amadam Advanced design rules for optimal dynamic properties of additive manufactured products

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Horizon 2020-MSCA-RISE

FATIGUE RESPONSE OF AS-BUILT DMLS MARAGING STEEL AND EFFECTS OF AGING, MACHINING, AND PEENING TREATMENTS

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PROJECT SUPPORTED BY European Commission

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  - DIN – University of Bologna /Italy/

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FATIGUE RESPONSE OF AS-BUILT DMLS MARAGING STEEL AND EFFECTS OF AGING, MACHINING, AND PEENING TREATMENTS

EOSINT M 280

Introduction

Maraging steel MS1 as a promising materials for AM.

High density, **hardness** up to 50 HRC after the aging heat treatment, comparable to that of wrought material.

High **corrosion resistance** and very high **static strength** (UTS > 2,000 MPa after the aging treat).

Few studies on high cycle **fatigue** properties; some mainly dealing with low cycle fatigue or metallurgic matters.

Studies are **missing** regarding Maraging parts in the **"as built"** state.

The only available scientific **results** deal with fatigued **Ti-6Al-4V** in the **as built condition**.

Motivation and subject

Motivations

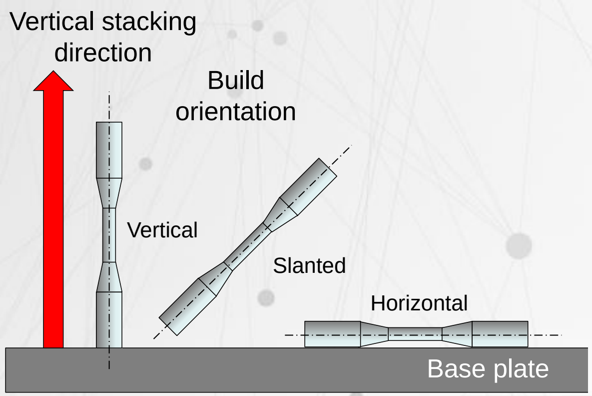
- Serious drawbacks may arise from missing post-processing.
- **Poor surface finishing** → high roughness acting as **crack trigger**
- High **tensile residual stresses** arising from the stacking process, which cannot be relaxed without aging.
- **No extensive studies** in the literature clarify if post-processing treatments, can be skipped and which is the **best compromise**.

Subject

Investigating the **joint effects** (and interaction) of **heat treatment**, **machining**, and s**hot-peening** on the fatigue response of DMLS-built Maraging Steel vs. the **as-fabricated state (as built)**.

Materials and methods

Build orientation

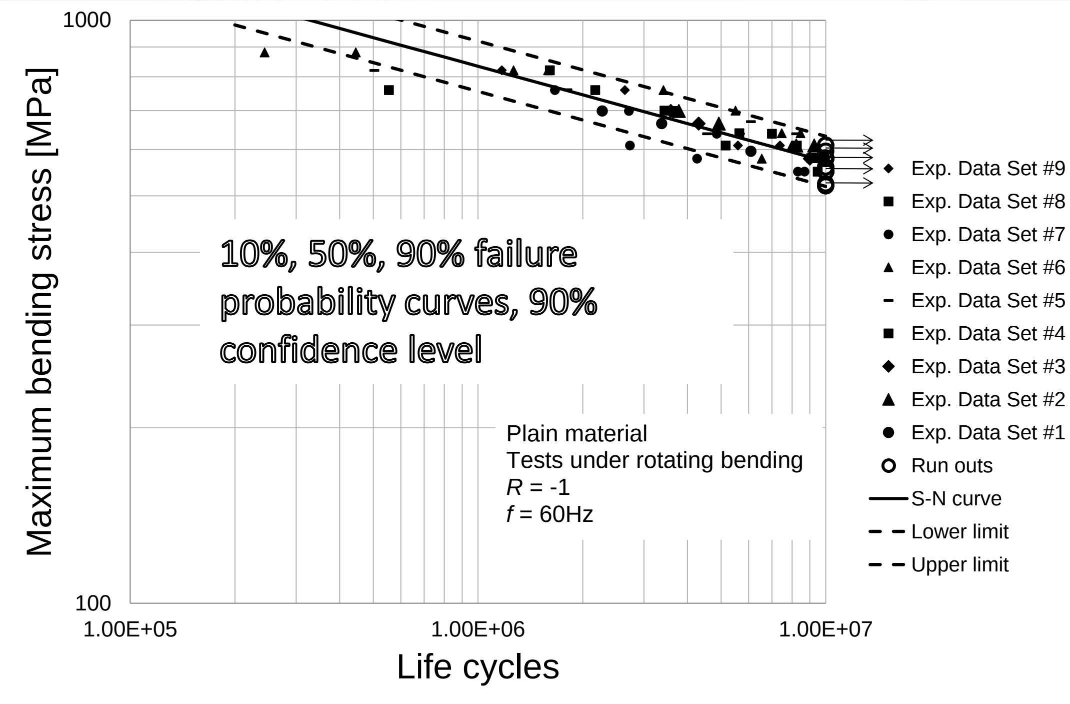


Allowance at specimen gage

	0.5mm	1mm	2mm	3mm	4mm
Vertical	Set #1	Set #7	Set #8	Set #6	Set #9
Slanted	Set #3			Set #5	
Horizontal	Set #2			Set #4	

- Maraging steel MS1 (18% Ni Maraging 300 or AISI 18Ni300).
- 10-15 samples per combination.
- Fatigue tests aimed at the determination of the S-N curves in the finite life domain and of fatigue limits.
- Data have been processed by ISO 12107 (S-N curves) and by the Dixon method for short staircase sequences.
- Statistical analysis.

Results

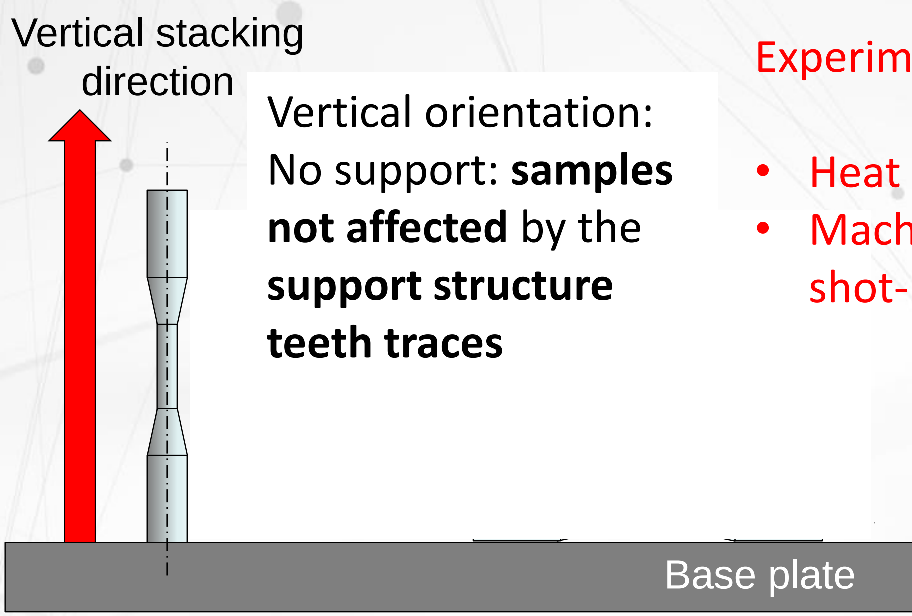


All aligned results → **Global S-N curve** interpolated through **56 data**.

One the **most complete, general and reliable curves** in the current literature on Maraging Steel.

Materials and method

- Maraging steel MS1 (18% Ni Maraging 300 or AISI 18Ni300).
- Tests under rotating bending (ISO 1143).



Vertical orientation:
No support: **samples not affected** by the **support structure teeth traces**

Experiment:

- Heat treatment (ON-OFF)
- Machining: no, yes, subsequent shot-peening

Materials and method

		Machining: No	Machining: Yes	Machined and shot-peenig
Aging treatment	No	Set N	Set M	MP
	Yes	Set H	Set HM	

- 15 samples per combination.
- Determination of the S-N curves and of fatigue limits.
- Data processed by ISO 12107 and by the Dixon method.
- Statistical analysis.

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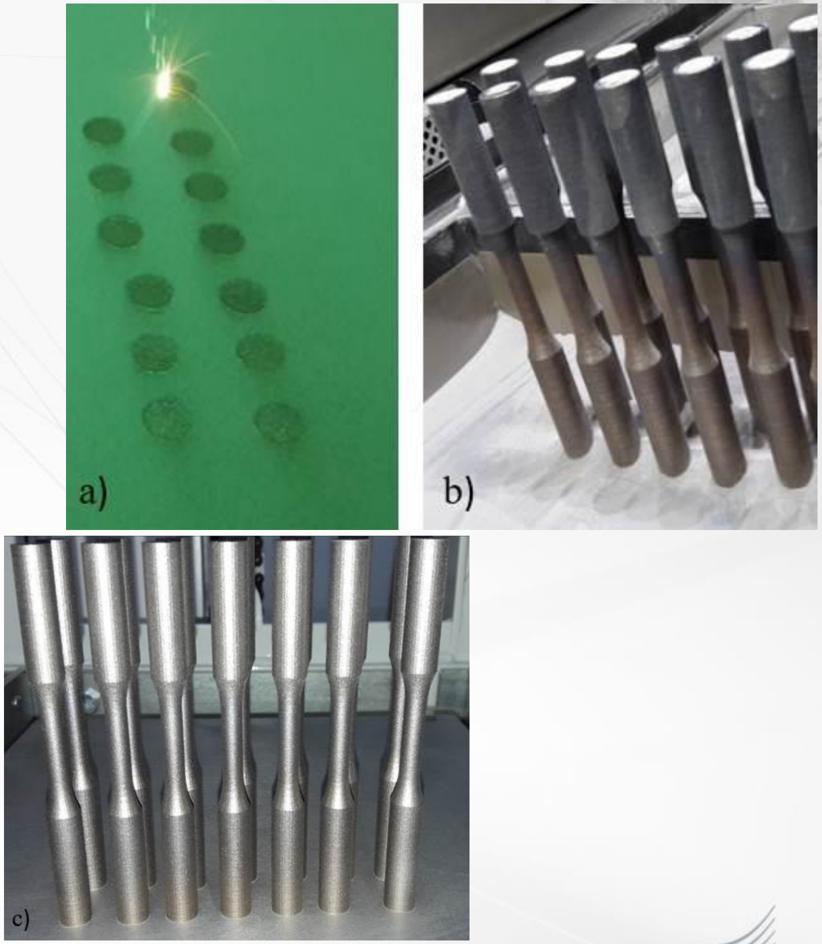
Materials and method

Production

Samples produced by EOSINT M280 system, layer thickness: 40 μm.

Post-manufacture treatments

- All the samples: micro-shot-peening (stainless steel spherical shots, 400μm diameter, 5 bar flow pressure).
- Sets H and HM: Age-hardening at 490°C for 6 hours.
- Sets M and HM: machining with 0.5 mm allowance.
- Sets MP: machining with 0.5 mm allowance, **then shot peening**



Materials and method

Aging treatment \ Machining	No	Yes	Yes with subseq. machining
No	Set N	Set M	Set MP
Yes	Set H	Set HM	

1-factor design

- Added a fifth treatment: **MP**
- 15 samples.
- **Machining** (0.5 mm allowance) and **shot-peening** (steel shots with 0.7 mm diameter, 5 bar) **after machining**.
- To take advantage of both **surface finishing** and peening induced **compressive residual stresses**.

Experimental procedure

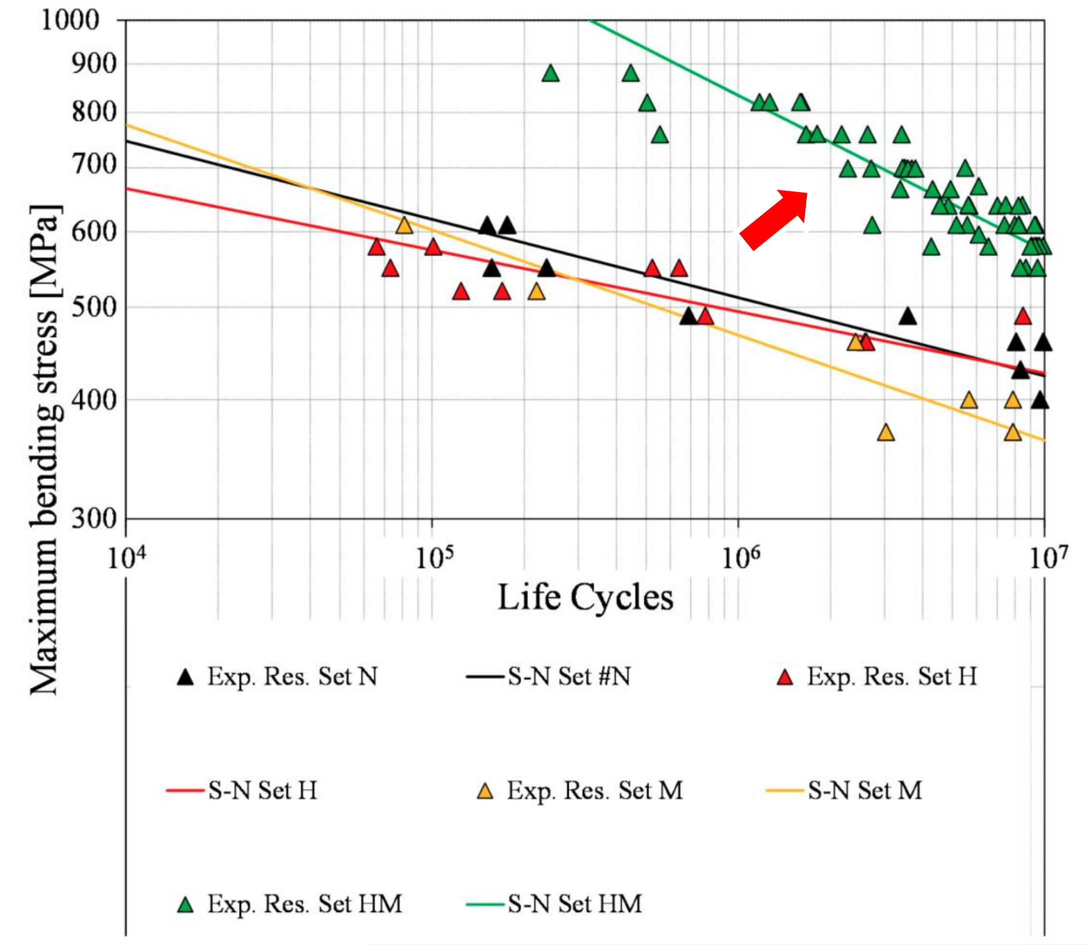
- All the samples have been checked for dimensions and roughness.

  “As fabricated”: R_a=4.1μm, machined: R_a=0.5μm, after shot-peening: R_a=1μm (impact dimples).

- Fatigue tests under four-point rotating bending. Machine by Italsigma, Forlì, Italy.
- Run-out: 10^7 cycles.
- Fractography and micrography by stereoscopic and optical microscopes.

Results

	Unmach.	Mach.
Not aged	Set N	Set M
Aged	Set H	Set HM



2-by-2 design: effects and interaction of heat treat. and machining.

Fatigue strength remarkably enhanced for Set HM

Discussion

Heat treatment (alone) is **not significant**.

Machining (alone) is **not significant**.

But Heat treatment & machining (together) are highly significant → **huge interaction**.

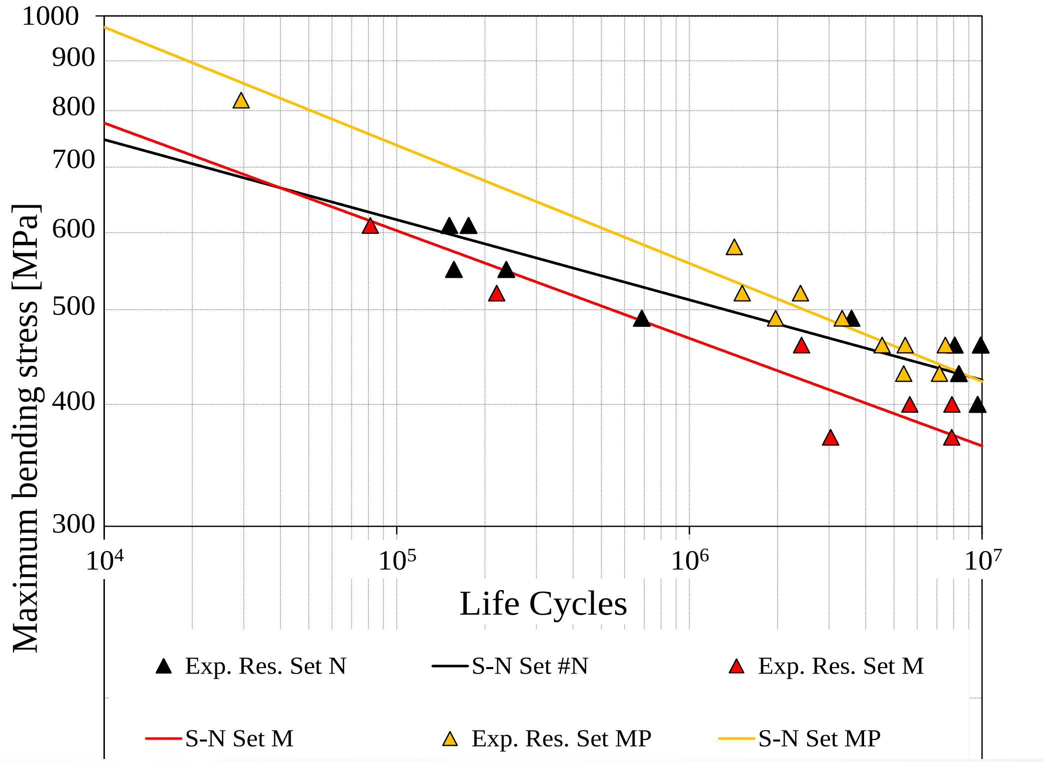
Possible reasons

- **Heat treatment** makes Maraging steel more **notch-sensitive**.
- **Not refined surface** → a lot of **surface asperities** (notches) → even (slightly) **detrimental effect**.
- **Machined ground surface** → no asperities → highly effective → great **interaction** with **synergic fatigue** behavior **enhancement**.

Results

One-factor table: machining and shot-peening.

Shot-peening after machining seems to have a beneficial impact on finite life fatigue.



No	Yes Machining	Yes with subseq. machining	
Set N	Set M	Set MP	Not aged

Discussion

1-factor ANOVA-based method: differences between the fatigue strengths vs. data scattering (uncertainty, sum of squares of the residuals)

$$SSBC = \left[\left(\overline{S_N} - \overline{S_{..}}\right)^2 + \left(\overline{S_M} - \overline{S_{..}}\right)^2 + \left(\overline{S_{MP}} - \overline{S_{..}}\right)^2\right]$$

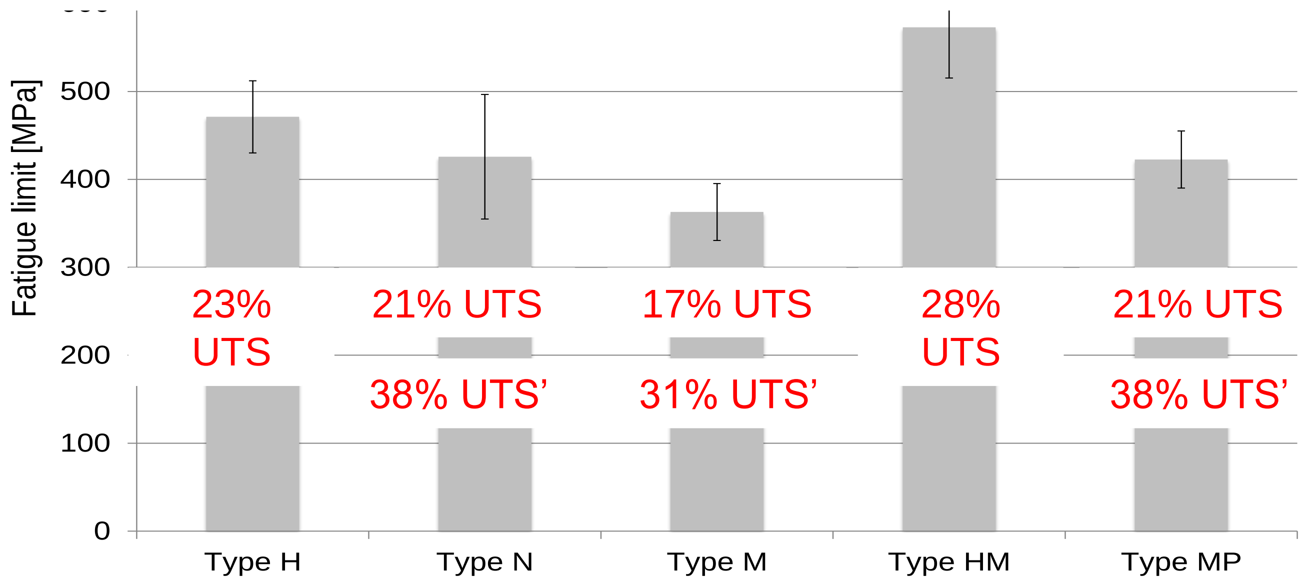
Effect of machining

Integral means over the considered life span (10^5 to 10^7) → scalars to be processed in a conventional ANOVA after being scaled by their d.o.f.

Shot-peening after machining significantly **improves** the fatigue strength (finite life domain) as an effect of additional **compressive residual stress**.

Shot-peening is conversely **usually recommended before machining** by EOS → original contribution to post-processing optimization.

Discussion



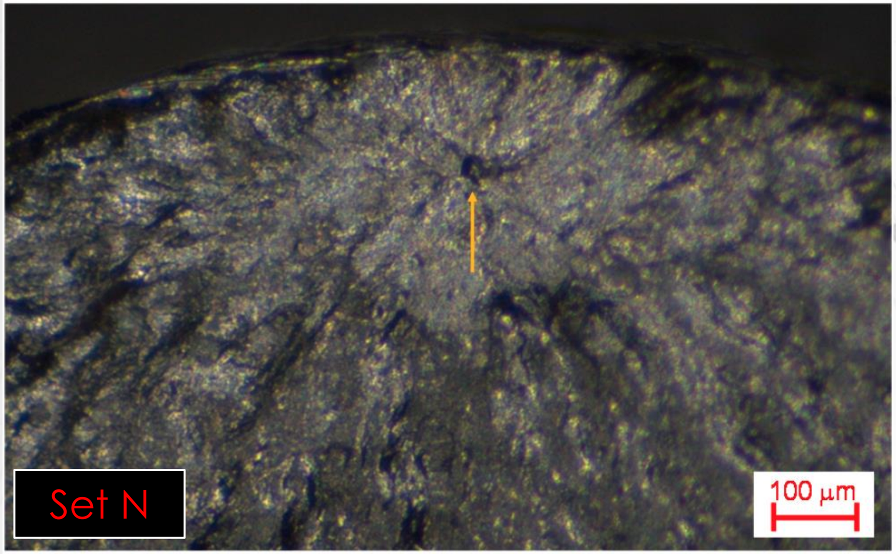
UTS=2050 MPa, after aging; **but** UTS' is just 1100 MPa, after building (no aging).

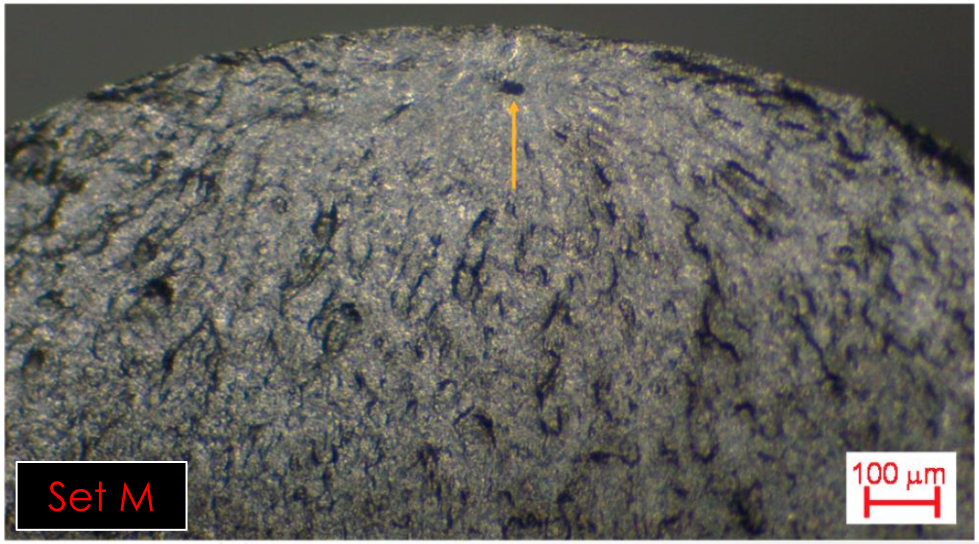
Set N: fatigue limit = 426 MPa

21% UTS (aged material)

38% UTS' (not aged material)

Fractography

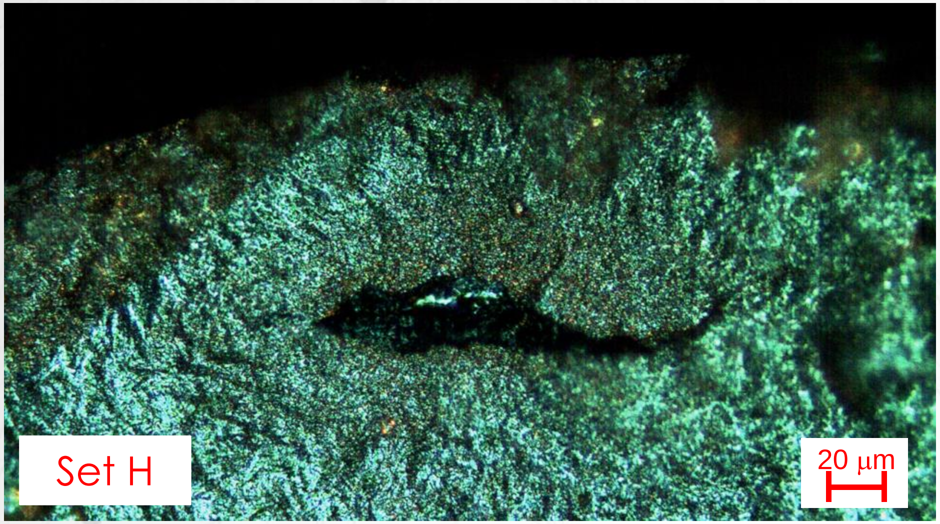


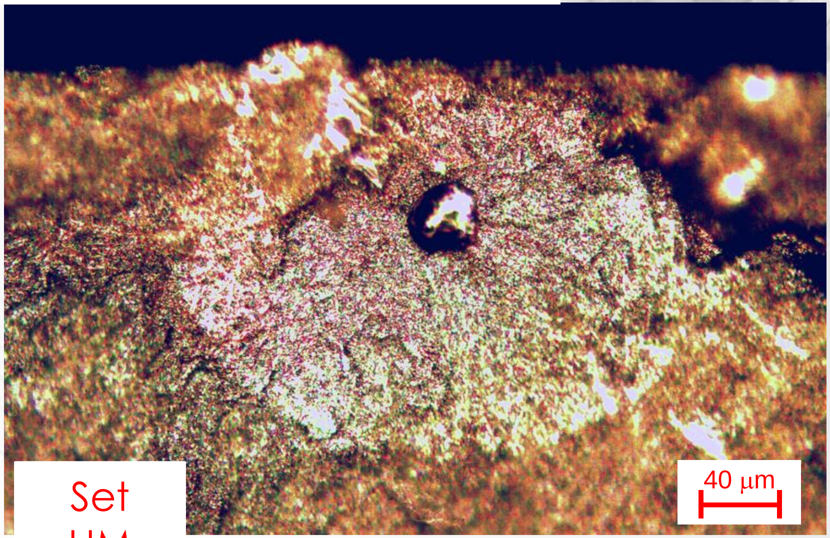


Failures started **from the surface** or, more often, **from sub-surface porosities** of voids.

Lack of penetration, unmolten particles, spots of oxides can be regarded as the **primary failure mechanisms**.

Fractography



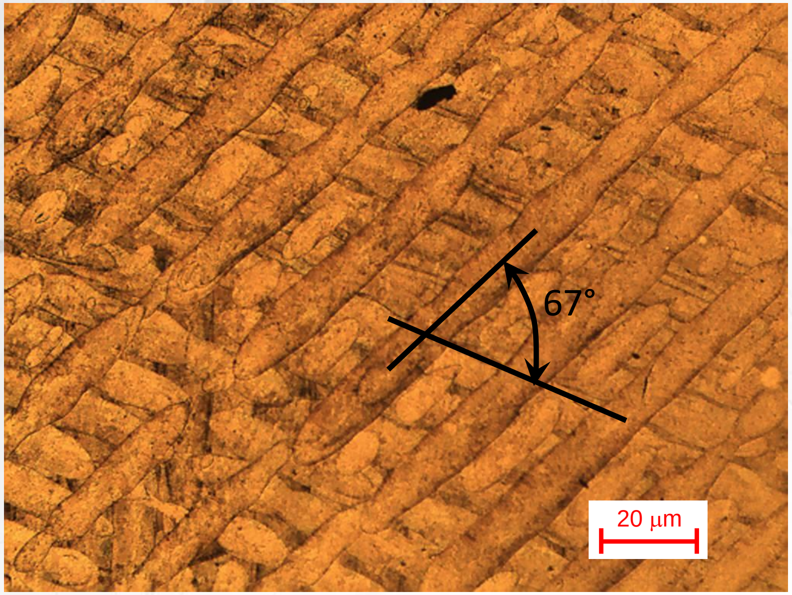


Set HM

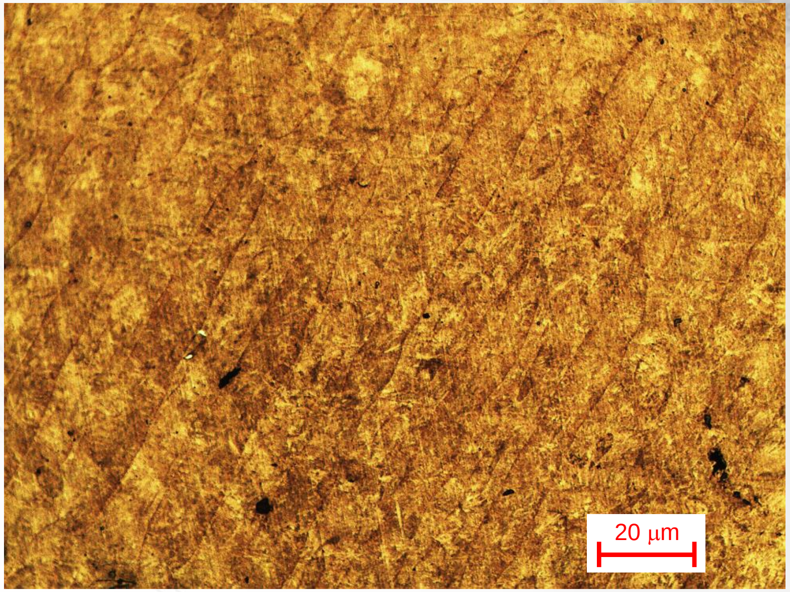
Failures started **from the surface** or, more often, **from sub-surface porosities** of voids.

Lack of penetration, unmolten particles, spots of oxides can be regarded as the **primary failure mechanisms**.

Micrography



Without aging



With aging

Laser scans on the build plane (sample cross section).

Reciprocally angled by 67°C on adjacent layers.

Samples **without heat treatment**: **well visible** scanning pattern.

Treated samples: **more uniform structure**, but scanning traces **still visible**.

Conclusion

- **Heat treatment** and **machining**, taken **alone**, do **not** have a **significant effect**.
- If applied **together**, they have a **beneficial synergic effect** (interaction). **Aging treatment** recommended on **refined surfaces**.
- **Shot peening after machining** has a **beneficial** effect even without heat treatment. → **Recommended** protocol for post-processing.
- Samples in the “**as built conditions**” have a fatigue limit corresponding to **426 MPa** (38% UTS’ for **not aged** material).

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.

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Thank you!

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