In-situ heat transfer performance and durability assessment of GeoHex developed coatings

This project has received funding from the European Union's Horizon2020 Research and Innovation Programme. Grant Agreement 851917

Introduction & aim

Organic Rankine Cycle (ORC)

- ORC powerplants are a great option for low-medium geothermal resources (80-160°C).
- Plate heat exchangers are often used where a working fluid is on one side and geothermal fluid on the other side.
- Working fluid is boiled and the vapor transfers energy to turbines which generate electricity.
- Working fluid is then condensed to repeat the continuous cycle.

Objectives:

- Increase heat transfer performance for single phase heat transfer application in the geothermal field.
- Increase anti-scaling and anti-corrosion properties of heat exchanger material.

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Introduction & aim

Material development in GeoHex:

- Multiple types of coatings have been developed
  - Thermal sprayed aluminum coating (TSA)
  - Physical vapor deposition coatings (Amorphous 1 & Amorphous 2)
  - Electroless nickel plated coatings (ENP)
  - Chemical vapor deposition coatings (MWCNT)
  - High velocity oxygen fuel coatings (Nanoporous)
- Various parameters optimized throughout the earlier stages of coating development

Heat transfer performance & durability assessment:

- In-situ heat exchanger test rig fitted with temperature and flow sensors
- Microstructural analysis of tested samples using SEM/EDX and XRD
- Pull off adhesion tests

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Laboratory vs in-situ testing

Laboratory testing:

- Controlled conditions
- More conclusive
- Corrosion effect can be accelerated more easily

In-situ testing:

- Real environment
- Often (but not always) less expensive
- More complex environment – more inconclusive

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Material systems tested

Coatings					
Coating ID	Name	Coating type	Composition	Substrate	Manufacturer
HST-10-150	Nanoporous	HVOF	TiO_2	Carbon steel & 316L	ULEIC
MWCNT	MWCNT	CVD	C	316L	UPB
GHX036	Amorphous 1	PVD	Si:Ta:Fe - 25:55:20	316L	Grein
GHX042	Amorphous 2	PVD	Si:Ta:Ti – 34:33:33	316L	Grein
HP-HP-PTFE	NiP	ENP	Ni-P	Carbon steel	ULEIC
TSA	TSA	Arc spray	Al	Carbon steel	TWI

Samples		
Substrate	Coating on working fluid side	Coating on brine side
SS	Nanoporous (N)	Amorphous 1 (A1)
SS	Nanoporous (N)	Amorphous 2 (A2)
SS	316L	Amorphous 2 (A2)
SS	MWCNT	Amorphous 1 (A1)
CS	Nanoporous (N)	NiP
CS	TSA	TSA

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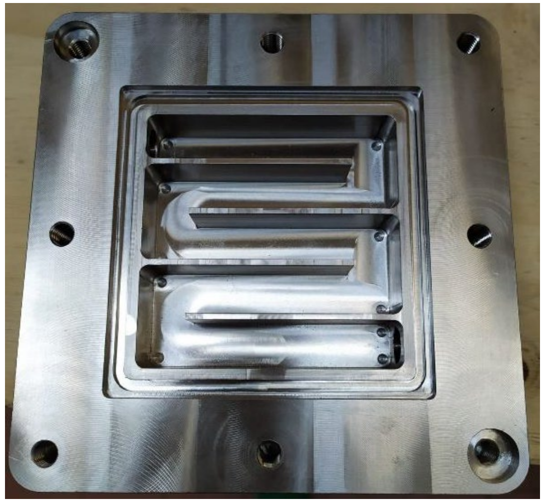
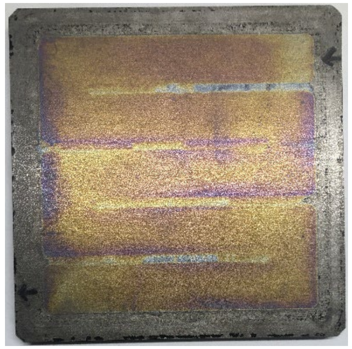
Test rig

- Located at Hellisheiði geothermal power plant.
- Geothermal brine used from seperator water, 1st flash
- Short testing: 24 hours
- Long testing: 200 hours

Pressure (bar-g)	8.4
Temperature [°C]	172
pH	8.7
Temperature @pH	26
CO2 [mg/kg]	30
H2S [mg/kg]	50
SiO2 [mg/kg]	676
Na [mg/kg]	206
K [mg/kg]	35
Ca [mg/kg]	0.74
Mg [mg/kg]	< 0.05
Fe [mg/kg]	0.05
Al [mg/kg]	1.7
SO4 [mg/kg]	16
Cl [mg/kg]	186
F [mg/kg]	1.15





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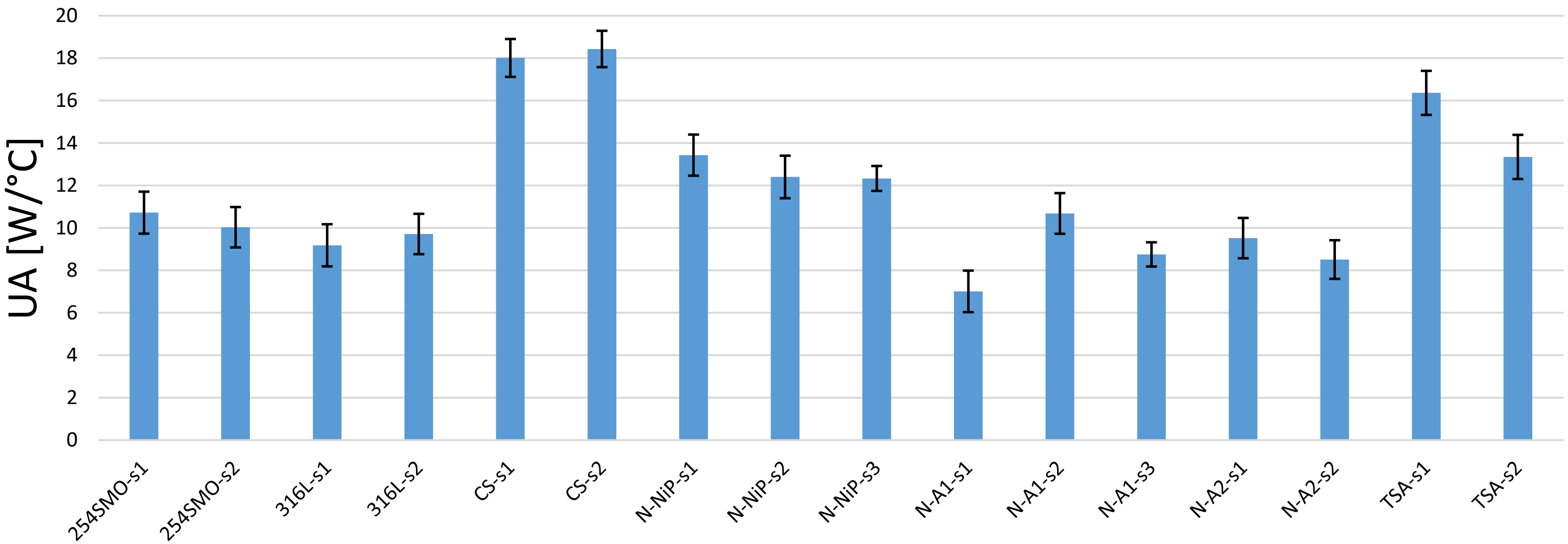
Heat transfer coefficient

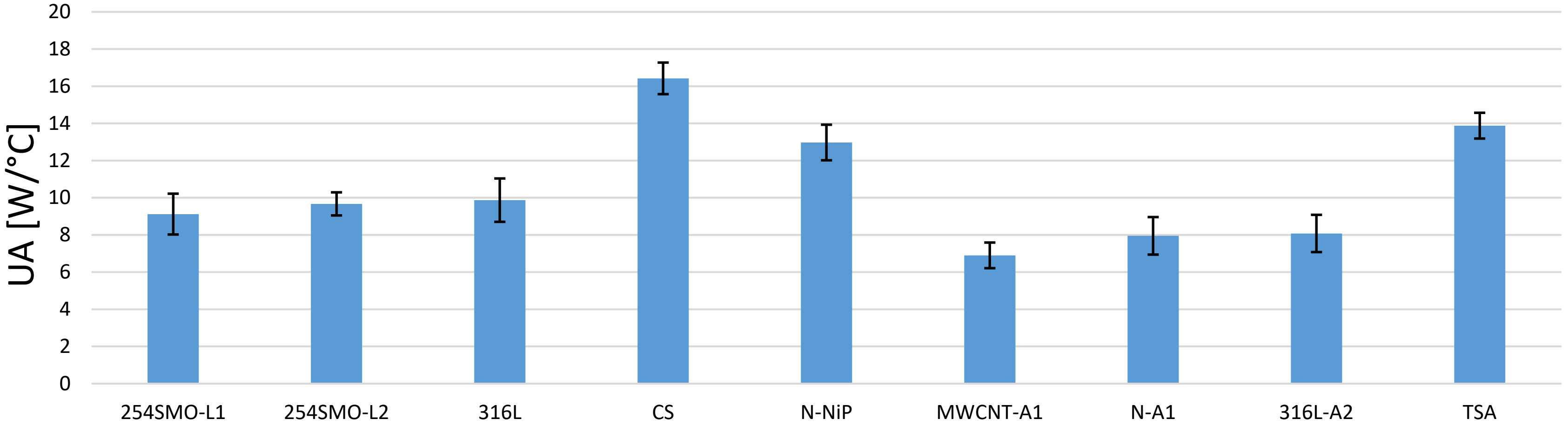
Short term testing	
Sample ID	UA [W/°C]
254SMO-s1	10.72 ± 0.99
254SMO-s2	10.03 ± 0.95
316L-s1	9.18 ± 0.99
316L-s2	9.71 ± 0.95
CS-s1	18.01 ± 0.89
CS-s2	18.43 ± 0.86
N-NiP-s1	13.43 ± 0.97
N-NiP-s2	12.40 ± 1.00
N-NiP-s3	12.33 ± 0.59
TSA-s1	16.36 ± 1.04
TSA-s2	13.35 ± 1.04
N-A1-s1	7.01 ± 0.98
N-A1-s2	10.68 ± 0.96
N-A1-s3	8.75 ± 0.57
N-A2-s1	9.52 ± 0.95
N-A2-s2	8.51 ± 0.91

Long term testing	
Sample ID	UA [W/°C]
254SMO-L1	9.12 ± 1.10
254SMO-L2	9.67 ± 0.62
316L	9.87 ± 1.17
CS	16.42 ± 0.85
N-NiP	12.97 ± 0.96
MWCNT-A1	6.90 ± 0.69
N-A1	7.95 ± 1.01
316L-A2	8.08 ± 1.00
TSA	13.88 ± 0.69

Short term testing



Long term testing



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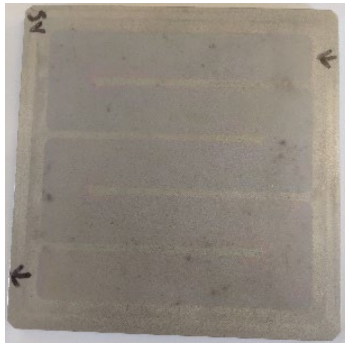
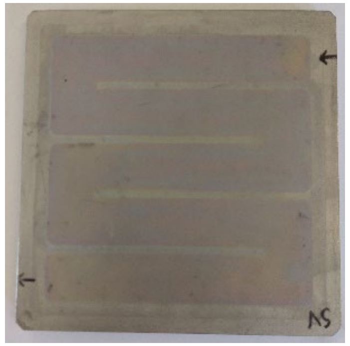
Sample overview after testing – Brine side, short term testing

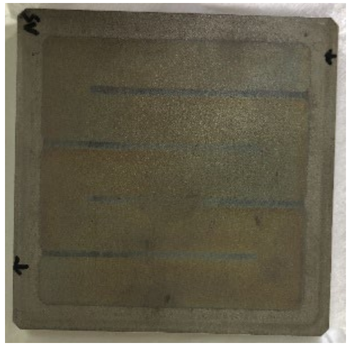
254SMO-s1



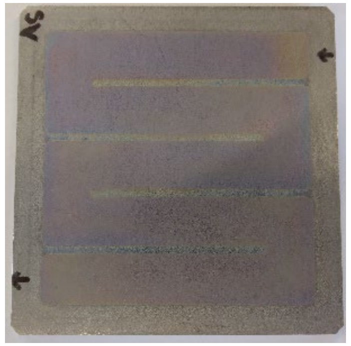
254SMO-s2



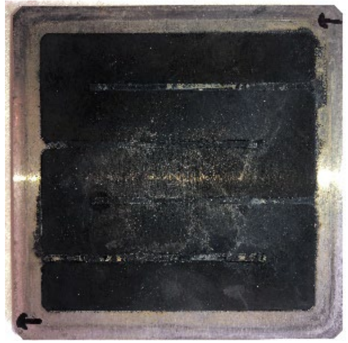
316L-s1



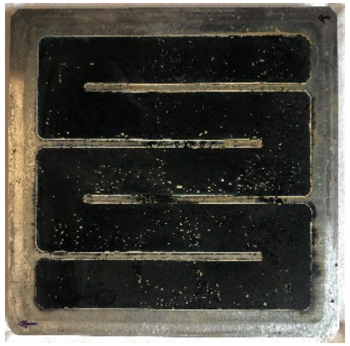
316L-s2



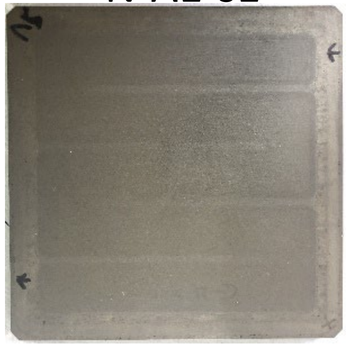
CS-s1



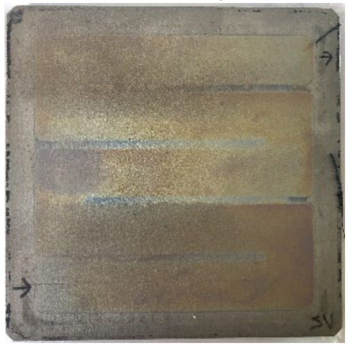
CS-s2



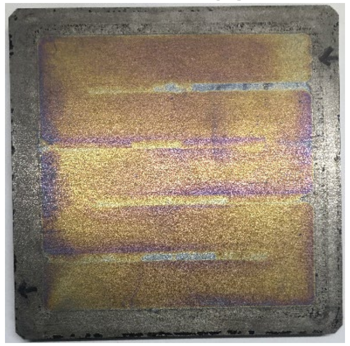
N-A1-s1



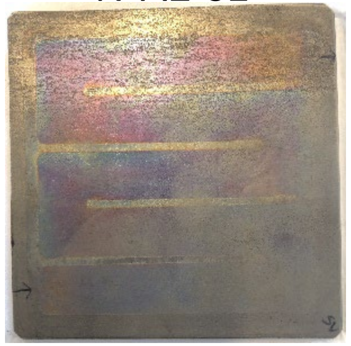
N-A1-s2



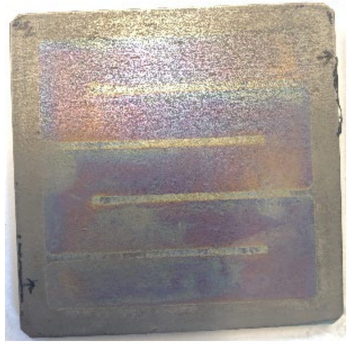
N-A1-s3



N-A2-s1

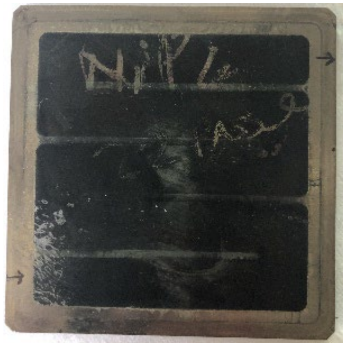


N-A2-s2

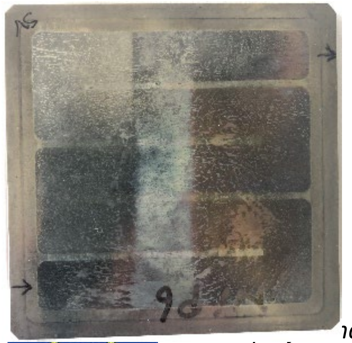


Nanoporous on the WF side

N-NiP-s1

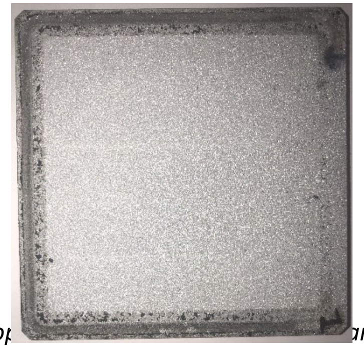


N-NiP-s2

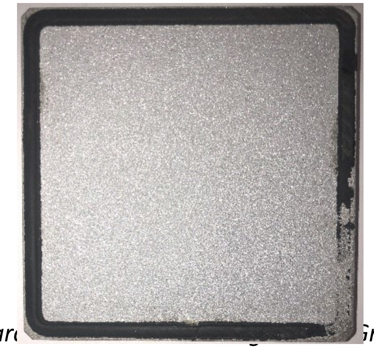


N-NiP-s3

TSA-s1



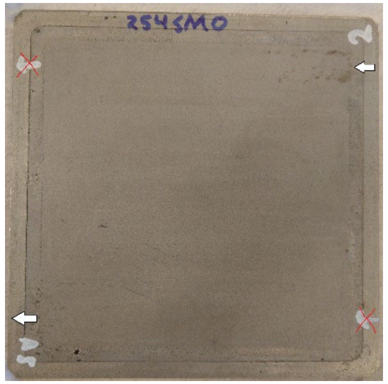
TSA-s2



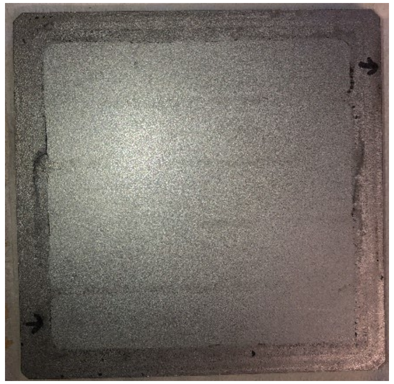
Sample overview after testing – Brine side, long term testing

GEOHEX

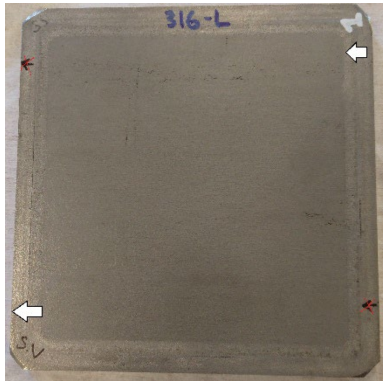
254SMO-L



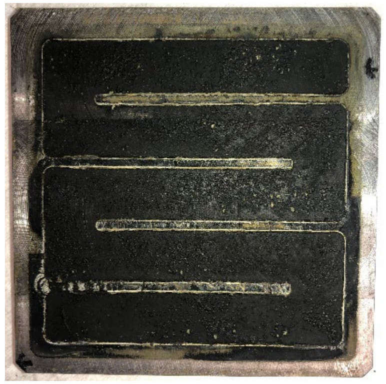
254SMO-L2



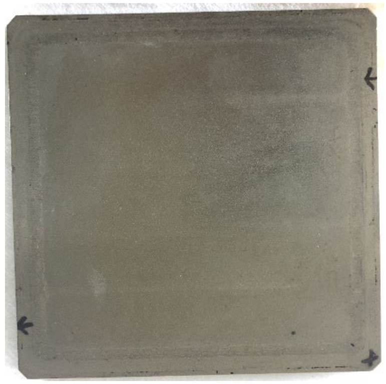
316L



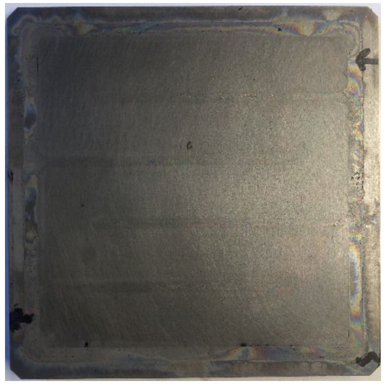
CS



N-A1



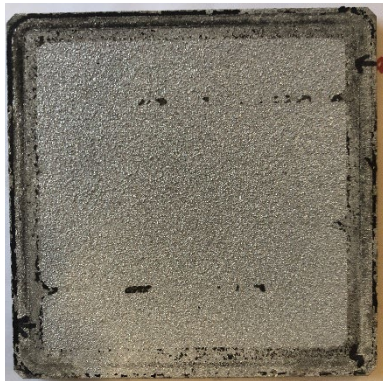
316L-A2

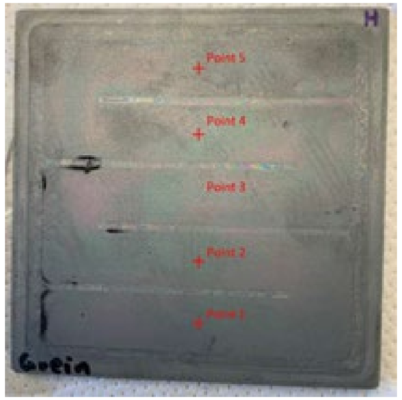


N-NiP

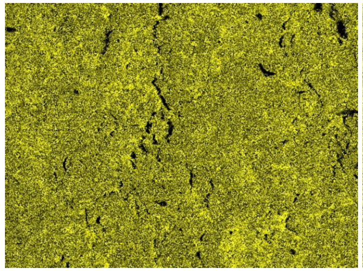
MWCNT-A1

TSA

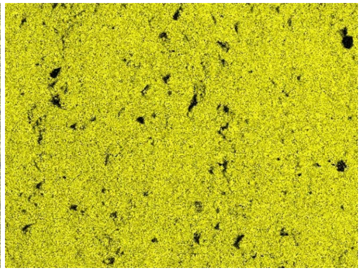




254SMO-s1



254SMO-L



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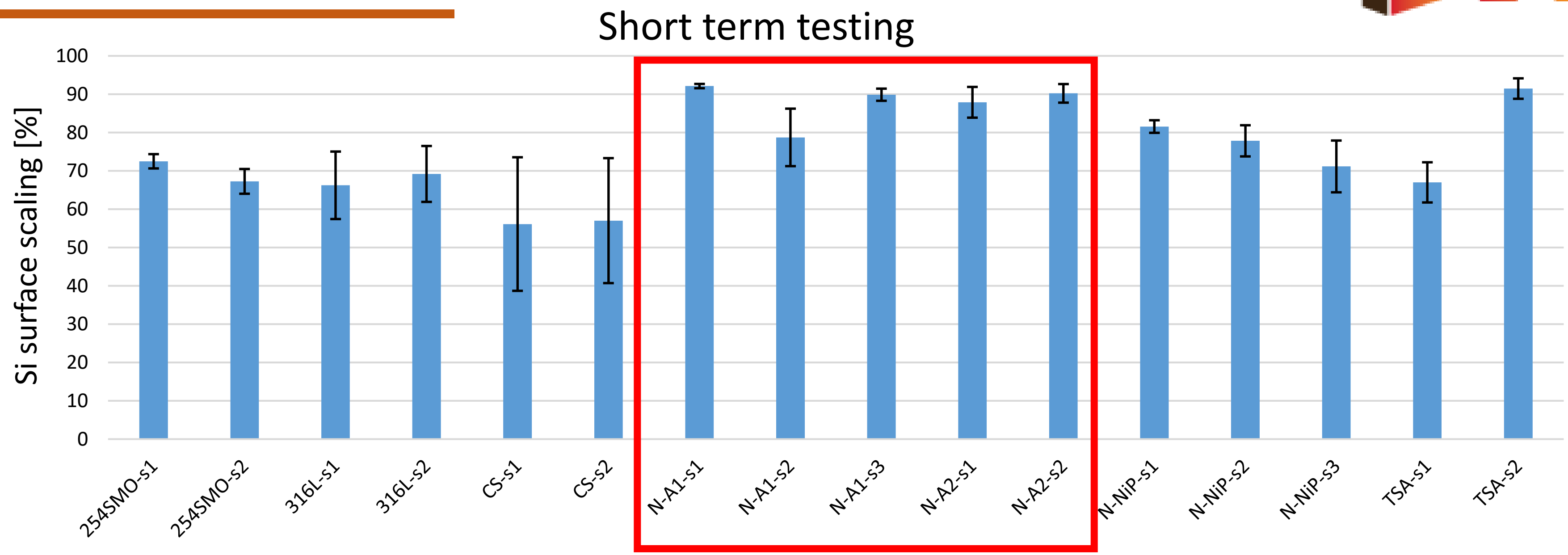
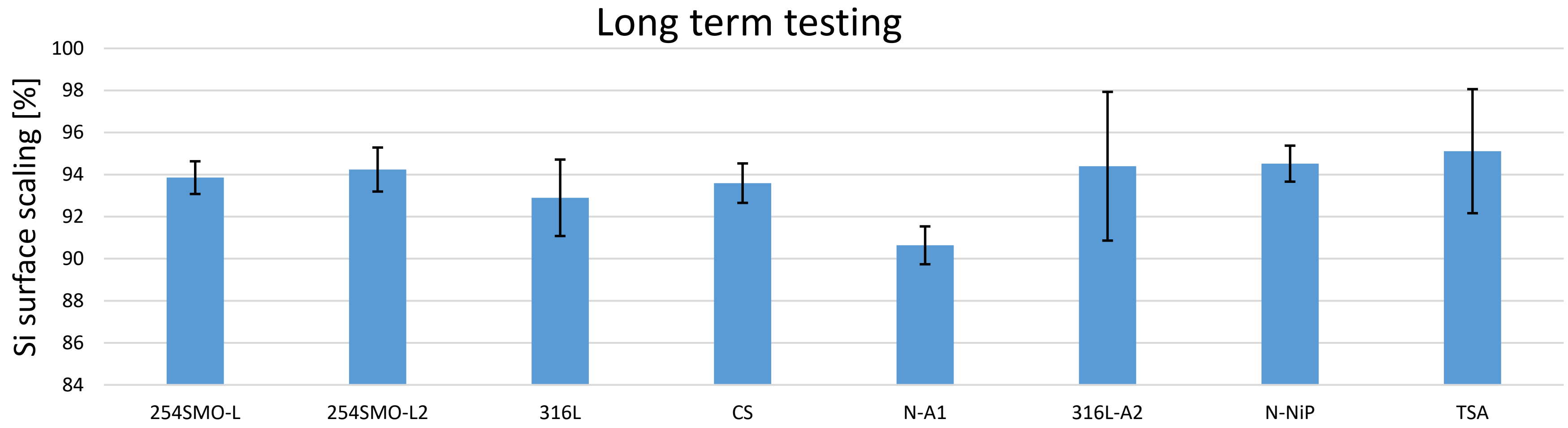
Silica scaling assessment – External surface

Short term testing		
Sample name	Average area covered in Si [%]	
254SMO-s1	72.51	± 1.85
254SMO-s2	67.27	± 3.24
316L-s1	66.25	± 8.82
316L-s2	69.22	± 7.30
CS-s1	56.13	± 17.43
CS-s2	57.02	± 16.30
N-A1-s1	92.14	± 0.55
N-A1-s2	78.74	± 7.50
N-A1-s3	89.88	± 1.60
N-A2-s1	87.90	± 4.00
N-A2-s2	90.24	± 2.41
N-NiP-s1	81.58	± 1.66
N-NiP-s2	77.86	± 4.07
N-NiP-s3	71.18	± 6.75
TSA-s1	67.02	± 5.25
TSA-s2	91.50	± 2.67

Long term testing		
Sample name	Average area covered in Si [%]	
254SMO-L	93.86	± 0.78
254SMO-L2	94.24	± 1.05
316L	92.90	± 1.82
CS	93.59	± 0.94
N-A1	90.64	± 0.90
316L-A2	94.40	± 3.54
N-NiP	94.52	± 0.86
TSA	95.11	± 2.95





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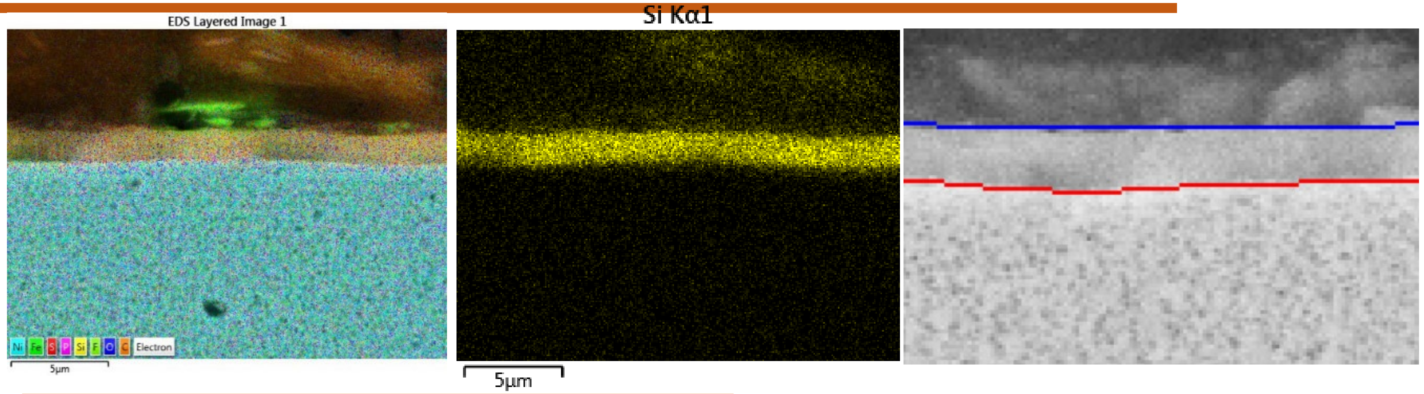
Silica scaling assessment – Cross section

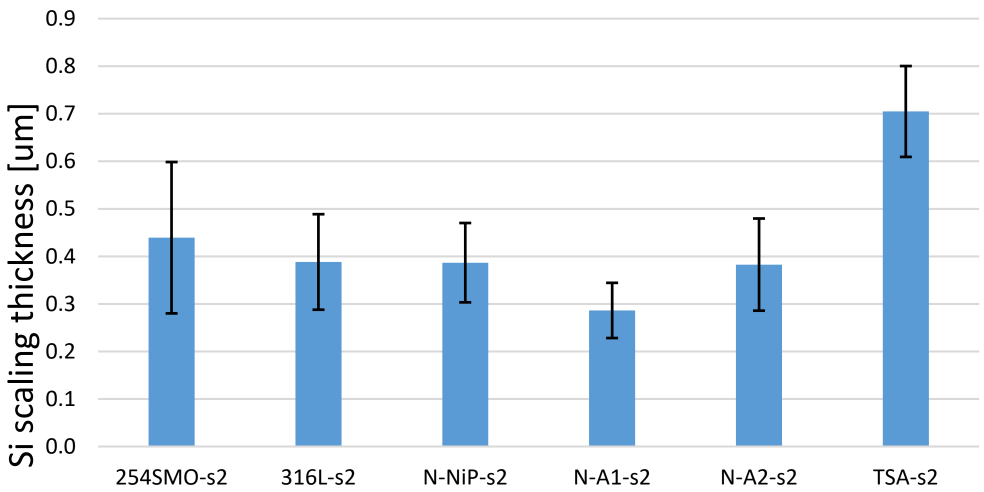
N-NiP long term test



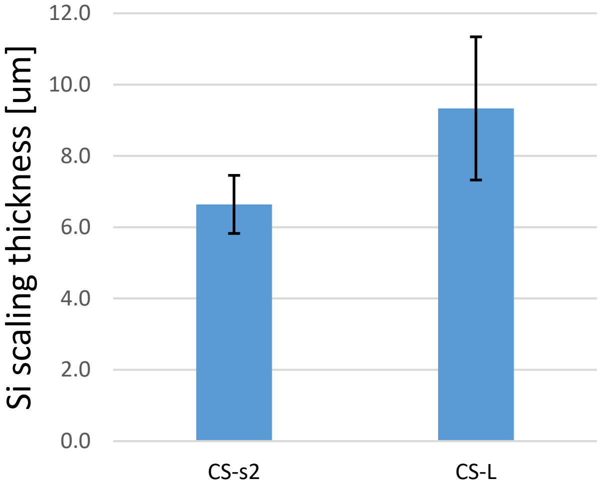
Short term testing	
Sample ID	Silica scaling thickness [um]
254SMO-s2	0.44 ± 0.16
316L-s2	0.39 ± 0.10
N-NiP-s2	0.39 ± 0.08
N-A1-s2	0.29 ± 0.06
N-A2-s2	0.38 ± 0.10
TSA-s2	0.70 ± 0.10
CS-s2	6.64 ± 0.81

Long term testing	
Sample ID	Silical scaling thickness [um]
254SMO-L	4.34 ± 1.36
254SMO-L2	3.07 ± 0.97
316L	2.68 ± 0.78
N-NiP	1.79 ± 0.23
N-A1	2.85 ± 1.00
316L-A2	2.75 ± 0.74
TSA	1.82 ± 0.35
CS-L	9.33 ± 2.01

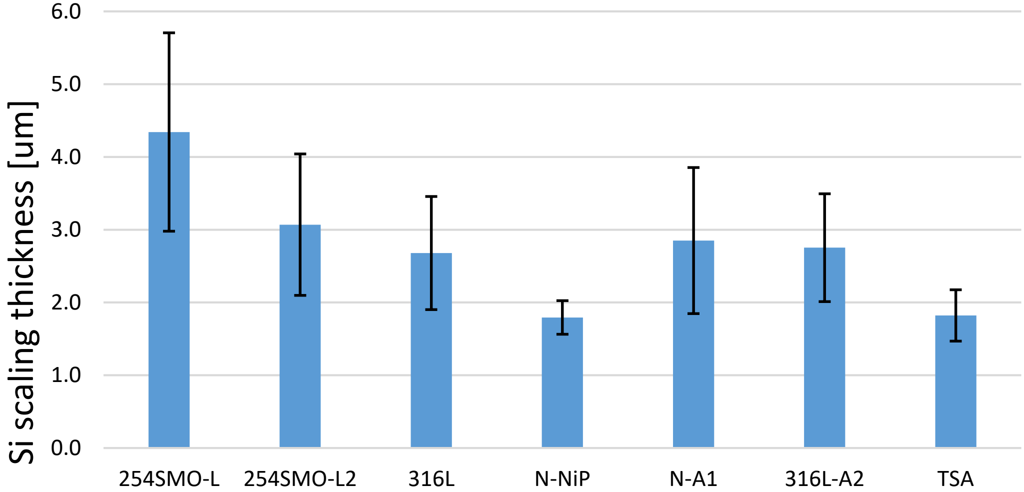
Short term testing



Carbon steel



Long term testing



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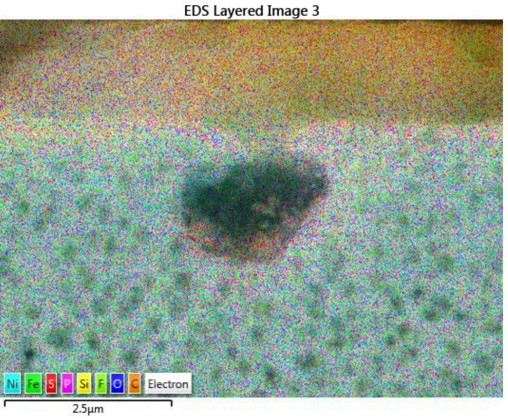
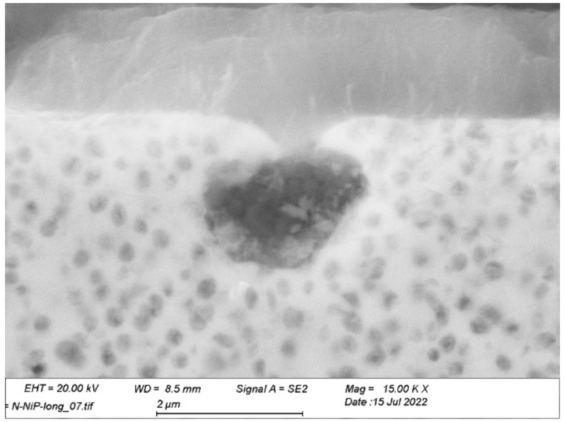
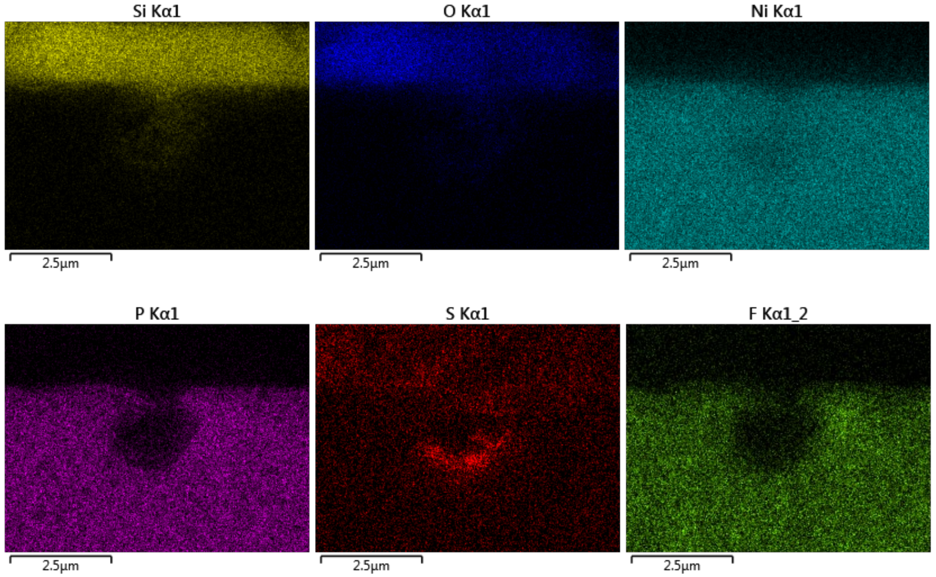
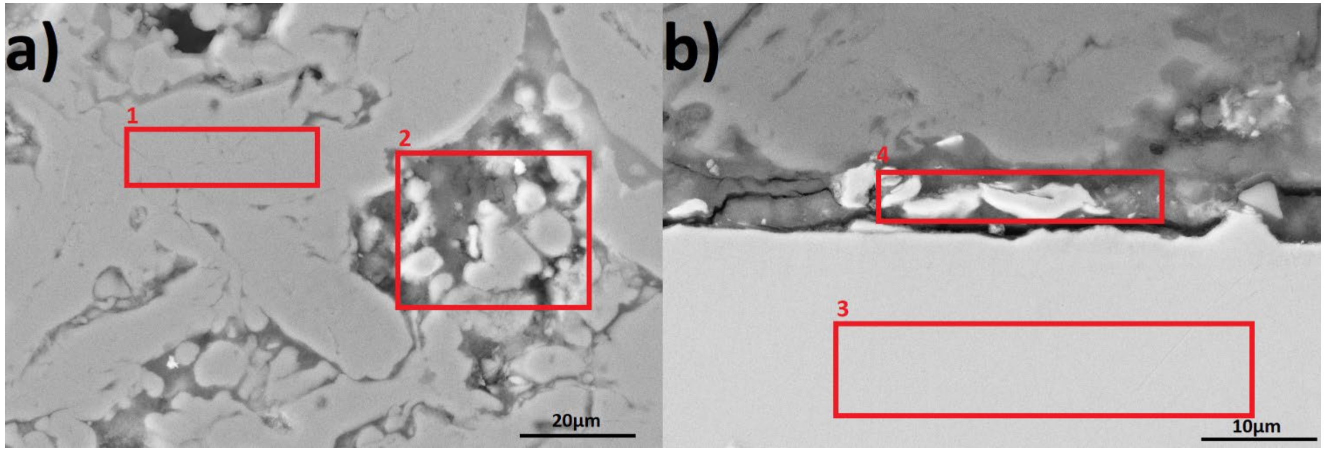
Microstructural analysis, long term – N-NiP and TSA







Element	Wt%
C	23.7
O	10.65
F	6.19
Al	0.7
Si	6.05
P	4.28
S	0.5
K	0.17
Ca	0.21
Fe	0.39
Ni	47.16
Total:	100



	Locations			
Element (wt. %)	1	2	3	4
C	6.75	11.55	4.63	9.62
O	2.49	26.14	-	20
Al	90.76	52.36	-	23
Si	-	8.87	0.23	1.19
S	-	0.2	-	0.54
Ca	-	0.27	-	-
Mn	-	-	1.48	0.74
Fe	-	0.61	93.66	44.9

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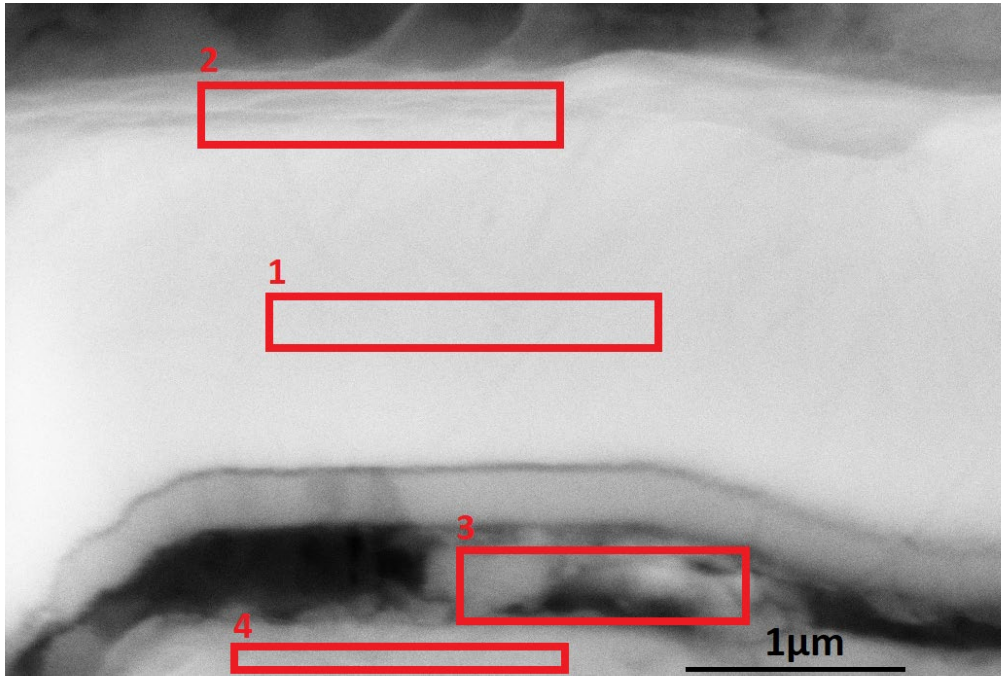
Microstructural analysis, Long term – 316L-A2



Element (wt%)	1	2	3	4
C	8.2	42.37	13.17	7.98
O	2.11	16.85	7.69	2.22
Na	-	0.88	1.08	0.7
Mg	-	0.22	-	-
Al	-	0.87	0.15	-
Si	9.5	5.22	3.26	1.27
S	-	0.11	0.29	-
Cl	-	0.09	-	-
Ar	0.52	0.15	-	-
K	-	0.45	0.14	-
Ca	0.19	0.69	0.13	-
Ti	12.6	4.01	2.64	0.31
Cr	1.66	0.29	28.96	16.01
Mn	-	-	-	0.94
Fe	1.73	0.87	24.84	60.1
Ni	0.34	-	3.06	8.73
Mo	-	-	0.77	1.56
Ta	63.15	26.92	13.82	

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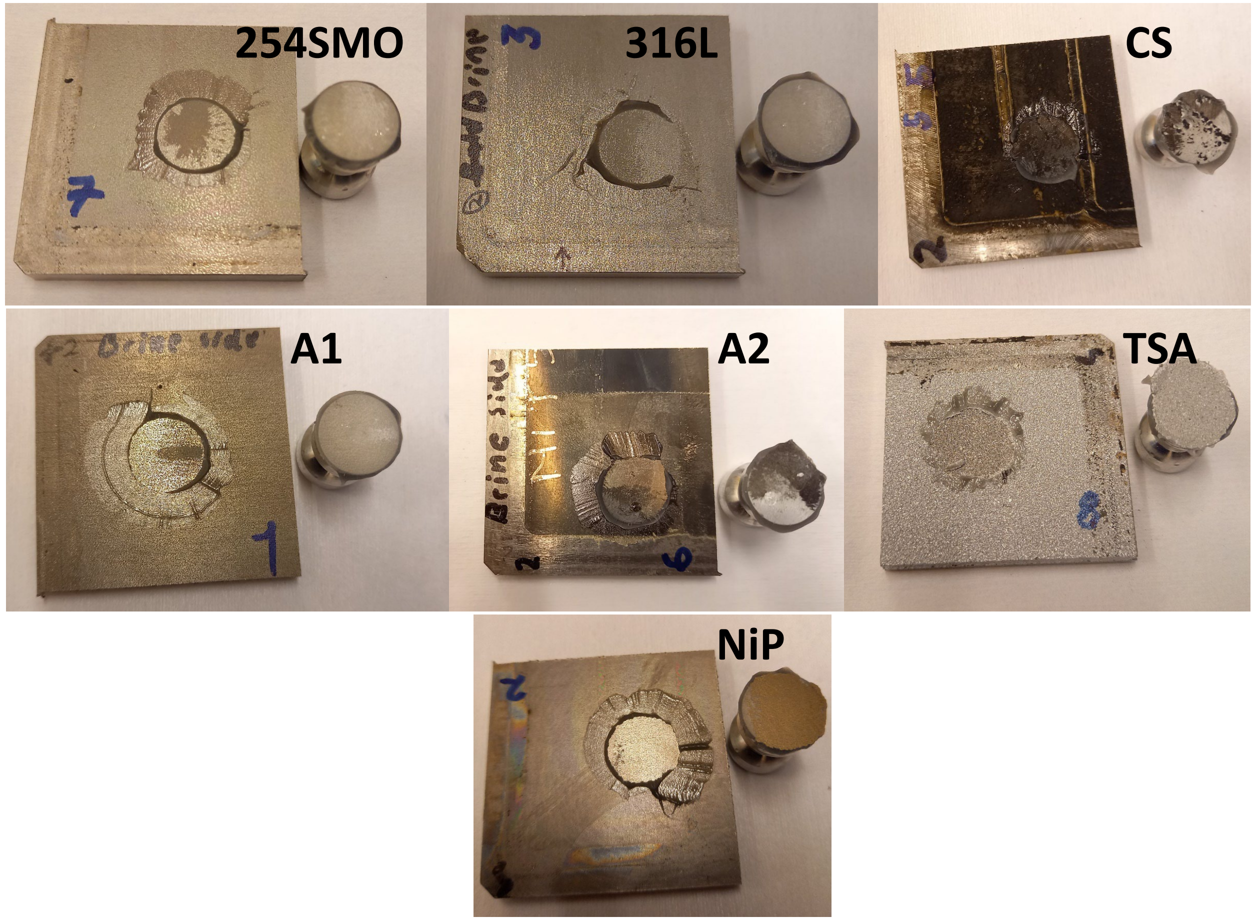
Adhesion tests

Sample name	Failure point [Mpa]	Observation
254SMO	27.03	40-50% silica removal
316L	18.1	50% silica removal
CS	19.42	30% FeO or FeS removal
A1	15.86	80-85% silica removal
A2	13.91	Total coating bond failure
NiP	9.24	70% coating removal
TSA	26.51	Total coating bond failure



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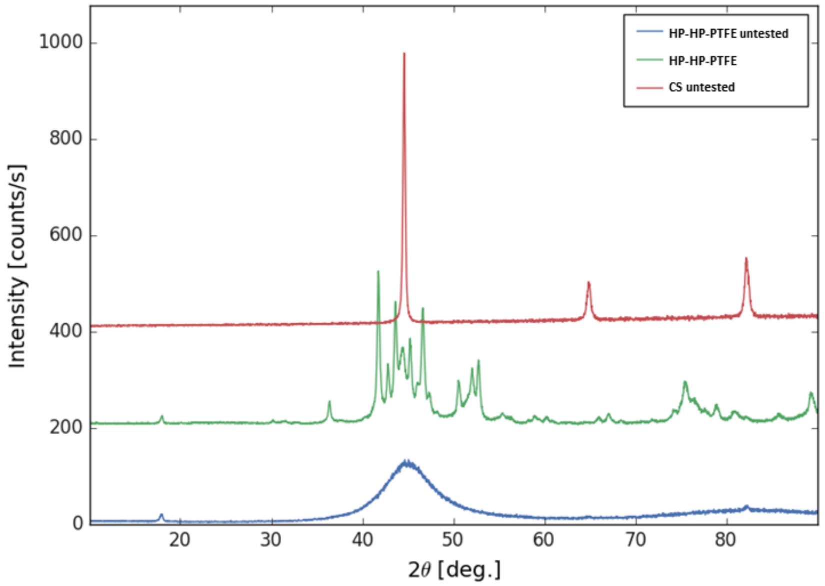
XRD analysis

N-NiP

- Untested NiP shows an amorphous peak at 45°
- Tested sample shows peaks corresponding to Iron Phosphide
- Change in morphology indicates corrosion or fouling in the form of FeS.



- XRD analysis of other coated samples showed amorphous silica and no corrosion.

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Summary and conclusions

To thoroughly assess the properties and qualities of developed materials, significant amount of testing was required

Heat transfer performance

- In-situ heat transfer performance test rig.

Durability assessment

- Scaling and corrosion was measured using SEM/EDX at the cross section and external surface.
- XRD analysis of tested samples.
- Adhesion testing of tested samples.

Based on the heat transfer, microstructural analysis and mechanical results, the following conclusions can be summarized for the single-phase GeoHex coatings:

- A1 shows great potential in silica removal where 80% of silica scaling was removed at 15.86 MPa but only 40-50% was removed on 254SMO and 316L at 27.03 MPa and 18.1 MPa respectively.
- TSA and NiP show a 45% and 35% increase in HTC respectively with low scaling accumulation compared to reference materials.
- 316L-A2 sample had 4.9% lower HTC compared to the N-A2 sample indicating better heat transfer performance of the Nanoporous coating.

Thanks for your attention!

Baldur Geir Gunnarsson – baldur@taeknisetur.is
GeoHex project – info@geohexproject.eu

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Development of amorphous metals for corrosion resistant thin film coatings

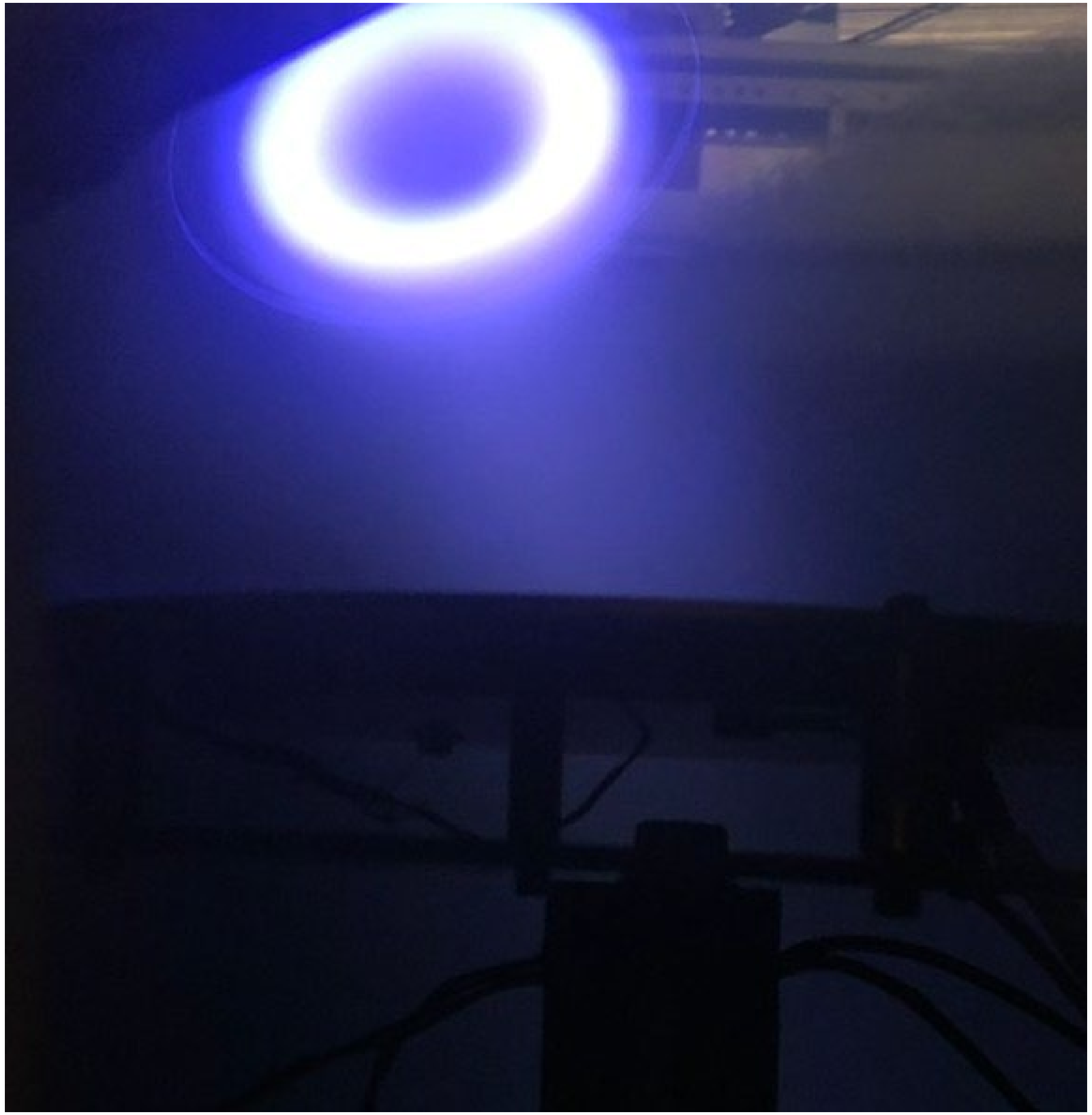
Davíð Ingvi Snorrason

GEOHEX

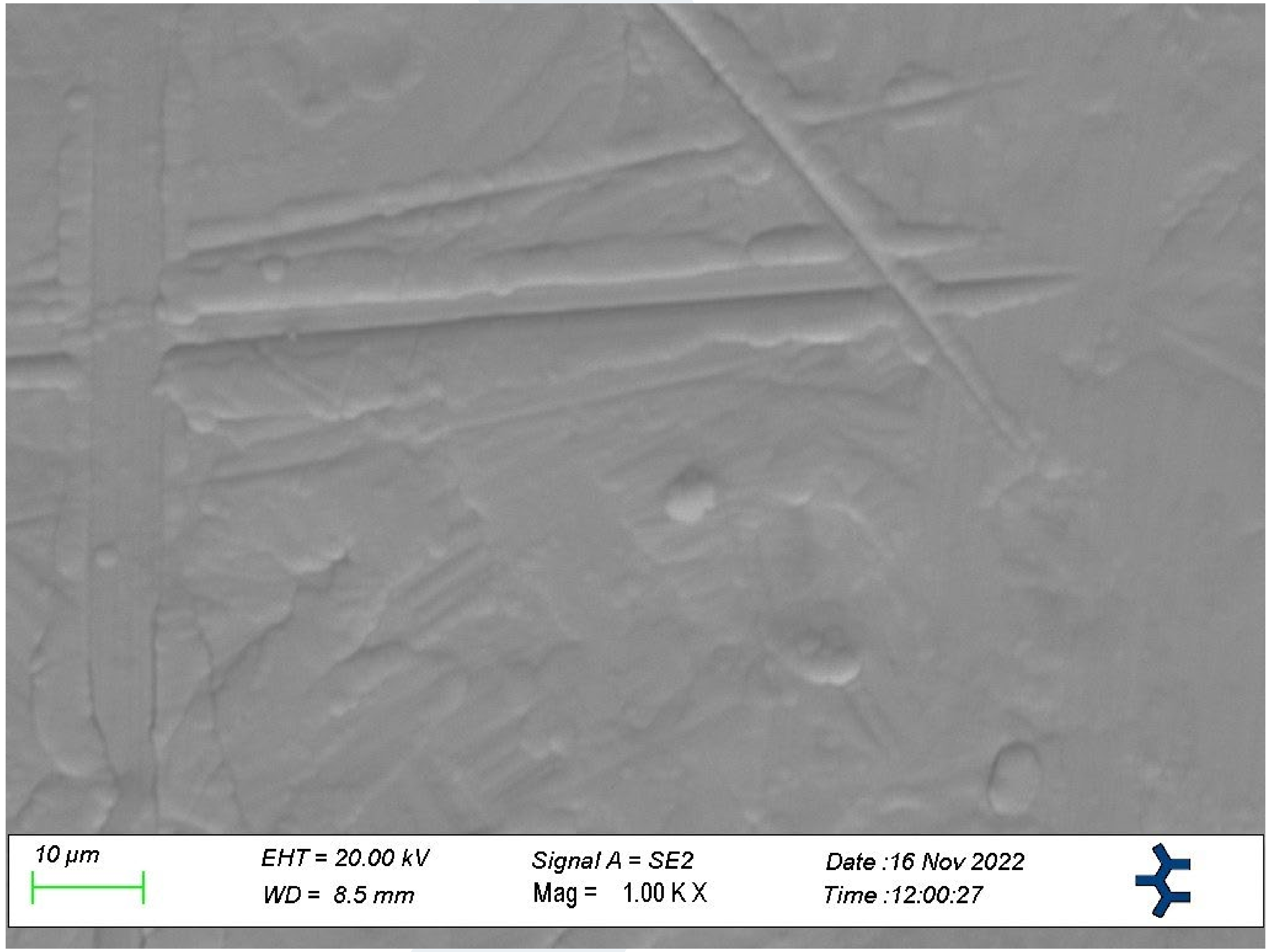
This project has received funding from the European Union's Horizon2020 Research and Innovation Programme.
Grant Agreement 851917.

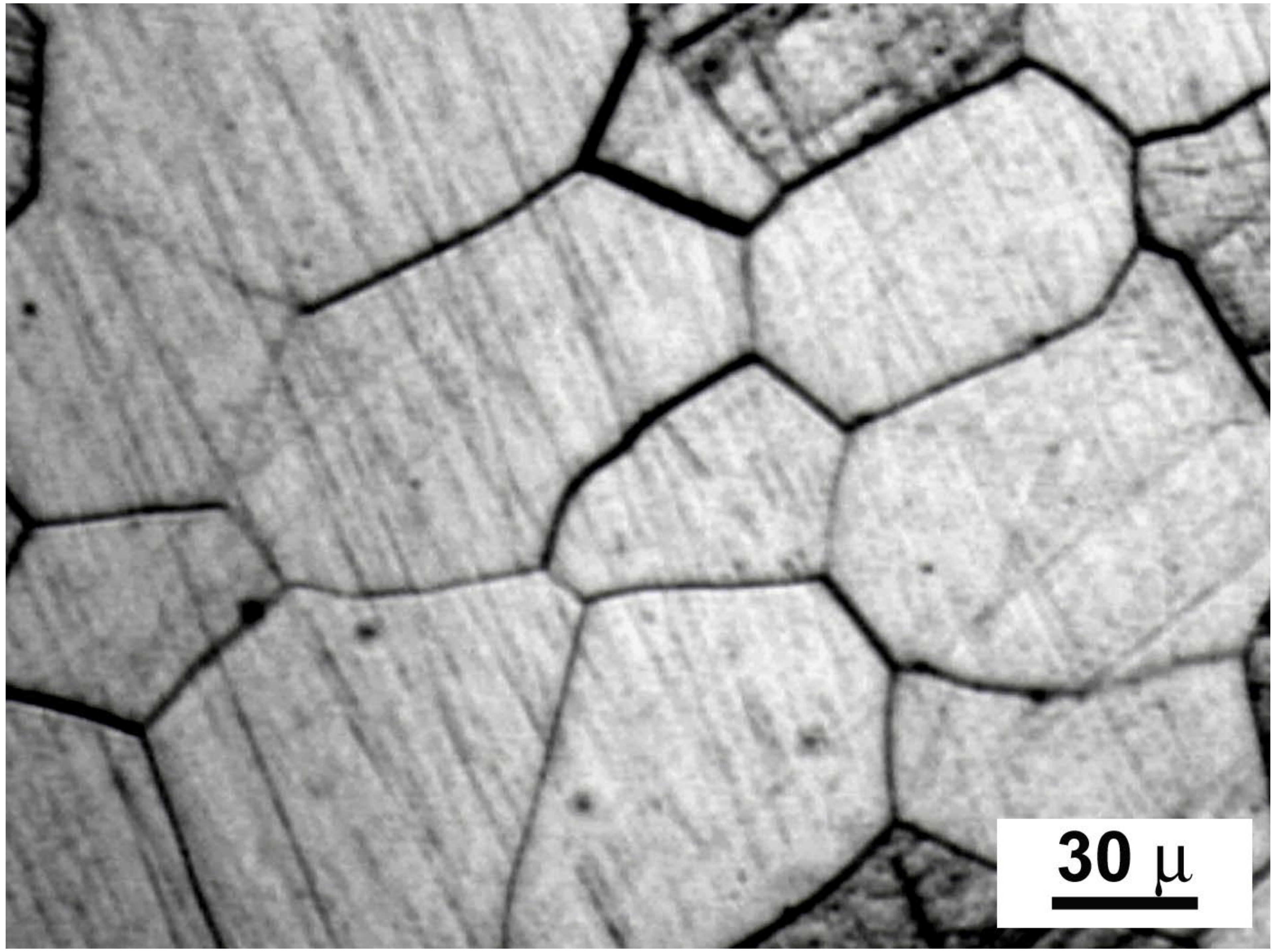
Why amorphous?

- No grain boundaries
- Corrosion resistant
- Anti scaling properties



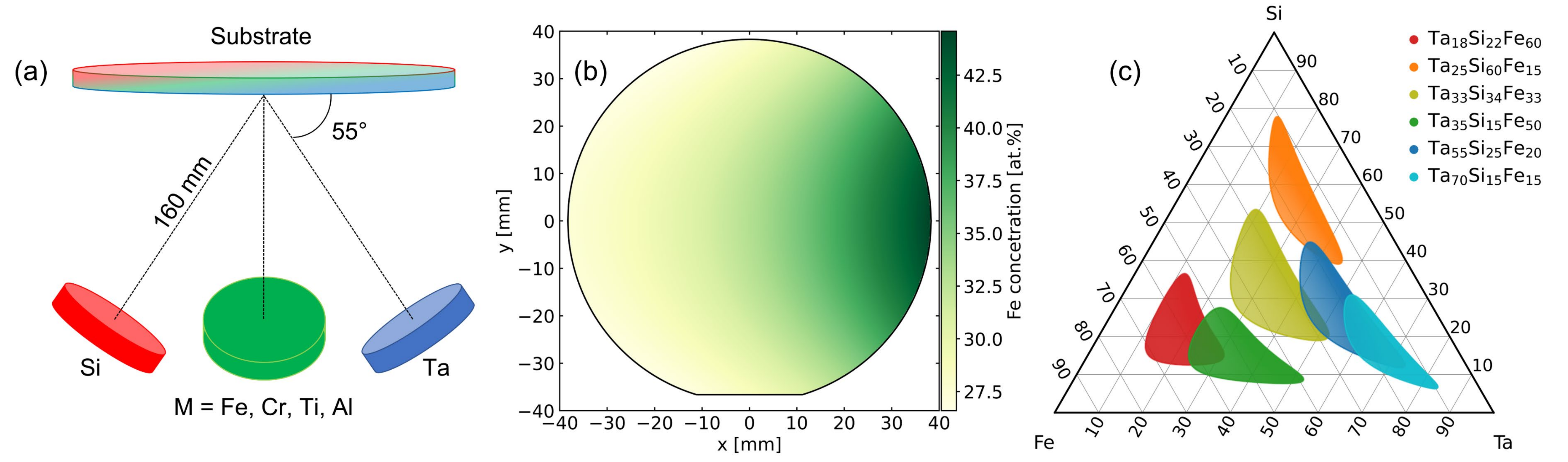
Amorphous and crystalline



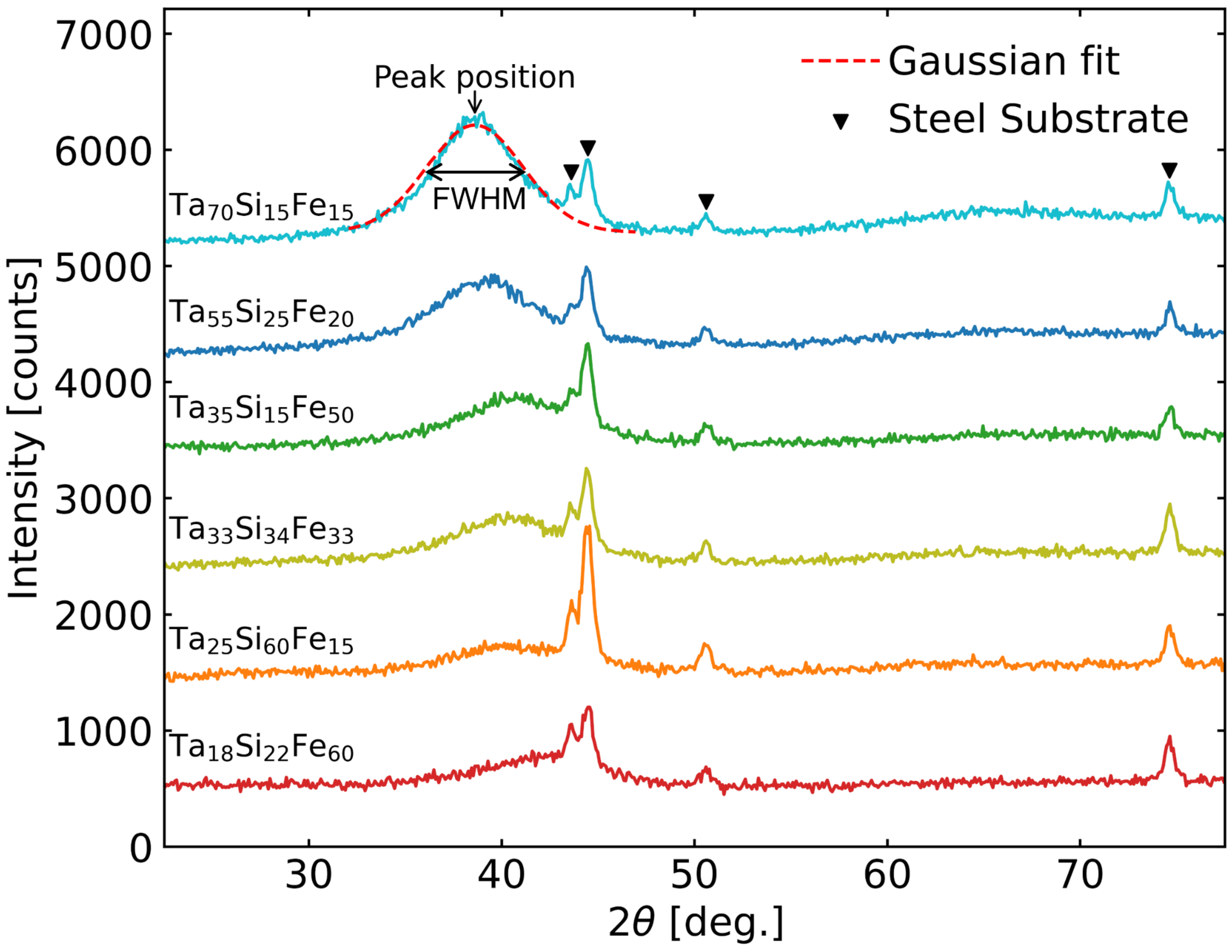


[1]

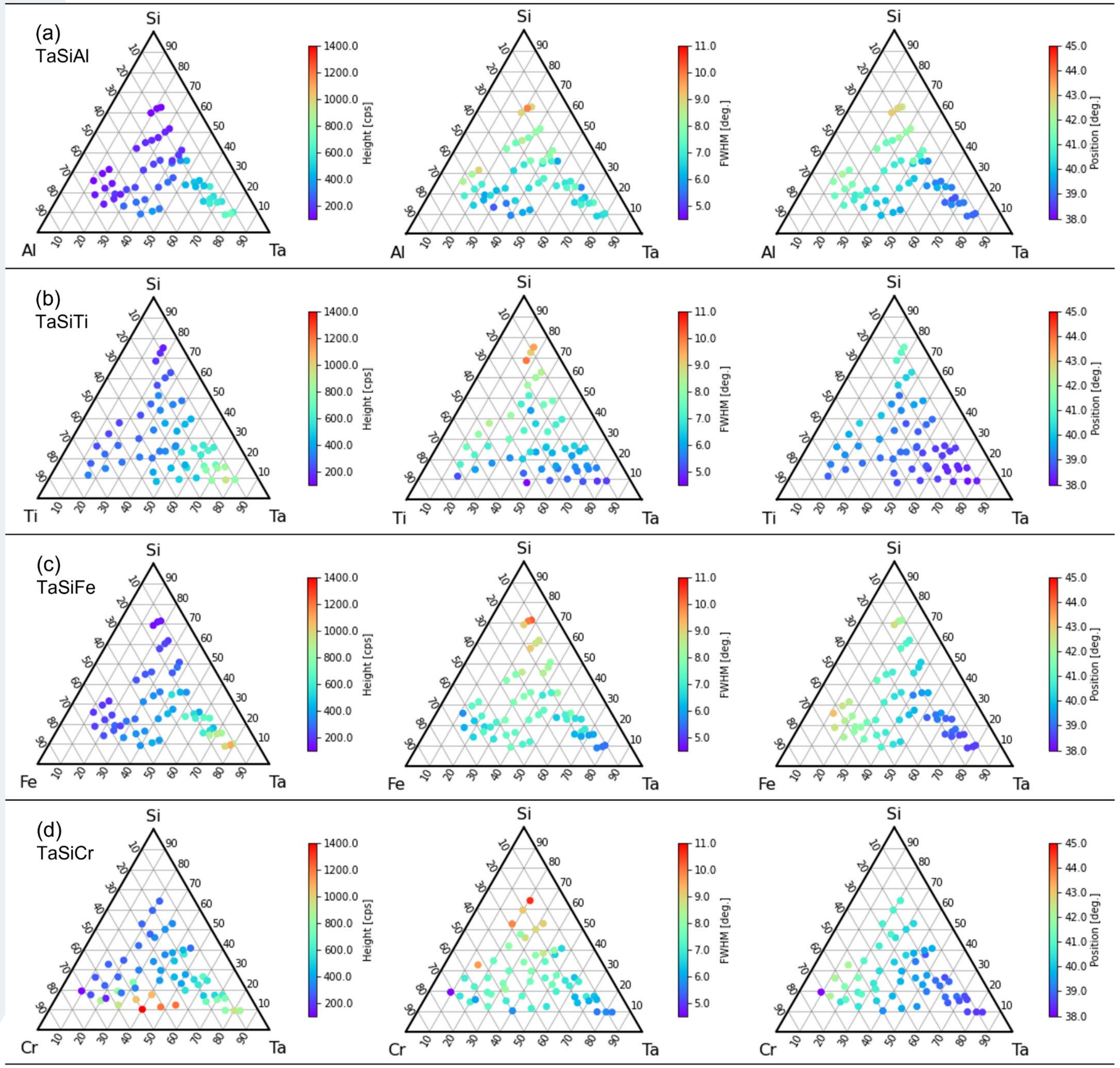
Combinatorial setup



XRD results

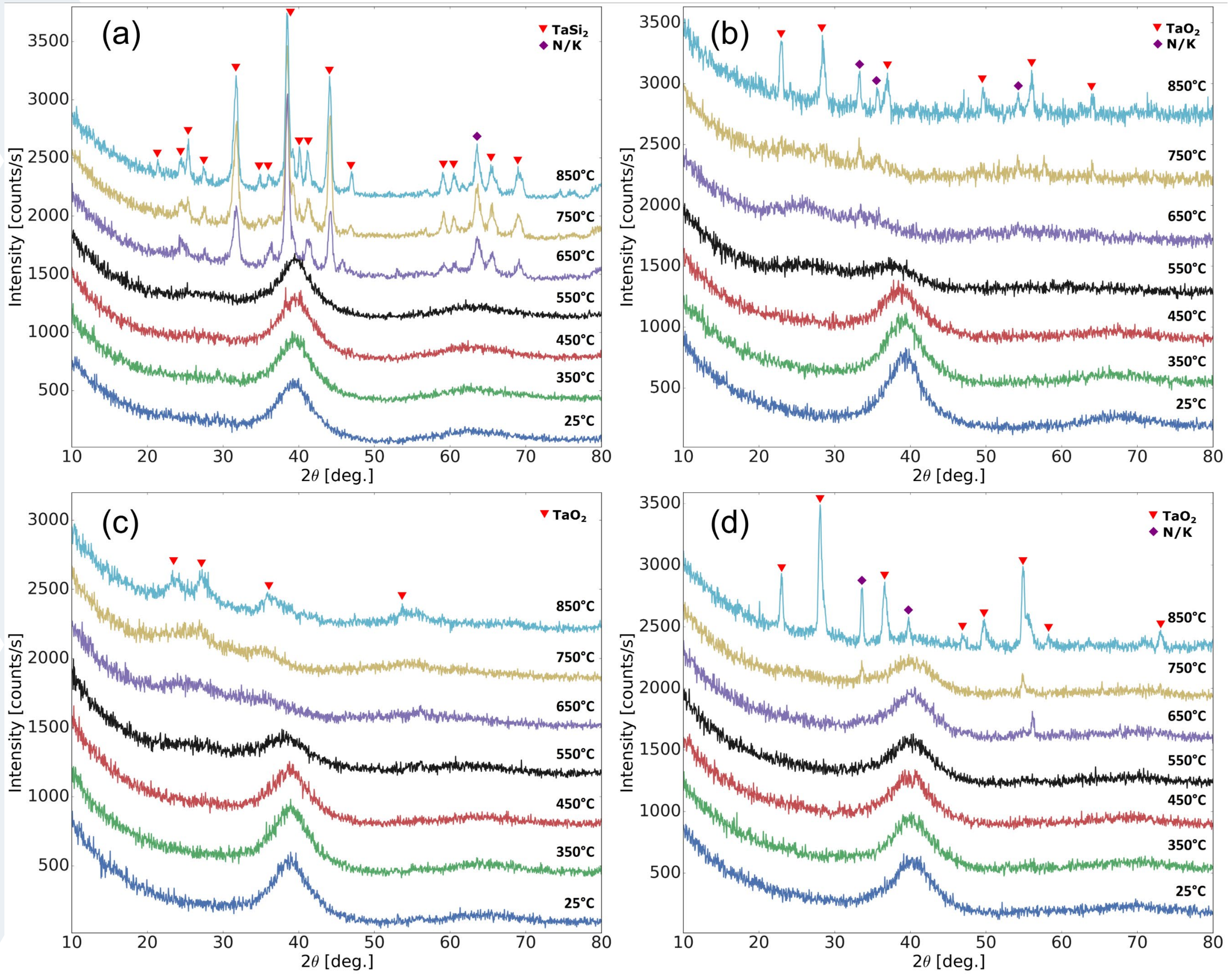

Gaussian fit
Steel Substrate
Peak position
FWHM
Ta70Si15Fe15
Ta55Si25Fe20
Ta35Si15Fe50
Ta33Si34Fe33
Ta25Si60Fe15
Ta18Si22Fe60
Intensity [counts]
2θ [deg.]
0
1000
2000
3000
4000
5000
6000
7000
30
40
50
60
70

XRD compiled and analyzed



XRD annealing study

- (a) TaSiAl
- (b) TaSiFe
- (c) TaSiTi
- (d) TaSiCr



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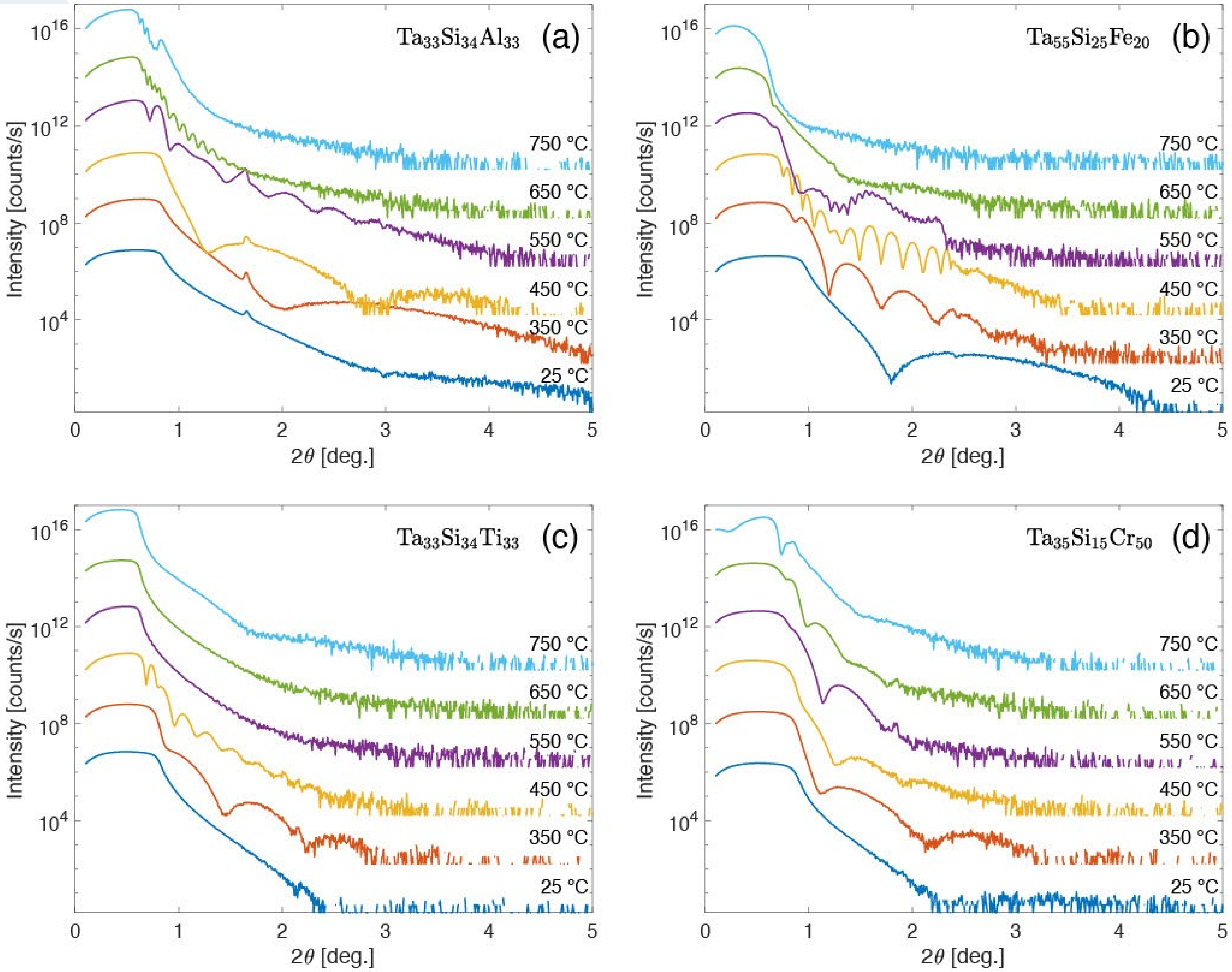
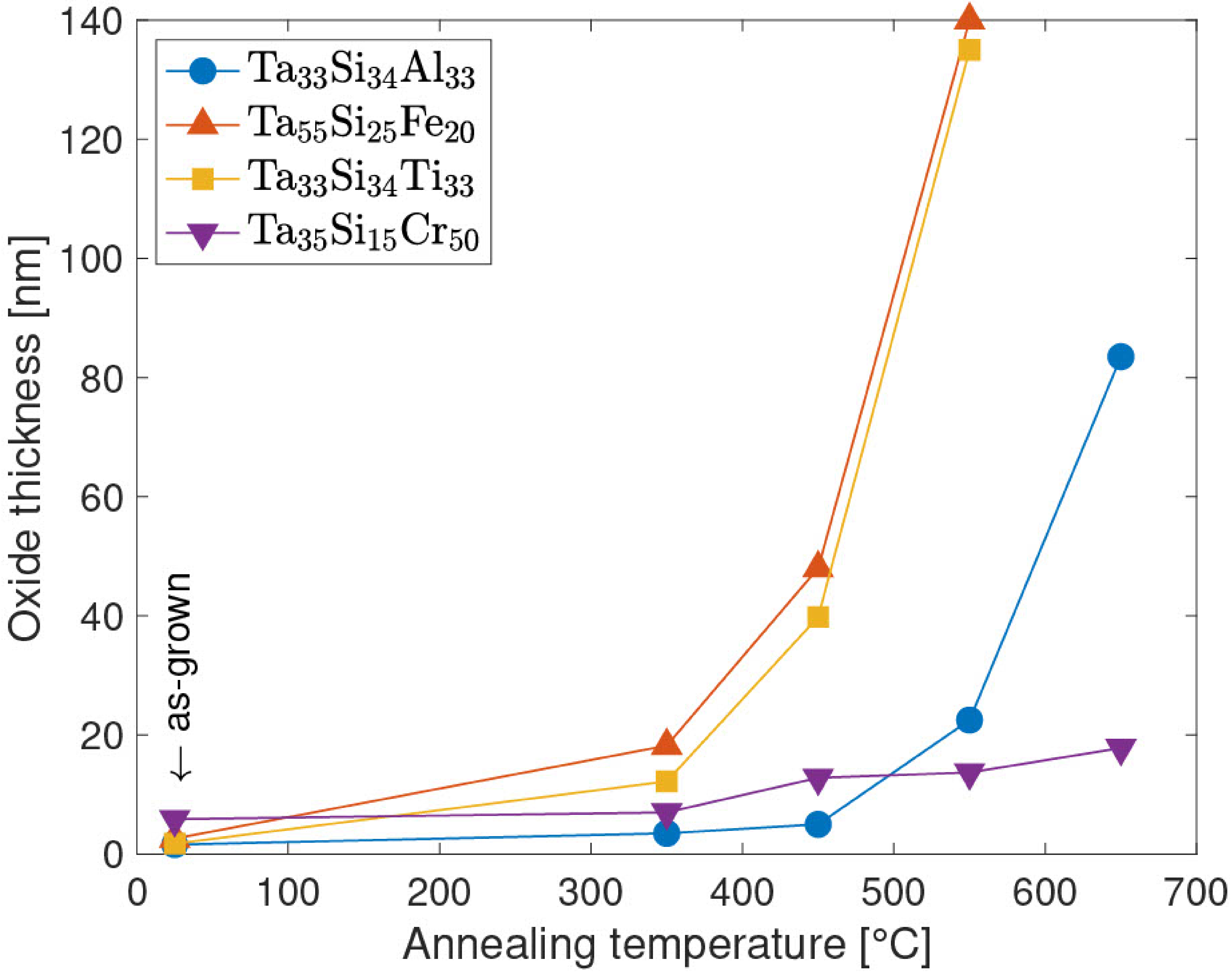
XRR annealing study



- (a) TaSiAl
- (b) TaSiFe
- (c) TaSiTi
- (d) TaSiCr

Oxide thickness



Sources

[1] By Edward Pleshakov - Own work, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=3912586

Thanks for listening!

Davíð Ingvi Snorrason
david@greinresearch.com
Forthcoming publication on this topic:
Structural stability and oxidation resistance of amorphous TaSi-based ternary alloy coatings