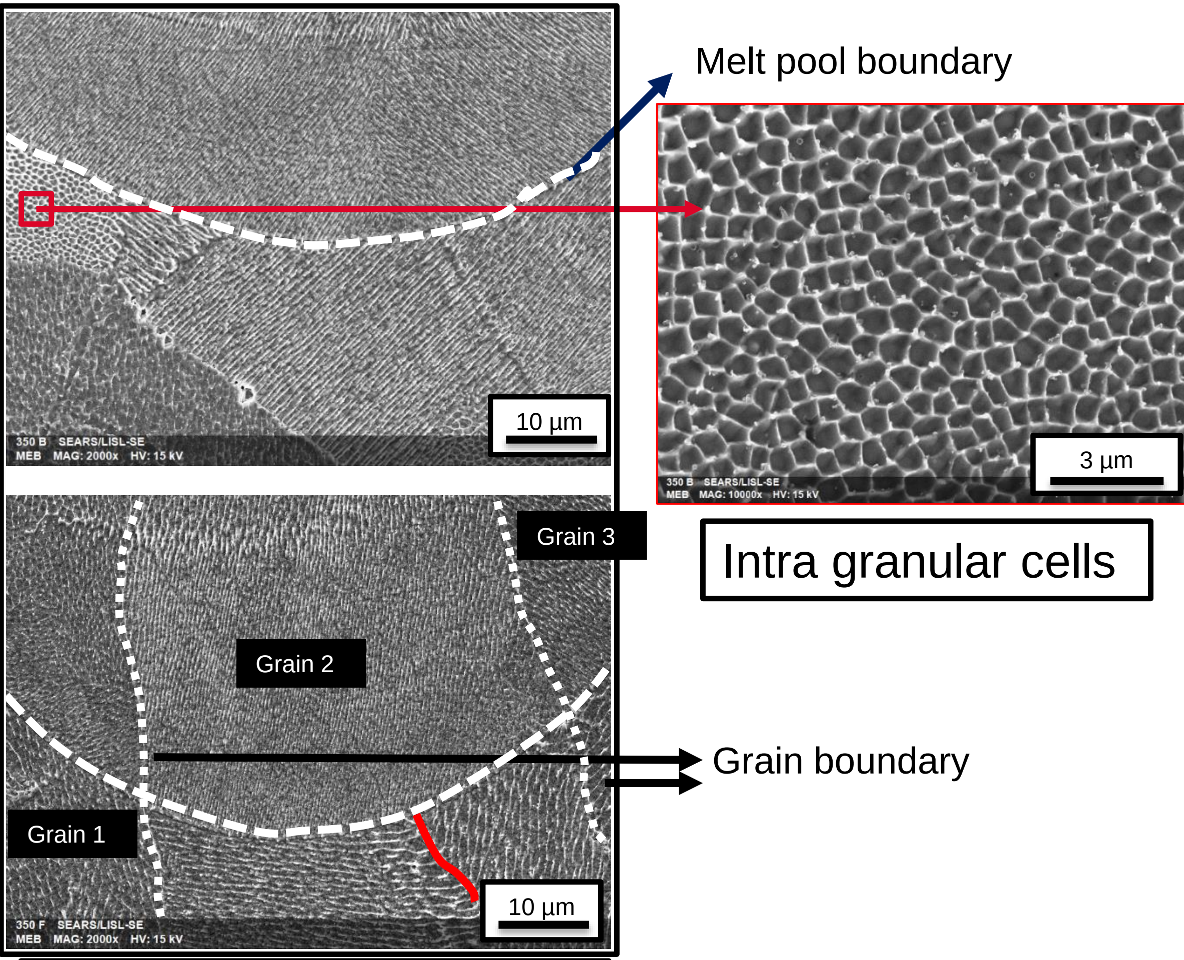


EBSD grains cartography



- Columnar grains along B.D.: length around 4 times width.
- Grains grow across layers (30 µm).
- Grains are more **elongated at 600°C on the BOTTOM** (L=220 µm)
  → Grains size influenced by the substrate temperature (Temperature higher at the bottom).
- No influence of temperature on grains width.

Micro scale: Grains



Substrate temperature 350 °C

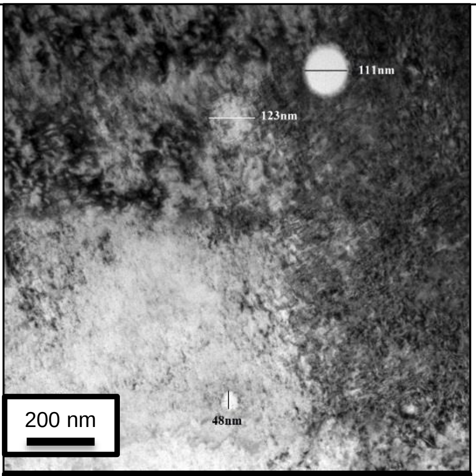
- No significant influence of the substrate temperature on the cells size:
- intra granular cells size between 0.6 and 1 µm.
- High cooling rate (10^3-10^6 K/s) - *Casati and al. Journal of Meterials Science and Technology ,2016, 32: 738-744*

- Inside a same grain: (grain 2)

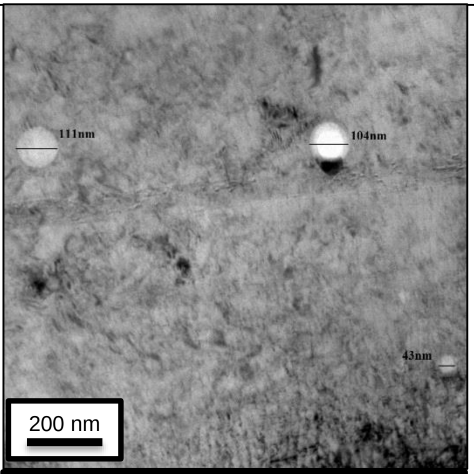
Direction of growth of S/L interface can vary from one melt pool to another – Mertens *and al., Materials Science, 2011, 783-786, 898-903*

Nano scale: Precipitates

- ❑ Analyse at the middle of the sample height (4.5 cm).
- ❑ **No influence of the substrate temperature on:**
  - **Structure: amorphous.**
  - **Shape: spherical.**
  - **Size: diameter ranging 10 to 170 nm.**
  - **Composition: O, Si, Mn.**
  - **Trace of S, Mo and Al in some precipitates.**



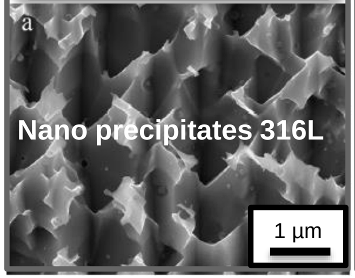
STEM BF
Substrate Temperature 350°C



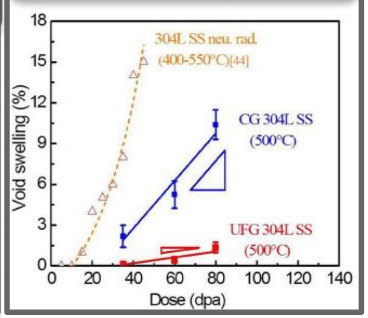
STEM BF
Substrate Temperature 600°C

- ❑ Nano oxydes formation in situ during the build process → improve mechanical properties - *K. Saeidi Ph. D. Thesis (2016).*
- ❑ Precipitates size and density are highly influenced by the oxygen content in the build chamber - *Zhou et al. Mater. Sci. Eng., 2017, 167.*
- ❑ Nano precipitates can improve swelling resistance under neutron irradiation - *Sun et al., Sci. Rep., 2015, 5, 7801.*

Zhong et al. J. Nucl. Mat. 470, 2016, 170

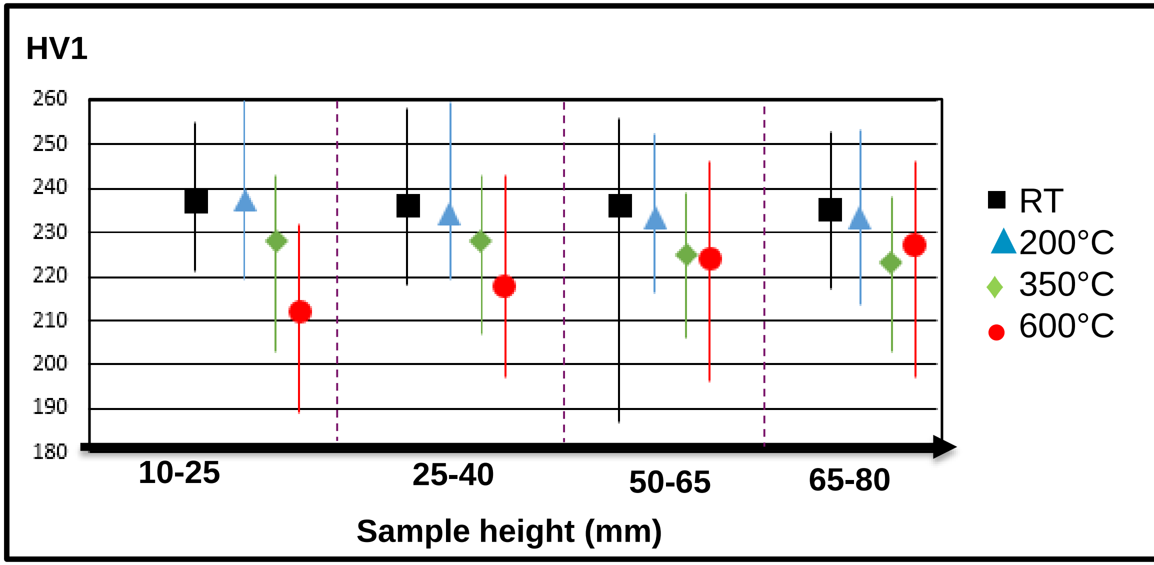


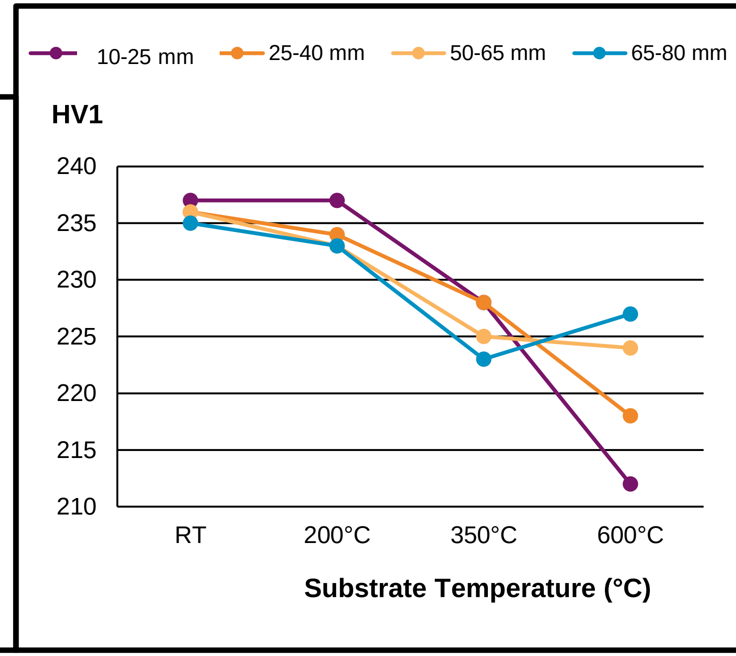
Sun et al. Sci. Rep., 5, 2015, 7801



Micro Hardness

❑ Microhardness along **building direction**, Z direction.





→ No influence of the height on microhardness for RT, 200°C and 350°C.

→ At **600°C**, microhardness increases linearly according to sample height.
- → Grains more columnar (Hall Petch effect)
- → Internal stresses relieved on the **BOTTOM**
- → **Thermal gradient.**

→ Microhardness decreases as a function of temperature.

→ Same trend observed after heat treatment - *Herliansyah and al., Proceedings, 2015.*

→ Same values reported by *Zhong:*

Zhong et al. J. Nucl. Mat. 470 (2016) 170.

Micro-hardness measured on the side (top and bottom in building direction) and cross-section surface (HV1) of as-built sample, *cf.* discussion in the text.

Bottom of side surface	Top of side surface	Cross-section	HIPed(Hv0.3) [26]
239 ± 5	219 ± 5	228 ± 4	~220

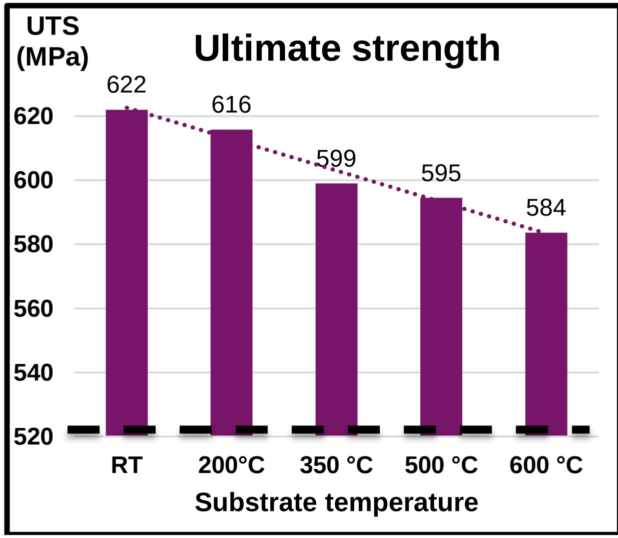
Tensile test

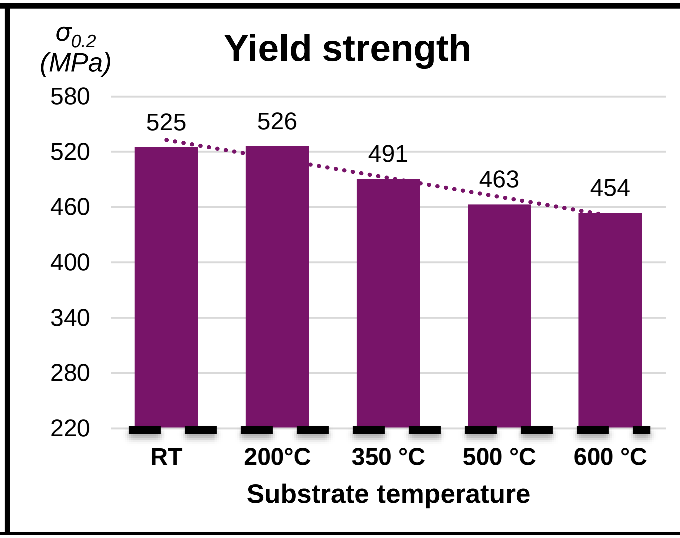
Samples manufactured along B.D.

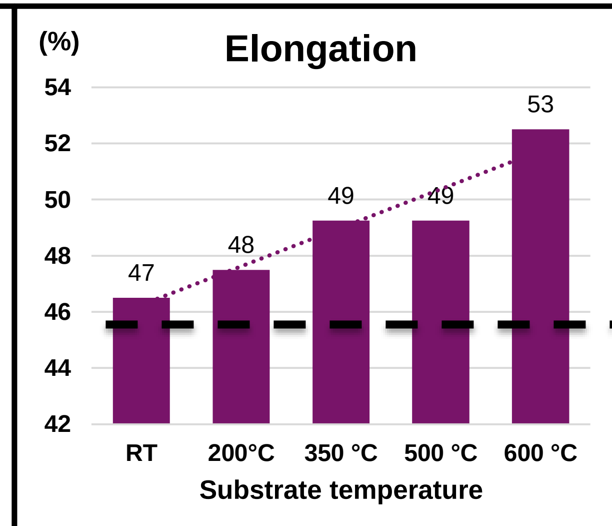
Influence of the substrate temperature

- ❑ Samples machined according the ISO 6892-1 standard.
- ❑ Test at room temperature.

▬ ▬ Forged 316LSS, RCC-MRx France nuclear Standard







- ➢ Strength and Yield strength decrease linearly as a function of temperature.
- ➢ Similar trend followed by the microhardness.

- ➢ Elongation increases linearly as a function of temperature.

- ➢ Same trend observed after heat treatment:

Dislocation / Internal stresses relieved ?

✚

Grains are more **columnar** along building direction when **temperature increases.**

- ➢ Mechanical properties respect the minimum requirement of the nuclear standard.

CONCLUSION/PERSPECTIVES

Microstructure:

- Columnar grains along the Z-direction with intra granular cells (around 0.6 to 1 µm).
- **Grains length** influenced by substrate temperature especially at **600°C** on the **bottom** of sample.

Mechanical properties:

- Same trend observed after heat treatment.
- **Mechanical properties respect the minimum requirement of the nuclear standard.**

Perspectives:

- Measurement of the internal stresses.
- Mechanical properties as a function of **build direction** at high substrate temperature.
- Post-processing heat treatments and hot isostatic pressing.

Thank you for your attention.