amadam additive manufacturing

Horizon 2020-MSCA-RISE

Fatigue of additively manufactured steels with particular regard to Maraging Stainless Steel CX

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PROJECT SUPPORTED BY European Commission

"Advanced design rules for optimal dynamic properties of additive manufacturing products". European Union's Horizon 2020 Marie Skłodowska-Curie research and innovation programme.

A_MADAM

- Consortium
  - FMG Kraljevo – University of Kragujevac /Serbia/
  - DIN – University of Bologna /Italy/
  - Topomatika, Zagreb /Croatia/
  - Studio Pedrini, Bologna /Italy/
  - Plamingo, Gračanica /Bosnia & Herzegovina/

A_MADAM

UniKV – Additive manufacturing (3D printing)

TOP-Optical measurements

SP-Rapid manufacturing

PLA – Rapid tooling

UniBo – Experimental mechanics

I was responsible for an extensive fatigue campaign assessing the effects of many factors for different materials.

Outcome	Factors	Levels	Values	Material	Sets
1	Machining	3	No	MS1	HG.MS.Vxx.STM = 01
			0.5 mm after SP		HG.MS.Vxx.SNN = 10
			0.5 mm before SP		HG.MS.Vxx.SMN = 11
	Aging	2	No		HG.MS.Vxx.STN = 18
			Yes		HG.MS.Vxx.MSN = 19
					HG.MS.VUx.TMS = 20
					HG.MS.VMx.TMS = 21
					HG.MS.VDx.TMS = 22

Outcome	Factors	Levels	Values	Material	Sets
2	Machining	3	No	PH1	HG.PH.Vxx.SNN = 23
			0.5 mm after SP		HG.PH.Vxx.SMN = 24
			0.5 mm before SP		HG.PH.Vxx.STN = 25
	Aging	2	No		HG.PH.Vxx.STM = 26
			Yes		HG.PH.Vxx.MSN = 27
					HG.PH.Vxx.TMS = 28

Effect of heat and surf. treatments (machining, shot-peening) and of the position in the chamber: MS1, PH1

Outcome	Factors	Levels	Values	Material	Sets
3	Orientation	3	Vertical	MS1	HG.MS.Vxx.STM = 01
			Horizontal		HG.MS.Hxx.STM = 02
			Slanted		HG.MS.Sxx.STM = 03
	Machining	2	0.5 mm		HG.MS.Vxx.ST3 = 04
			3 mm		HG.MS.Hxx.ST3 = 05
					HG.MS.Sxx.ST3 = 06

Outcome	Factors	Levels	Values	Material	Sets
4	Orientation	3	Vertical	PH1	HG.PH.Hxx.ST1 = 12
			Horizontal		HG.PH.Vxx.ST1 = 13
			Slanted		HG.PH.Sxx.ST1 = 14
	Machining	2	1 mm		HG.PH.Hxx.ST3 = 15
			3 mm		HG.PH.Vxx.ST3 = 16
					HG.PH.Sxx.ST3 = 17

Effect of build orientation and allowance for machining: MS1, PH1

Outcome	Factors	Levels	Values	Material	Sets
5	Machining	5	No	MS1	HG.MS.Vxx.STM = 01
			0.5 mm		HG.MS.Vxx.ST1 = 07
			1 mm		HG.MS.Vxx.ST3 = 08
			3 mm		HG.MS.Vxx.ST4 = 09
			4 mm		HG.MS.Vxx.STN = 18

Deepening the effect of allowance for machining: MS1

Outcome	Factors	Levels	Values	Material	Sets
8	Position	3	Upstream	MS1	HG.MS.VUx.TMS = 20
			Middle		HG.MS.VMx.TMS = 21
			Downstream		HG.MS.VDx.TMS = 22

Position in the chamber: MS1

6	Orientation	3	Vertical	CX	HG.CX.Hxx.SMT = 29
			Horizontal		HG.CX.Sxx.SMT = 30
			Slanted		HG.CX.Vxx.SMT = 31

Effect of build orientation: CX

Outcome	Factors	Levels	Values	Material	Sets
7	Machining	2	No	CX	HG.CX.Vxx.SNN = 32
			0.5 mm after SP		HG.CX.Vxx.STN = 33
	Aging	2	No		HG.CX.Vxx.MSN = 34
			Yes		HG.CX.Vxx.TMS = 35

Effects of machining and heat treatment: CX

9	Combined production technology (Up-built)	3	No	MS1	HG.MS.VUx.TMS = 20
					HG.MS.VMx.TMS = 21
			At middle		HG.MS.VDx.TMS = 22
			At quarter		HG.MS.VxM.TMS = 36
					HG.MS.VxQ.TMS = 37

Wrought material upgrade by AM

About 550 samples have been tested under fatigue!

EFFECT OF HEAT TREATMENT AND MACHINING ON THE FATIGUE RESPONSE OF MARAGING STAINLESS STEEL CX FOLLOWING POWDER BED FUSION

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OUTLINE

- Introduction, motivations and subject
- Material, design of the experiment and experimental procedure
- Results: fatigue strengths and S-N curves
- Effect of machining: remarks and discussion
- Effect of heat treatment: remarks and discussion
- Conclusions

Supported by microscope analyses

INTRODUCTION

- **Laser Powder Bed Fusion (LPBF)** largely applied in many fields (automotive, aerospace, biomedical devices, moulding)
- Wrought material components: fatigue limit (FL) = **50%** ultimate tensile strength (UTS)
- **Much lower value** for parts fabricated by **Additive Manufacturing (AM):** FL is 29% of UTS for Maraging Steel MS1 [1-2]. **Uncertainty with regard to the achievable fatigue response**
- **Heat treatments** (austenitization, aging, …) and **machining** are likely to improve the performance: enhanced microstructure and defect erasing

[1] Croccolo D, De Agostinis M, Fini S, Olmi G, Robusto F, Ćirić-Kostić S, Bogojević N. Sensitivity of direct metal laser sintering maraging steel fatigue strength to build orientation and allowance for machining. Fatigue Fract Eng Mater Struct. 2019; 42(1): 374–386.
[2] Croccolo D, De Agostinis M, Fini S, Olmi G, Robusto F, Ćirić-Kostić S, Bogojević N. Fatigue response of as-built DMLS maraging steel and effects of aging, machining, and peening treatments. Metals. 2018: 8: 7.

MOTIVATIONS

- **Stainless Steel CX** is a **recently introduced** material for **AM**
- It is a **Maraging Stainless Steel**: low **Ni** and **C**, high **Cr**
- Some studies are available in the literature [3-6], **but are focused on static properties only**
- **Studies dealing with fatigue performance are missing**. The effects of heat and surface finishing treatments are also still unexplored.

3 Asgari H, Mohammadi M. Microstructure and mechanical properties of stainless steel CX manufactured by Direct Metal Laser Sintering. Mater Sci Eng A. 2018; 709: 82–89.
4 Hadadzadeh A, Shahriari A, Amirkhiz BS, Li J, Mohammadi M. Additive manufacturing of an Fe–Cr–Ni–Al maraging stainless steel: Microstructure evolution, heat treatment, and strengthening mechanisms. Mater Sci Eng A. 2020; 787: 139470.
5 Chang C, Yan X, Bolot R, Gardan J, Gao S, Liu M, Liao H, Chemkhi M, Deng S. Influence of post-heat treatments on the mechanical properties of CX stainless steel fabricated by selective laser melting. J Mater Sci. 2020; 55: 8303–8316.
6 Shahriari A, Khaksar L, Nasiri A, Hadadzadeh A, Amirkhiz BS, Mohammadi M. Microstructure and corrosion behavior of a novel additively manufactured maraging stainless steel. Electrochim Acta. 2020; 339: 135925.

SUBJECT AND INNOVATION

- Experimental investigation regarding the fatigue response of CX.
- **Heat treatment** (austenitization and aging) **and machining effects** have been assessed.
- **Fractographic as well as micrographic analyses** for result interpretation.
- **First study in the scientific literature that tackles the fatigue assessment of this material**. This has different properties, if compared to other Maraging or Stainless Steels (low Ni and C, high Cr).

MATERIALS AND METHODS

Maraging Stainless Steel CX

Cr [%]	Ni [%]	Mo [%]	Al [%]	Mn [%]	Si [%]	C [%]	Fe [%]
11-13	8.4-10	1.1-1.7	1.2-2	≤0.4	≤0.4	≤0.05	Bal.

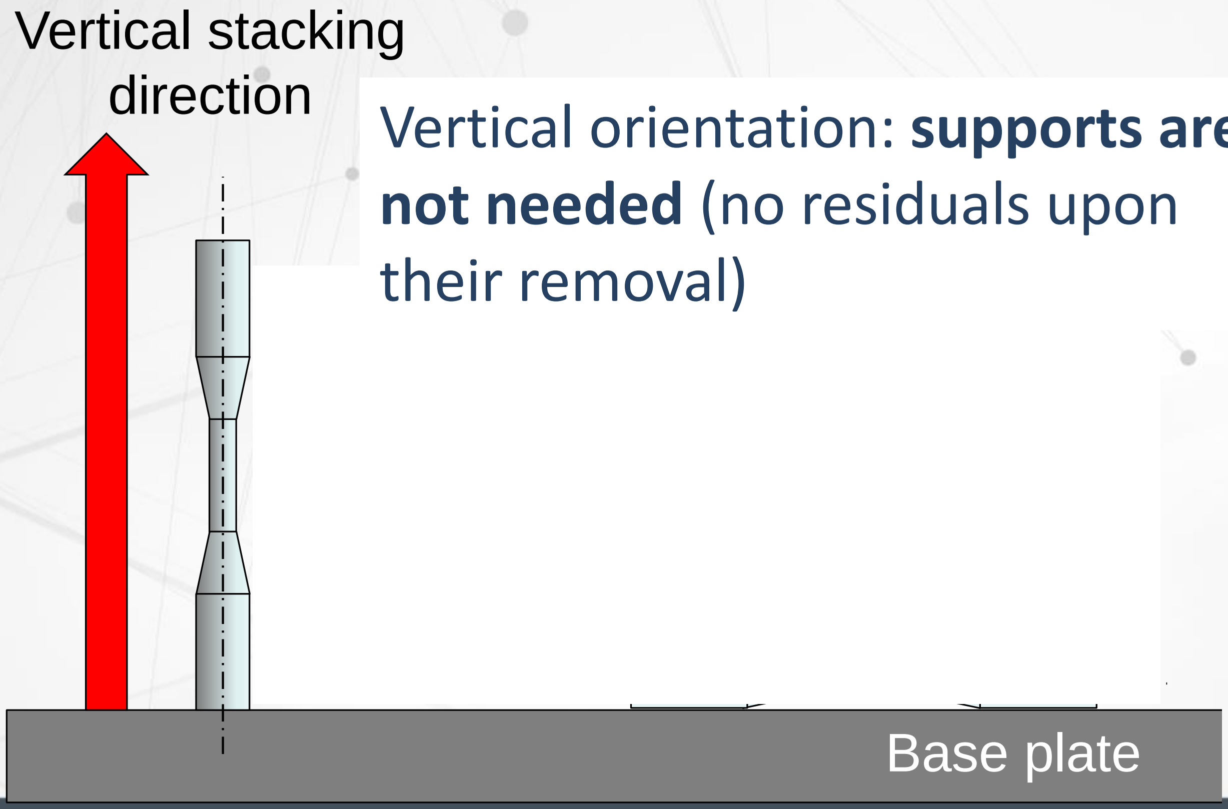
UTS=1080MPa, YP=840MPa without heat treatment

UTS=1760MPa, YP=1670MPa with heat treatment (austenitization and aging)

MATERIALS AND METHODS

- **Maraging Stainless Steel CX**
- **60 specimens** fabricated by AM (EOSINT M290)
- **Geometry complying with ISO 1143** (for rotary bending fatigue tests)

Vertical orientation: **supports are not needed** (no residuals upon their removal)



MATERIALS AND METHODS

		Machining: No	Machining: Yes
Heat treatment	No	Set NN	Set NM
Heat treatment	Yes	Set HN	Set HM

2 by 2 design

- **Heat treatment** (900°C austenitization, followed by aging at 530°C), recommended by EOS
- **Machining**: **grinding** with **0.5 mm allowance**
- **All the samples have been peened** (if machined, after machining), to take advantage of the induced **compressive residual stress state** [2]
- **15** specimens per **combination**
- **Output**: **S-N curves and fatigue limits**

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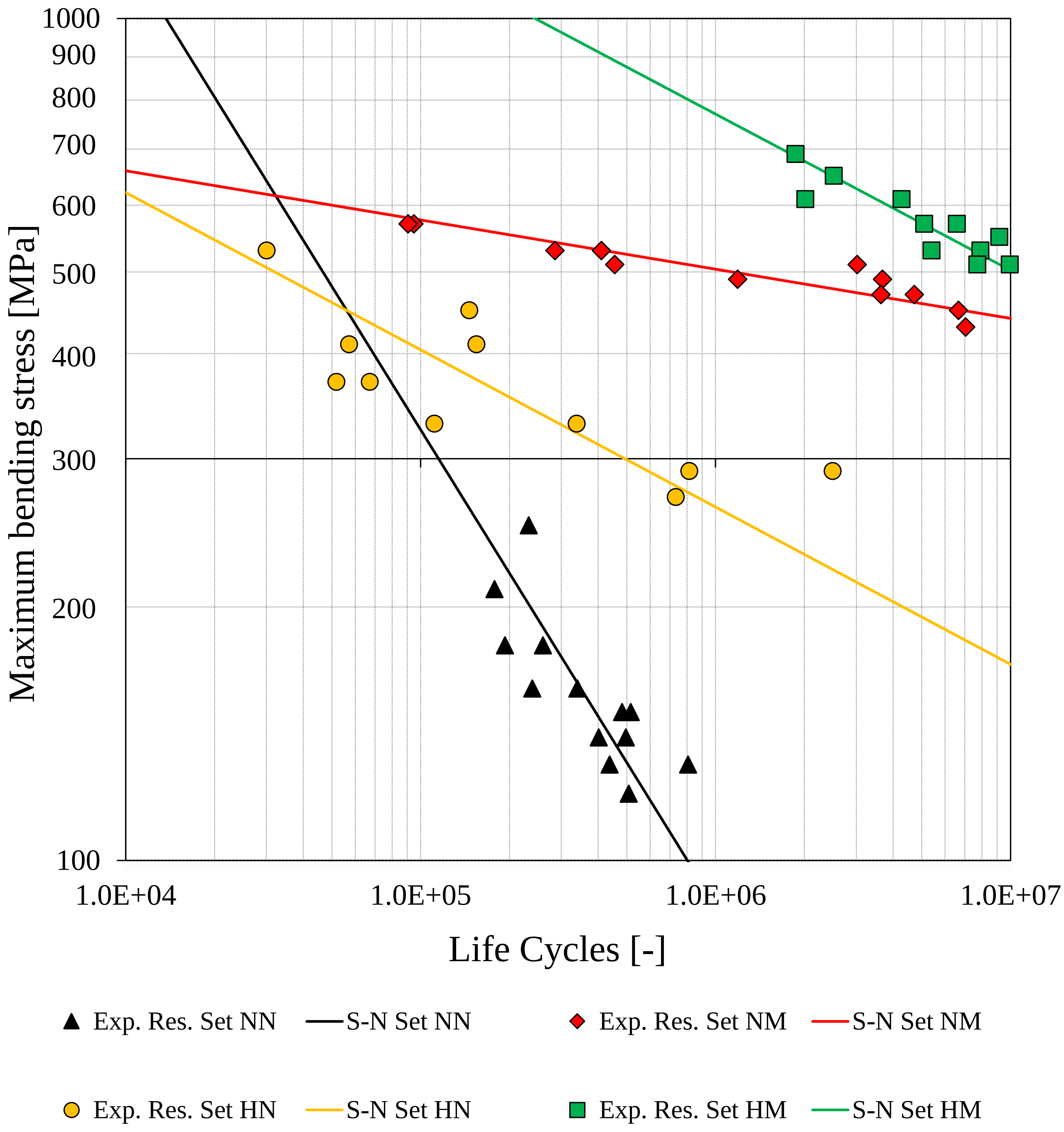
EXPERIMENTAL PROCEDURE

- All sample **dimensions** ad **roughness** have been measured.
- **HRC hardness** estimation
- **Relative densities** estimations (by Archimedes’ principle)
- **Porosity** amount estimated (by microscopy analyses and subsequent image processing)
- **Fatigue tests under rotary bending** (R=-1), 80 Hz frequency

RESULTS

	Not mach.	Mach.
Not H.T.	NN	NM
H.T.	HN	HM

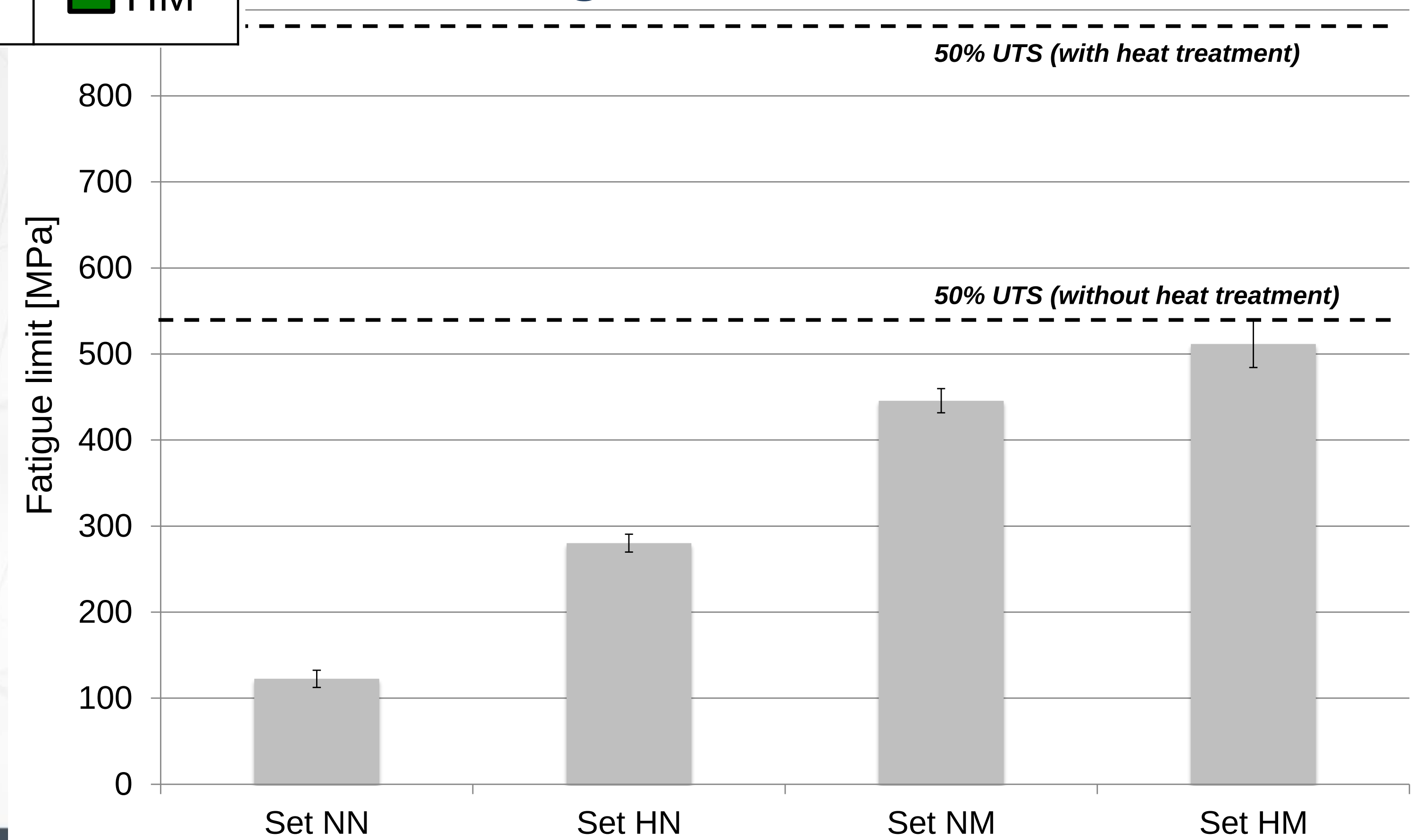
- **Beneficial effect** arising from **heat treatment…**
- … and **especially from machining**
- **Synergic effect** if **both** are applied



RESULTS

	Not mach.	Mach.
Not H.T.	▲ NN	◆ NM
H.T.	● HN	■ HM

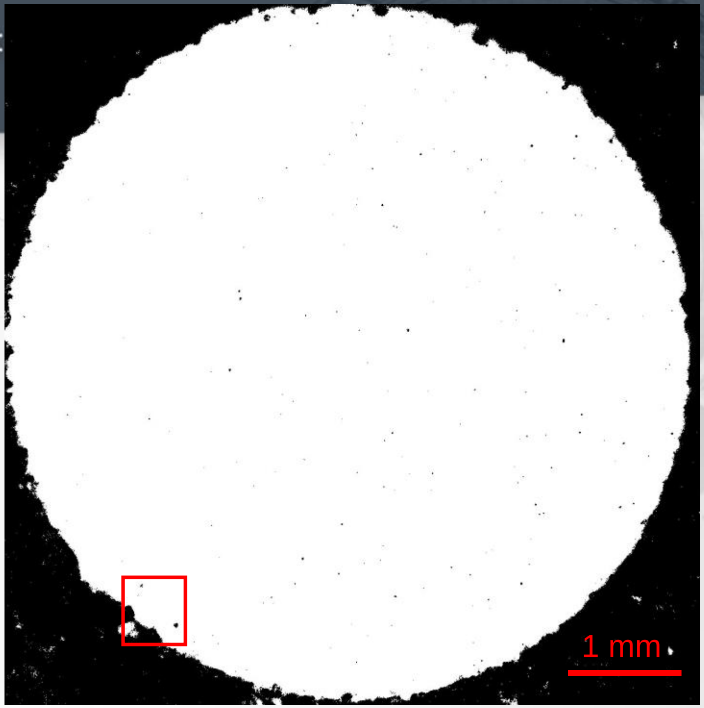
Fatigue limit 5 times incremented following **heat treatment and machining**

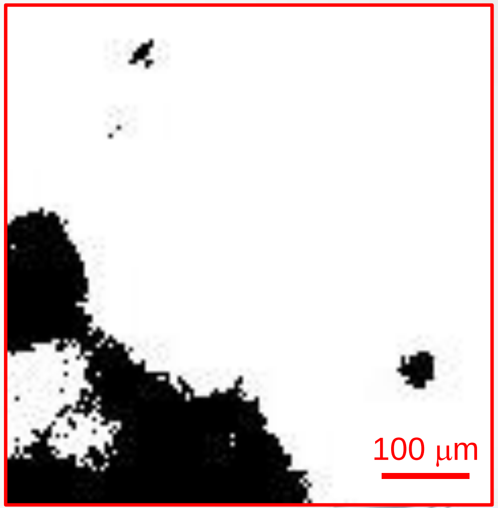


RESULTS

	Not mach.	Mach.
Not H.T.	▲ NN	◆ NM
H.T.	● HN	■ HM

- **Relative density: more than 99%**
- **Porosity**: **0.2%** regardless of sample set
- **Hardness**: **31HRC** (not heat treated), **47HRC** (heat treated)
- All the data are consistent with [3]





3 Asgari H, Mohammadi M. Microstructure and mechanical properties of stainless steel CX manufactured by Direct Metal Laser Sintering. Mater Sci Eng A. 2018; 709: 82–89.

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DISCUSSION

The S-N curves have been compared by an original ANOVA-extended method for the comparison of fatigue trends. [7]

Thus assessing the effects of heat treatment, machining and interaction.

$$SSBR = (R_1 - \bar{S})^2 + (R_2 - \bar{S})^2$$

Effect of heat treatment

$$SSBC = (C_1 - \bar{S})^2 + (C_2 - \bar{S})^2$$

Effect of machining

$$SSI = \sum_{i=1}^{2} \sum_{j=1}^{2} R_i C_j^{\ 2}$$

Interaction

$$SSE = \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{n_{i,j}} (S_{exp_{i,j,k}} - S_{calc_{i,j,k}})^2$$

Scattering of the exp. data (uncertainty)

All the results are statistically significant

[7] Croccolo, Dario; De Agostinis, Massimiliano; Fini, Stefano; Olmi, Giorgio; Bogojevic, Nebojsa; Ciric-kostic, Snezana, Effects of build orientation and thickness of allowance on the fatigue behaviour of 15–5 PH stainless steel manufactured by DMLS, «FATIGUE & FRACTURE OF ENGINEERING MATERIALS & STRUCTURES», 2018, 41, pp. 900 – 916.

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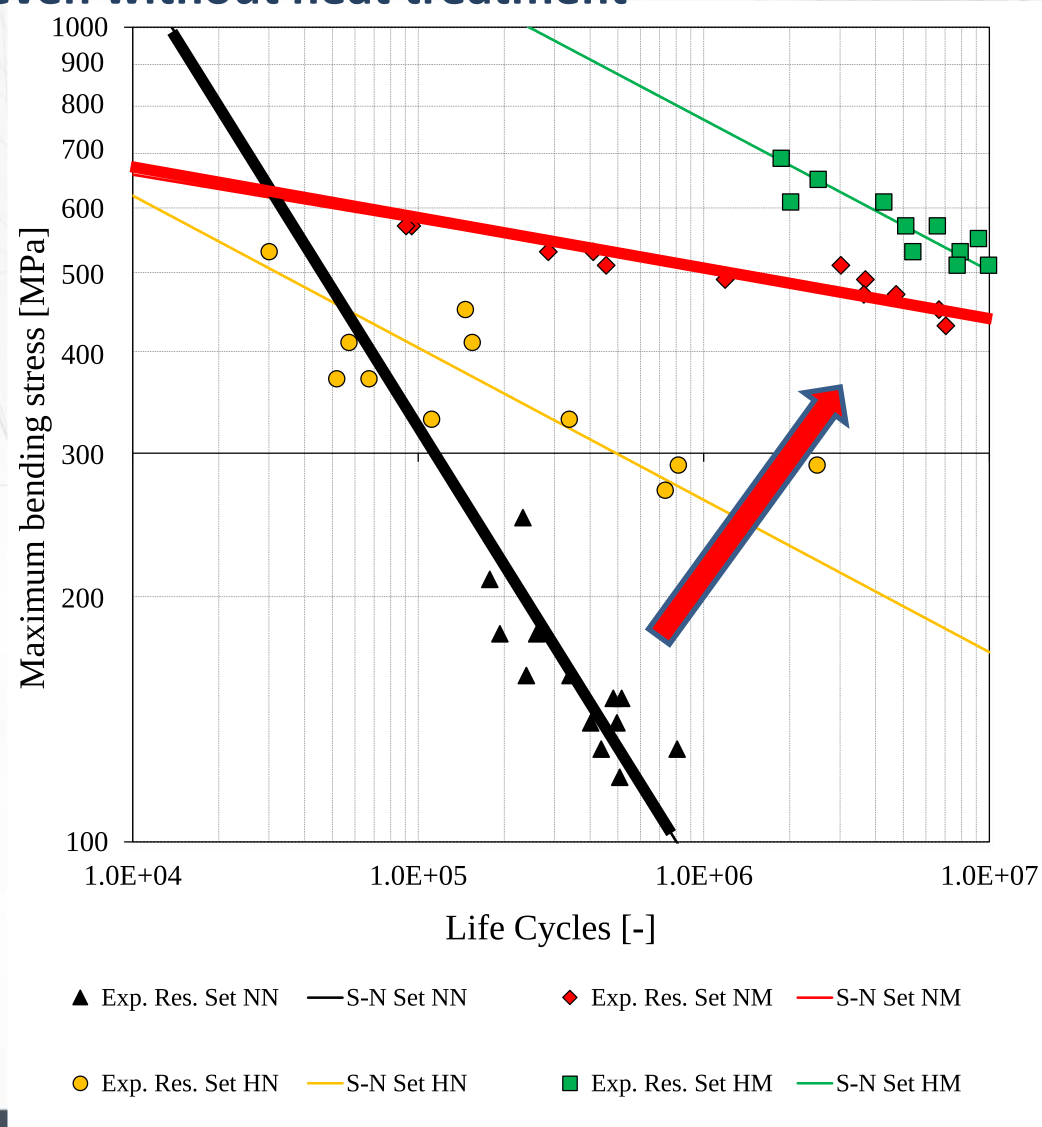
DISCUSSION

Machining is highly significant, even without heat treatment

	Not mach.	Mach.
Not H.T.	NN	NM
H.T.	HN	HM

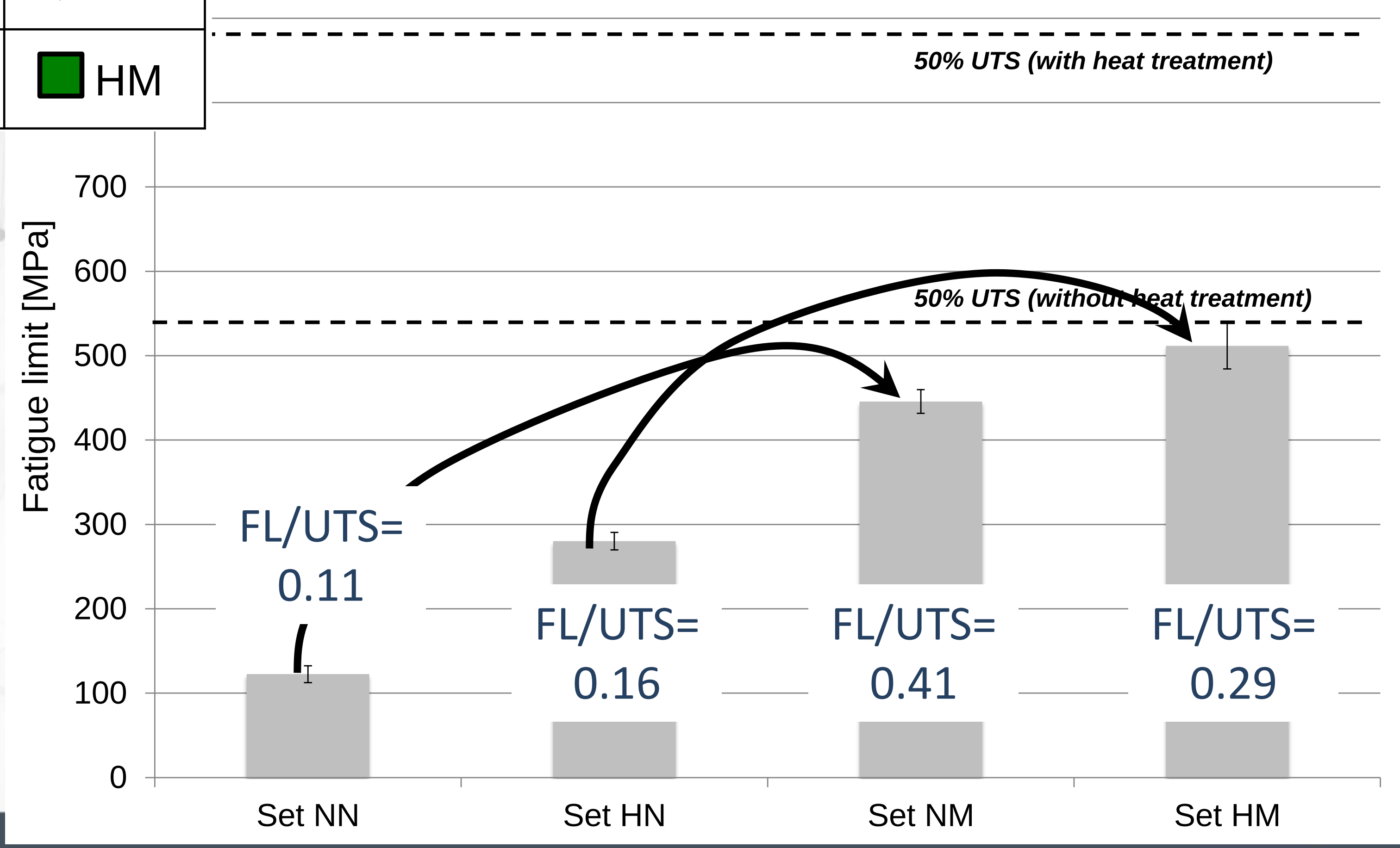
- Machining (+shot-peening) **reduces roughness from 6-7 µm to 1 µm → lower chances for crack initiation**
- **Machining removes contour lines** (0.3 mm thick) and **interface defects**



DISCUSSION

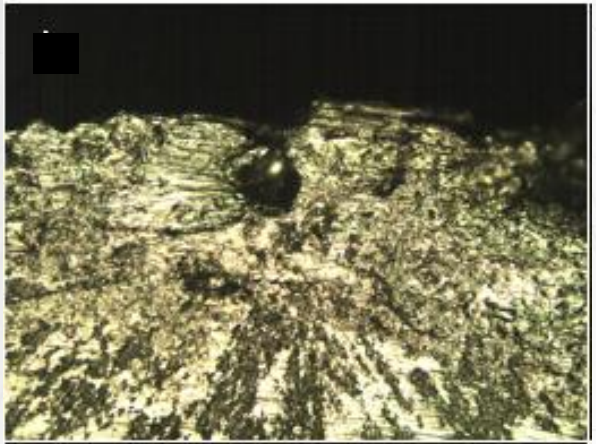
Machining is highly significant, even without heat treatment

	Not mach.	Mach.
Not H.T.	▲ NN	◆ NM
H.T.	● HN	■ HM

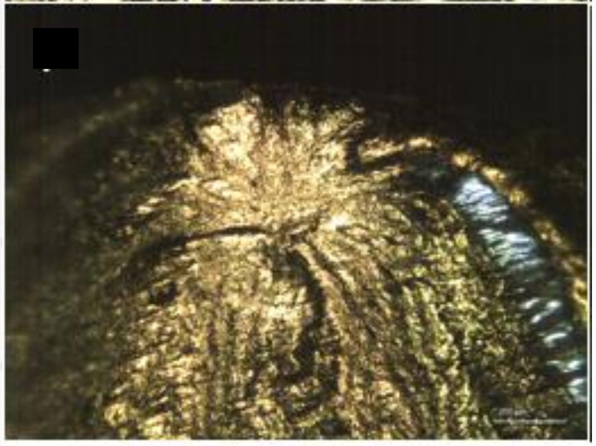


DISCUSSION

Machining is highly significant, even without heat treatment



Not machined



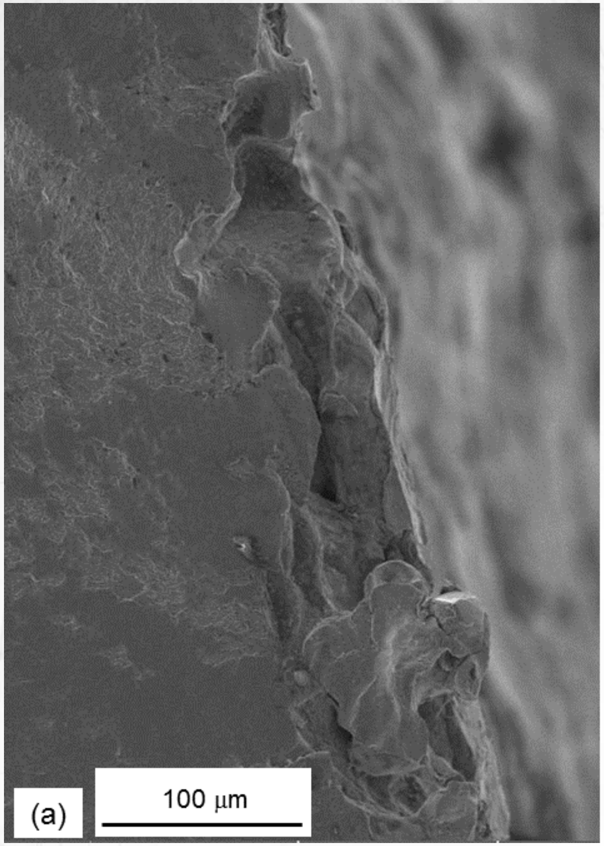
Machined

Analyses by **optical microscope**

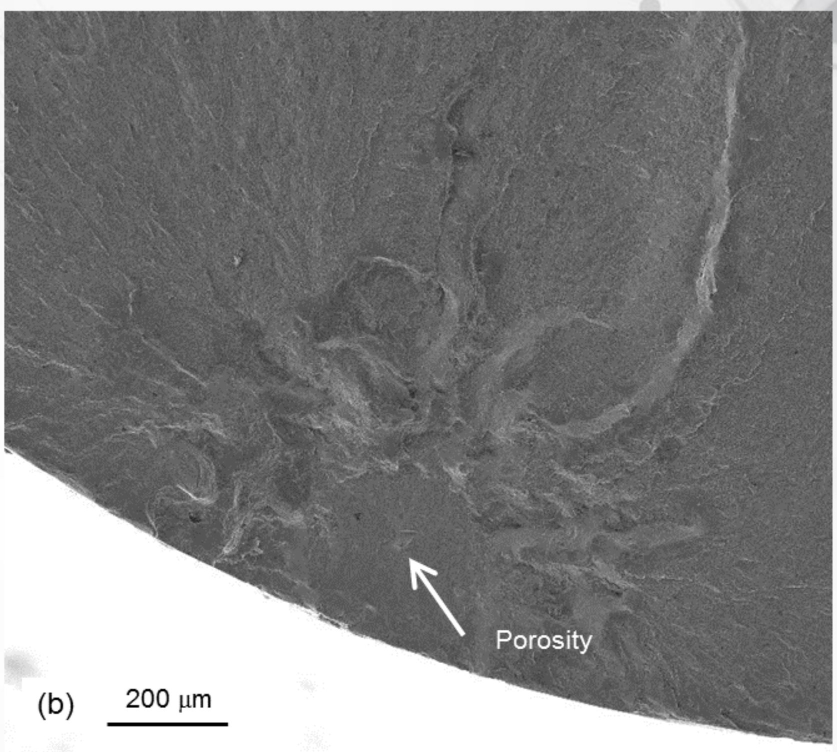
Machining moves **crack initiation beneath the surface**. Cracking is generally promoted by an **internal porosity**.

DISCUSSION

Machining is highly significant, even without heat treatment



Not machined



Machined

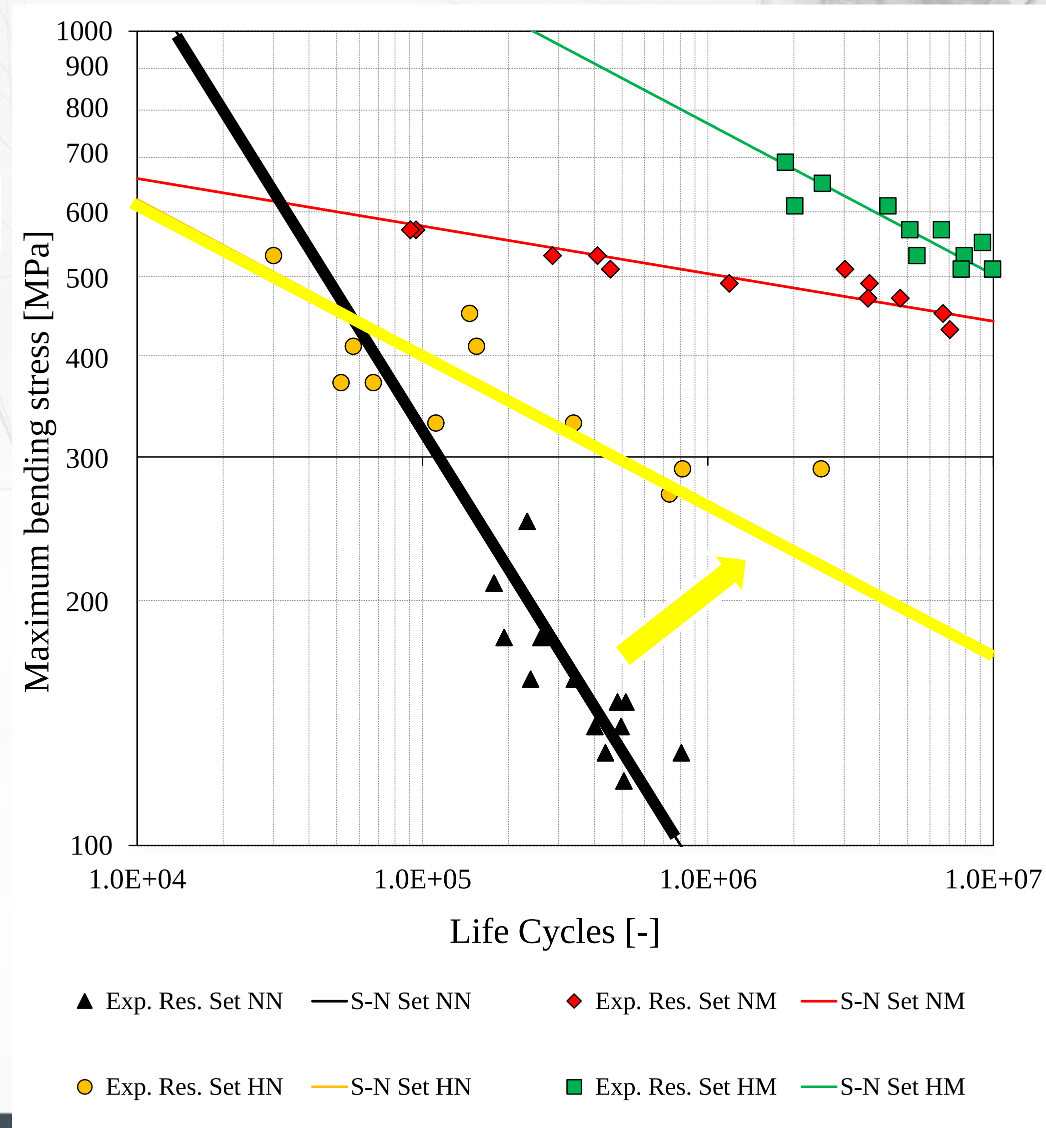
Analyses by **Field Emission Gun Scanning Electron Microscope (SEM-FEG)**

DISCUSSION

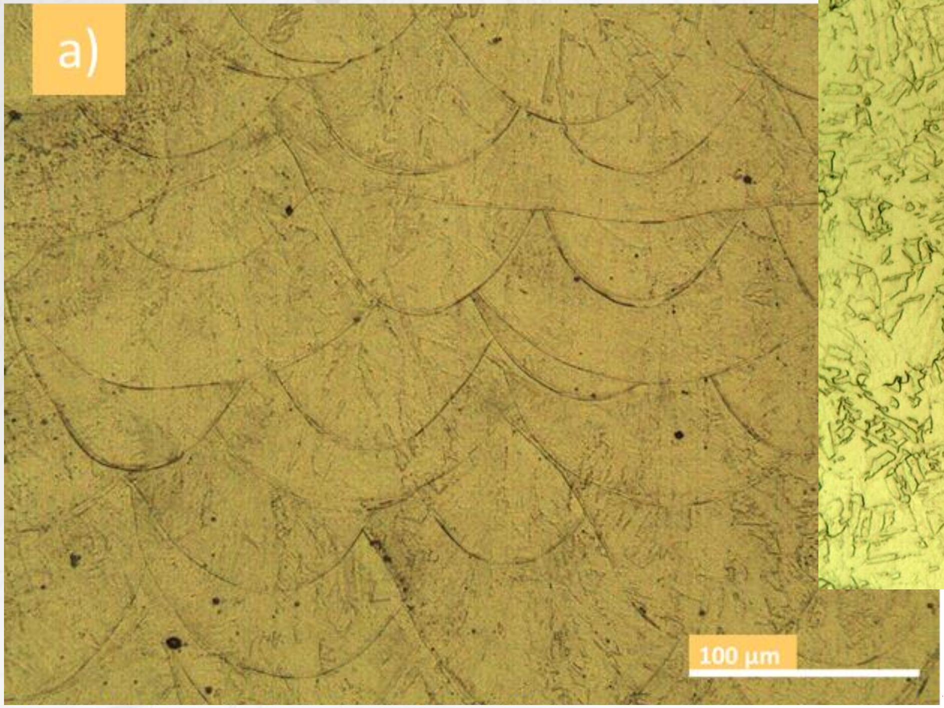
Heat treatment is also significant

	Not mach.	Mach.
Not H.T.	▲ NN	◆ NM
H.T.	● HN	■ HM

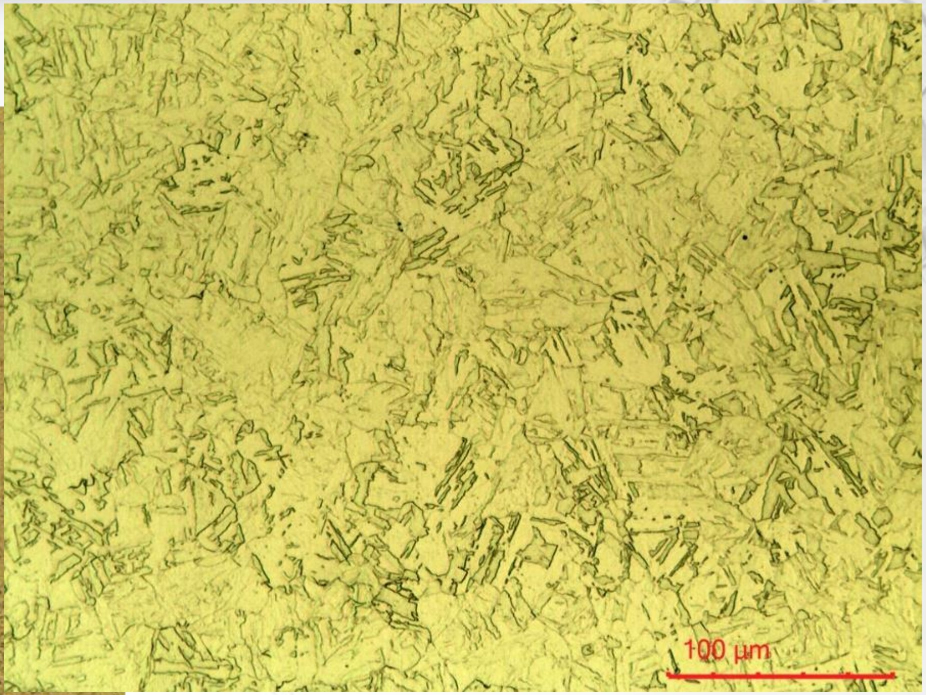
- How to explain the effect of heat treatment?
- Estimated by **microstructural analyses by optical microscope and SEM-FEG**



DISCUSSION



Not treated



Treated

Analyses by optical microscope

Heat treatment modifies microstructure. The **stacked structure is no longer visible**

DISCUSSION

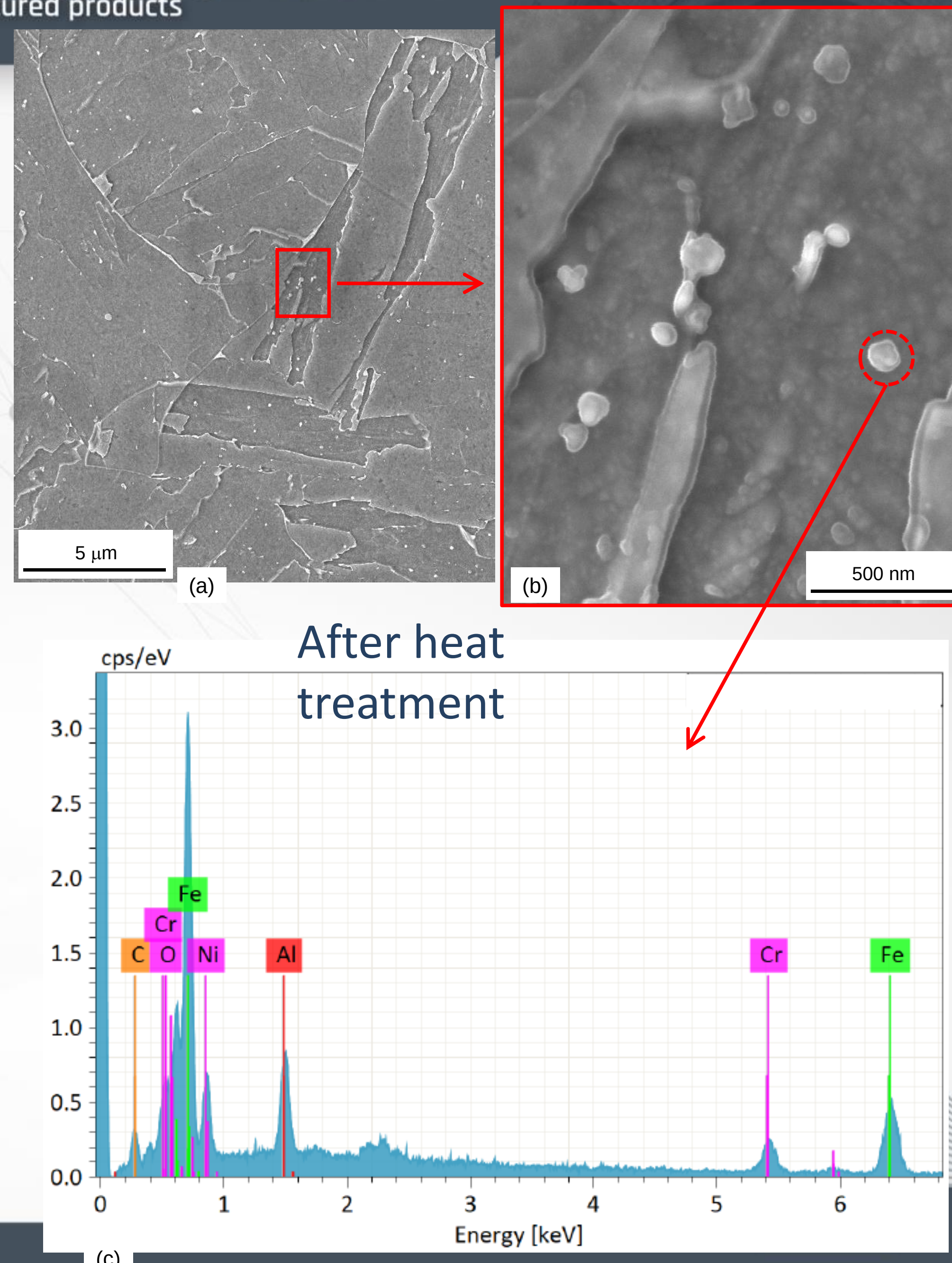
SEM-FEG analyses

β-NiAl precipitates are present

Following heat treatment, **precipitate size tends to rise**, while **new precipitates are generated** at dislocation tangles

Not treated: diameter from 20nm to 70nm

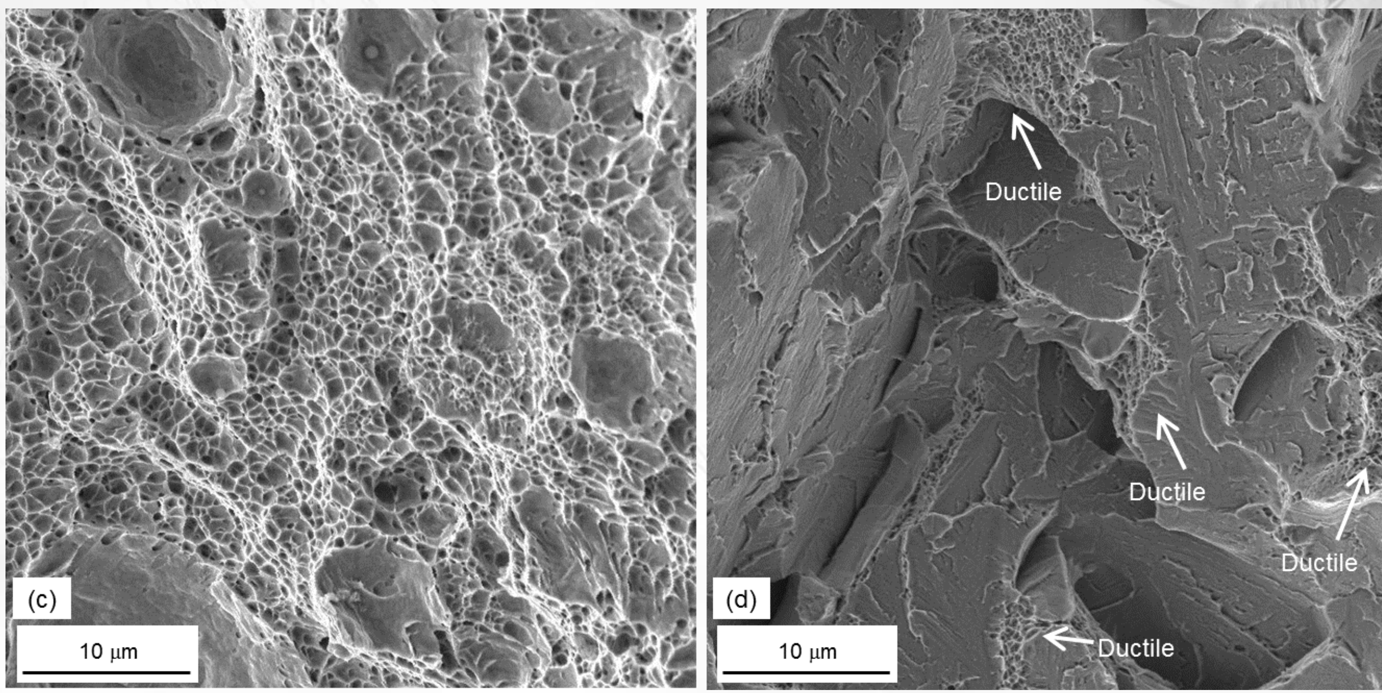
Treated: diameter from 50nm to 130nm



DISCUSSION

Precipitates strengthen the material,[5] acting as **obstacles against crack propagation**, thus **improving** static and **fatigue resistances**.

However, **fracture mode** is turned **from ductile to mainly brittle** (with some areas where the ductile mode is maintained)



Not treated

Treated

5 Chang C, Yan X, Bolot R, Gardan J, Gao S, Liu M, Liao H, Chemkhi M, Deng S. Influence of post-heat treatments on the mechanical properties of CX stainless steel fabricated by selective laser melting. J Mater Sci. 2020; 55: 8303–8316.

CONCLUSIONS

Experimental assessment of the **fatigue behaviour of Maraging stainless steel CX**, following **PBF** process, evaluating **heat treatment and machining effects**

- **First study in the literature** that addresses this topic for this novel material (**low Ni and C** and **high Cr**)
- **Machining is highly effective** for erasing surface and subsurface defects (at the interface between contour lines and the inner part of the cross section): **even without heat treatment FL/UTS beyond 40%**
- **Heat treatment also provides a significant beneficial contribution** that arises from the enlargement of Ni-Al precipitates as well as from the generation of new ones. On the other hand the **fracture mode is made more brittle**.
- Through the **synergic effect of machining and heat treatment**, the **fatigue limit is incremented by 5 times** with respect to as received conditions

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Publications (Journals only)

- S. CIRIC-KOSTIC, D. CROCCOLO, M. DE AGOSTINIS, S. FINI, **G. OLMI**, L. PAIARDINI, F. ROBUSTO, Z. SOSKIC, N. BOGOJEVIC, “Fatigue response of additively manufactured Maraging Stainless Steel CX and effects of heat treatment and surface finishing”, Fatigue & Fracture of Engineering Materials & Structures, 2021, published online, DOI: 10.1111/ffe.13611, ISSN: 8756-758X.
- D. CROCCOLO, M. DE AGOSTINIS, S. FINI, **G. OLMI**, F. ROBUSTO, S. CIRIC-KOSTIC, S. MORACA, N. BOGOJEVIC, “Sensitivity of direct metal laser sintering Maraging steel fatigue strength to build orientation and allowance for machining”, Fatigue & Fracture of Engineering Materials & Structures, 2019, 42 (1), 374-386, DOI: 10.1111/ffe.12917, ISSN: 8756-758X.
- D. CROCCOLO, M. DE AGOSTINIS, S. FINI, **G. OLMI**, F. ROBUSTO, S. CIRIC-KOSTIC, A. VRANIC, N. BOGOJEVIC, “Fatigue Response of As-Built DMLS Maraging Steel and Effects of Aging, Machining, and Peening Treatments”, Metals, 2018, 8 (7), article ID: 505, 1-21, DOI: 10.3390/met8070505, ISSN: 2075-4701.
- D. CROCCOLO, M. DE AGOSTINIS, S. FINI, **G. OLMI**, N. BOGOJEVIC, S. CIRIC-KOSTIC, “Effects of build orientation and thickness of allowance on the fatigue behaviour of 15–5 PH stainless steel manufactured by DMLS”, Fatigue & Fracture of Engineering Materials & Structures, 41, 2018, 900-916, DOI: 10.1111/ffe.12737, ISSN: 8756-758X.

G. Olmi coordinated these dissemination tasks, acting as Corresponding Author of all the aforementioned Journal papers.

G. Olmi Co-Edited the SI “Mechanical Characterization of Parts Fabricated by Additive Manufacturing” on Proc IMechE Part C: J Mechanical Engineering Science → other papers related to the project have been published

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Unit: REA/A/03

Thank you!

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