FACULTY OF ENGINEERING
AND ARCHITECTURE

DEPARTMENT OF ELECTROMECHANICAL, SYSTEMS AND METAL ENGINEERING
MATERIALS SCIENCE AND TECHNOLOGY GROUP

METALLURGICAL ASPECTS OF THE ET BEAMPIPE DESIGN

FWO workshop | Alexey Gervasyev | 27 November 2023

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OUTLINE

- General ET beampipe design considerations
- Overview of steels potentially to be used as the beampipe material
- Ferritic stainless steel welded joint formability

GENERAL ET BEAMPIPE DESIGN CONSIDERATIONS

120 km long, 1 m diameter ultra-high vacuum pipeline

Pipe making technology:

– Spiral welded

– Longitudinally welded

– Double longitudinally welded

Reinforcement:

– Stiffener rings

– Corrugations

– No reinforcement

Material:

– Austenitic stainless steel

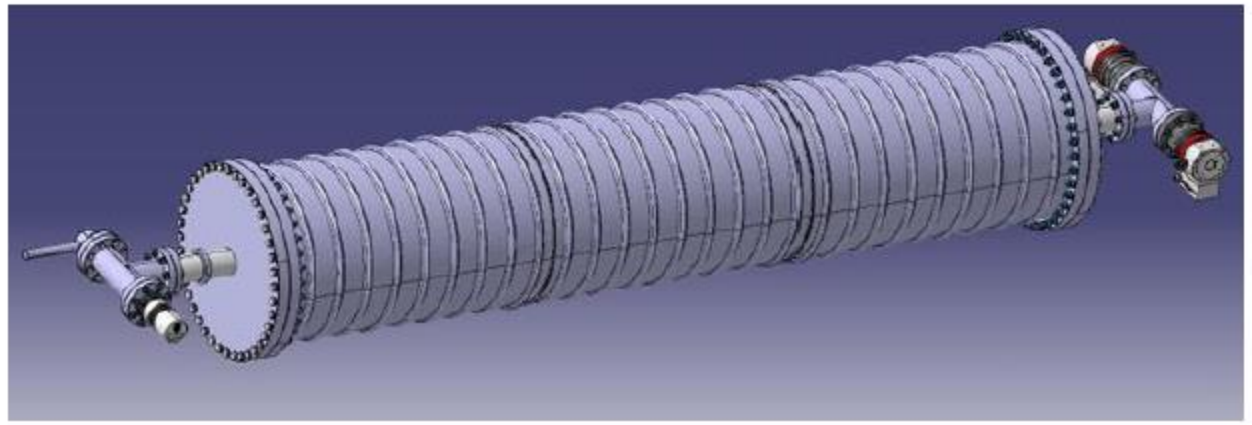
– Ferritic stainless steel

– Non-stainless low-carbon steel

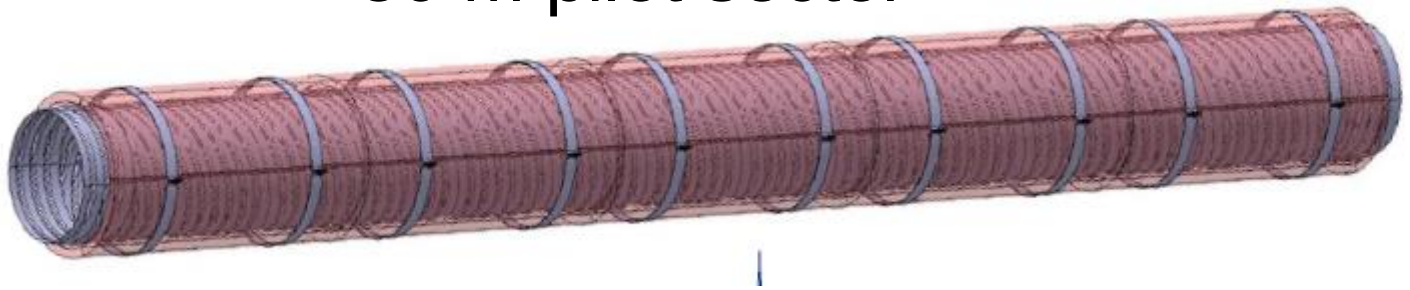
NEW

Already 27 combinations, but there are other aspects…

3 (sub-size) pre-prototypes made of the 3 materials



50 m pilot sector



To be produced at CERN

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GENERAL ET BEAMPIPE DESIGN CONSIDERATIONS

	Virgo	LIGO	KAGRA	GEO600
Material (AISI)	304L	304L	304L	316L
Length (Km)	6	2x8	6	1.2
Diameter (m)	1.2	1.24	.81	0.6
Section length (m)	15	20	12	4.5
Thickness (mm)	4	3.23	8	0.8
Tube type	Sheet welded	Spiral weld	Sheet welded	Sheet weld +cold formed deep corrugated
Pipe cost (euro/m)	2400	2200	4745[a]	440
Vacuum (H_2O) mbar	5.6×10^{-10}	1.3×10^{-10}	1.5×10^{-8} [b]	1.5×10^{-7}
Distance among pumps (m)	600	2000	600	600
Firing Temp (°C)	400	455	200	200
Firing duration	5 days	36 h	20 h	48 h
Bakeout Temp	150	160	Electro-polishing + ex-situ vacuum baking @200 deg 20 h	250
Bakeout duration	1 week	3 weeks		5 days
pumps	Turbo, Ti Sub. pumps	Turbo, Ion +NEGs	Turbo, Ion	Turbo

[a]bellowsSS316L, flanges, crow clamp, EP-finished, baked [b]upgrade vacuum system in 2021

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[Aniello Grado, Beampipes for Gravitational Wave Telescopes seminar at CERN, March 2023]

Background : Ferritic stainless steel

Why Ferritic stainless steel :

- As received Ferritic SS, H_2 outgassing rate in line with mild steel
- No need for Air bakeout/vacuum firing
- Ferritic SS is 2 to 3 times cheaper than the Austenitic SS(304L)

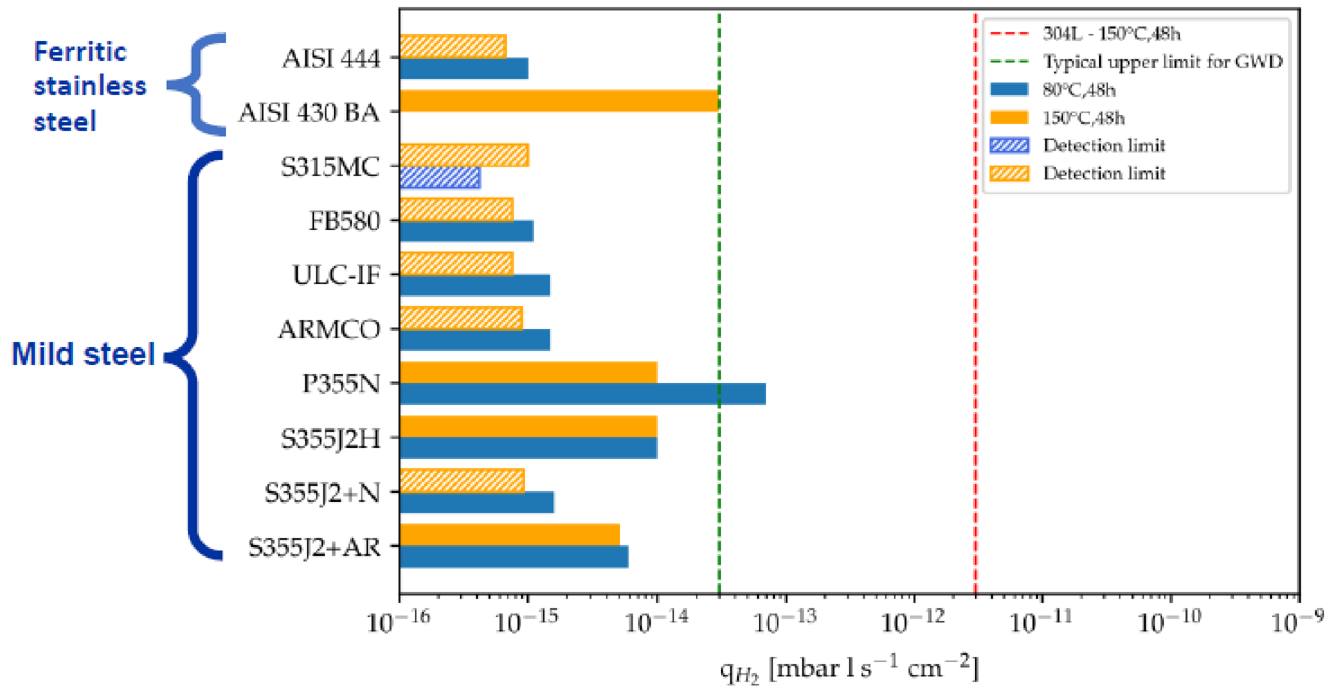

Table credits: work of Carlo Scarcia

Ferritic SS: Studied Grades

- AISI 430 with BA surface finish
- AISI 444 with 2D surface finish
- AISI 441 with 2B surface finish

Composition of the Ferritic SS grades

Type	C	Mn	Si	P	S	Cr	Mo	Ni	N	Ti	Nb
AISI 444	0.011	0.30	0.38	0.029	0.0150	18.89	1.89	-	0.016	0.80	0.80
AISI 441	0.015	0.38	0.58	0.025	0.001	17.57	-	0.242	0.014	0.16	-
AISI 430	0.044	0.320	0.370	0.027	0.001	16.05	0.07	0.22	0.042	-	-

**All the specimens have 1.5 mm thickness

[CERN]

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OVERVIEW OF STEELS POTENTIALLY TO BE USED AS THE BEAMPIPE MATERIAL

Commercially available line pipes

[muelheim-pipecoatings.com]

OVERVIEW OF STEELS POTENTIALLY TO BE USED AS THE BEAMPIPE MATERIAL

Commercially available line pipe – product range

		Wanddicke Wall thickness Epaisseur paroi																											
	inch		0,281	0,312		0,344		0,375		0,406		0,438	0,469		0,500		0,562	0,625		0,688		0,750		0,812		0,875	0,938		1
Ø außen	mm		7,1	7,9		8,7		9,5		10,3		11,1	11,9		12,7		14,3	15,9		17,5		19,1		20,6		22,2	23,8		25,4
Ø O.D.	mm	7,1			8		8,8		10		11			12,5		14,2			16		17,5		20		21			25	
Ø extérieur																													
mm	inch																												
610	24	106	105,56	117,30	119	129,00	130	140,68	148	152,32	162	163,93	175,51	184	187,06	209	210,07	232,94	234	255,69	256	278,32							
660	26	114	114,31	127,04	129	139,73	141	152,39	160	165,02	176	177,62	190,19	200	202,72	226	227,70	252,55	254	277,27	277	301,87							
711	28	123	123,24	136,97	139	150,67	152	164,34	173	177,98	190	191,58	205,15	215	218,69	244	245,68	272,54	274	299,28	299	325,89	341	350,72	356	377,11			
762	30	132	132,17	146,91	149	161,61	163	176,29	185	190,93	204	205,54	220,12	231	234,67	262	263,67	292,54	294	321,29	321	349,91	366	376,63	384	405,03			
813	32	141	141,10	156,84	159	172,56	175	188,24	198	203,88	218	219,50	235,09	247	250,46	280	281,65	312,54	314	343,30	343	373,93	391	402,54	410	432,95	463,22		
864	34	150	150,03	166,78	169	183,50	186	200,18	211	216,84	231	233,46	250,05	262	266,61	298	299,64	332,53	335	365,31	365	397,95	416	428,44	437	460,87	493,15		
914	36	159	158,79	176,52	179	194,22	196	211,90	223	229,54	245	247,15	264,72	278	282,27	315	317,27	352,14	354	386,88	387	421,50	441	453,84	462	488,25	522,50		
965	38	168	167,72	186,46	189	205,17	208	223,84	236	242,49	259	261,11	279,69	294	298,24	333	335,25	372,14	374	408,89	409	445,52	466	479,75	489	516,17	552,43	580	588,57
1016	40	177	176,65	196,39	199	216,11	219	235,79	248	255,45	273	275,07	294,66	309	314,22	351	353,24	392,13	395	430,90	431	469,55	491	505,66	515	544,09	582,37	611	620,51
1067	42				209	227,05	230	247,74	261	268,40	286	289,03	309,62	325	330,19	369	371,22	412,13	415	452,91	453	493,57	516	531,57	542	572,01	612,30	642	652,46
1118	44				219	237,99	241	259,69	273	281,35	300	302,99	324,59	341	346,16	387	389,21	432,13	435	474,92	475	517,59	542	557,47	568	599,93	642,23	674	684,41
1168	46					248,72	252	271,40	286	294,05	314	316,67	339,26	356	361,82	404	406,84	451,73	455	496,50	497	541,14	566	582,87	594	627,31	671,58	705	715,73
1220	48							283,35	298	307,01	328	330,63	354,23	372	377,79	422	424,28	471,73	475	518,51	519	565,16	592	608,78	621	655,78	702,10	737	748,30
1321	52								323	332,92	355	358,55	384,16	403	409,74	458	460,79	511,72	515	562,53	563	613,20	642	660,60	673	711,07	761,38	799	811,57
1420	56								348	358,57	382	386,20	413,80	434	441,37	492	496,41	551,32	554	606,11	605	660,77	691	711,91	725	765,27	819,49	860	873,58
1524	60										410	414,15	443,76	466	473,31	529	532,38	591,32	595	650,13	650	708,82	742	763,72	778	822,21	880,53	924	938,73
1620	64											442,04	473,66	496	505,26	562	568,35	631,31	633	694,15	692	756,86	789	815,54	828	874,77	936,88	983	998,86
1676	66														520,94	582	586,00	650,94	655	715,75	716	780,44	817	840,99	857	905,43	969,75	1018	1033,94

[mannesmann-grossrohr.com]

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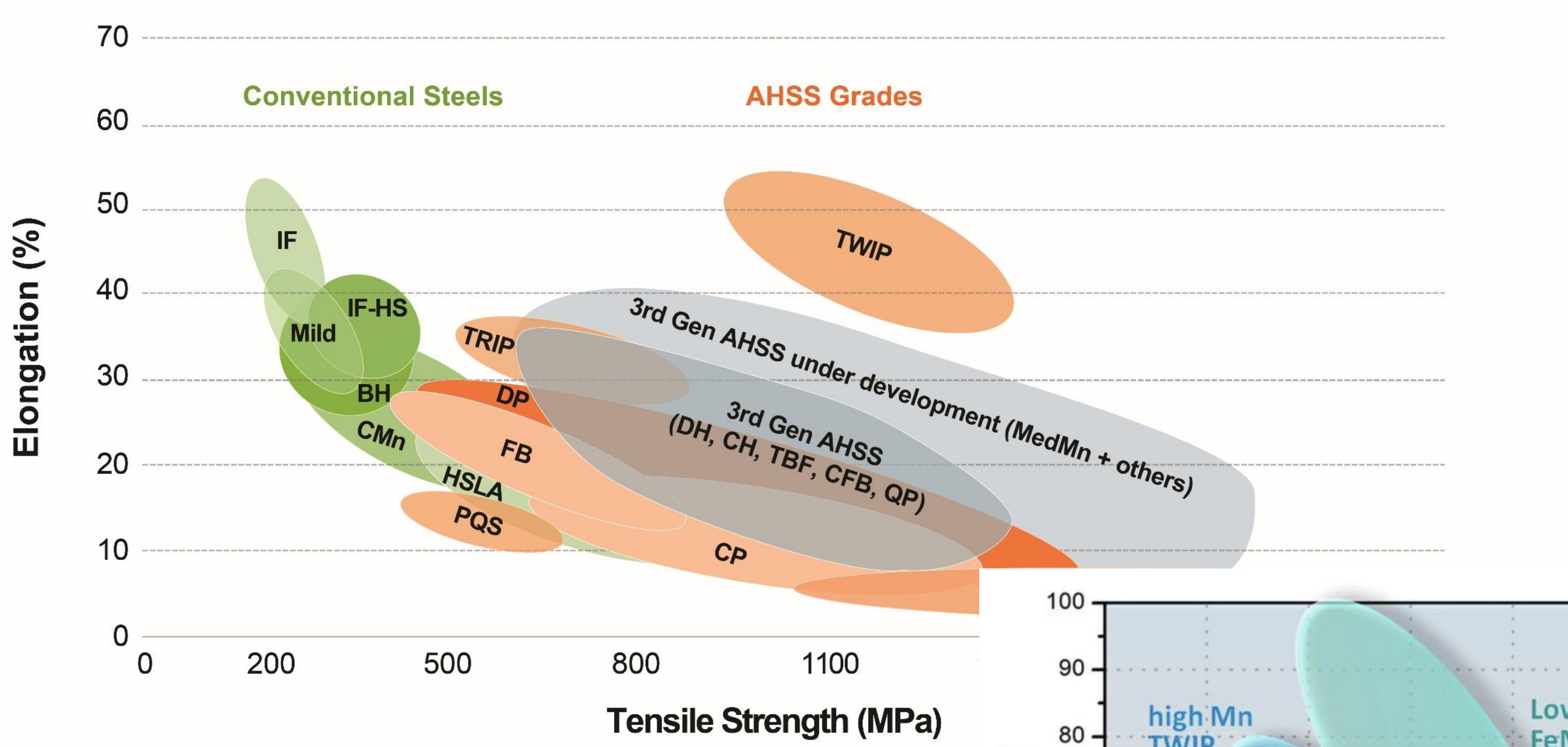
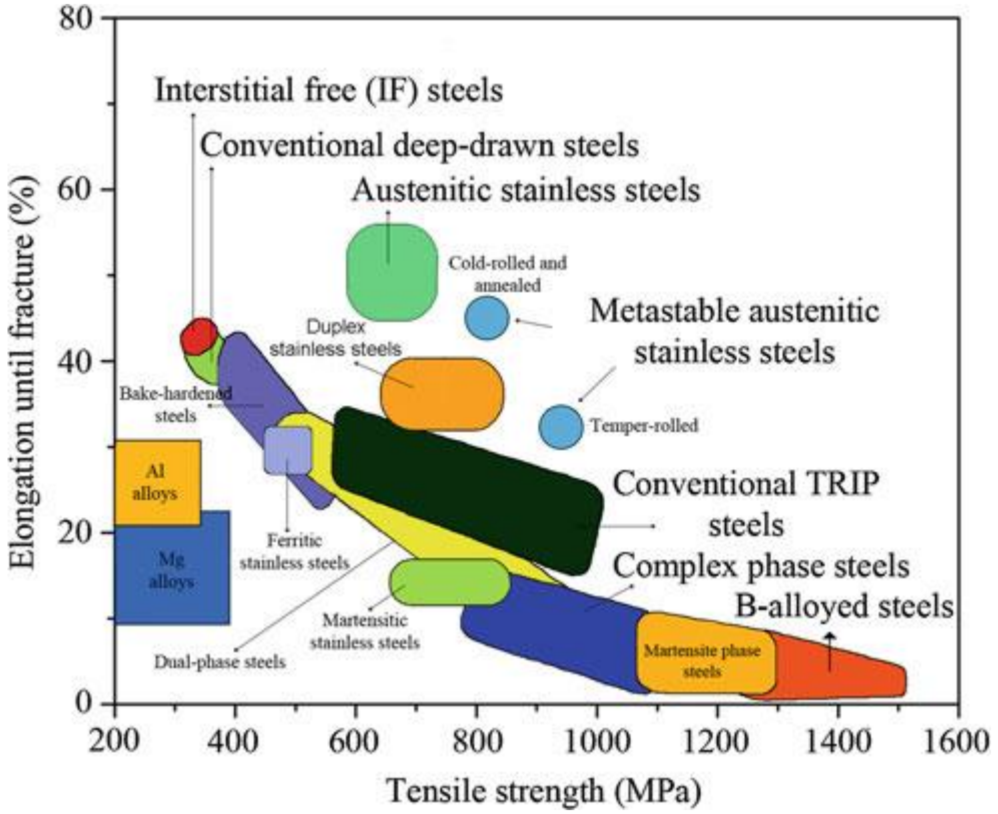
OVERVIEW OF STEELS POTENTIALLY TO BE USED AS THE BEAMPIPE MATERIAL

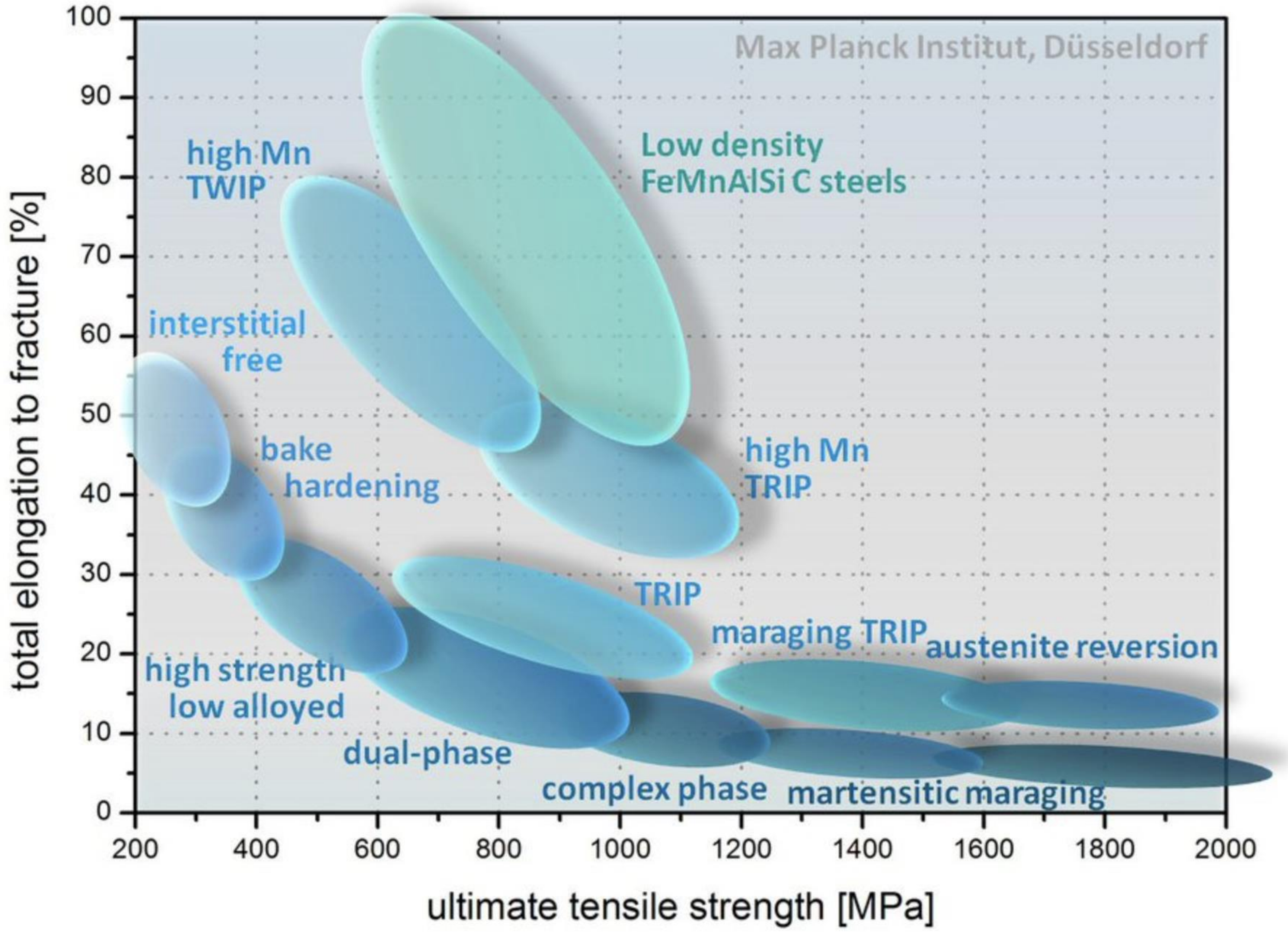


[WorldAutoSteel]

Steel can be very different



[Rajasekhara et al 2011]



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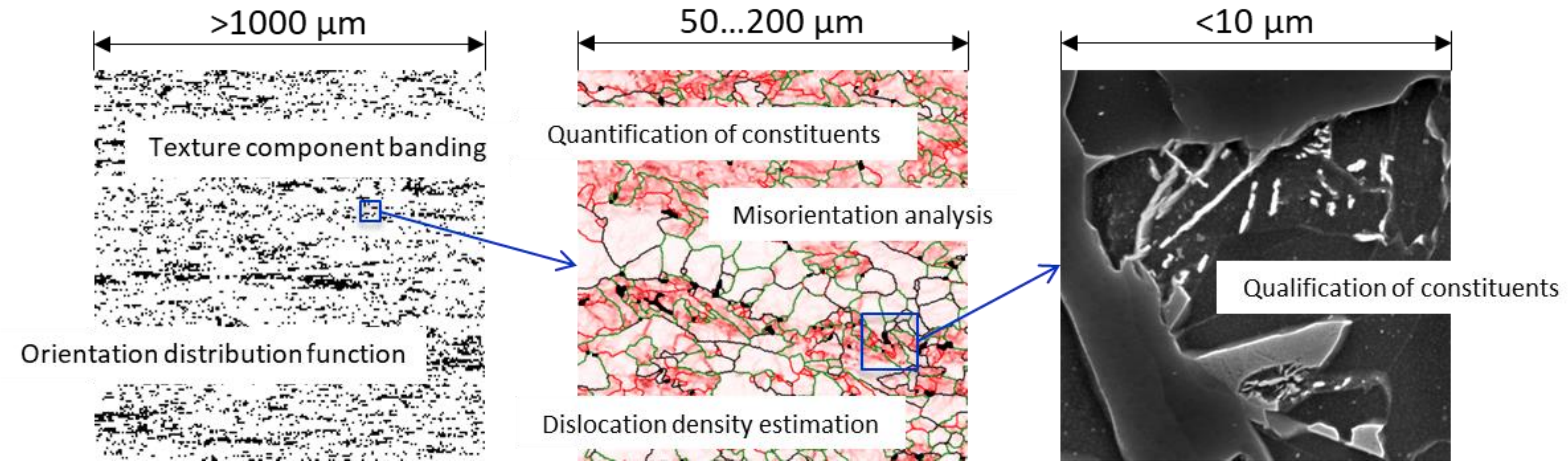
OVERVIEW OF STEELS POTENTIALLY TO BE USED AS THE BEAMPIPE MATERIAL

Steel microstructure complexity



[Gervasyev at al]

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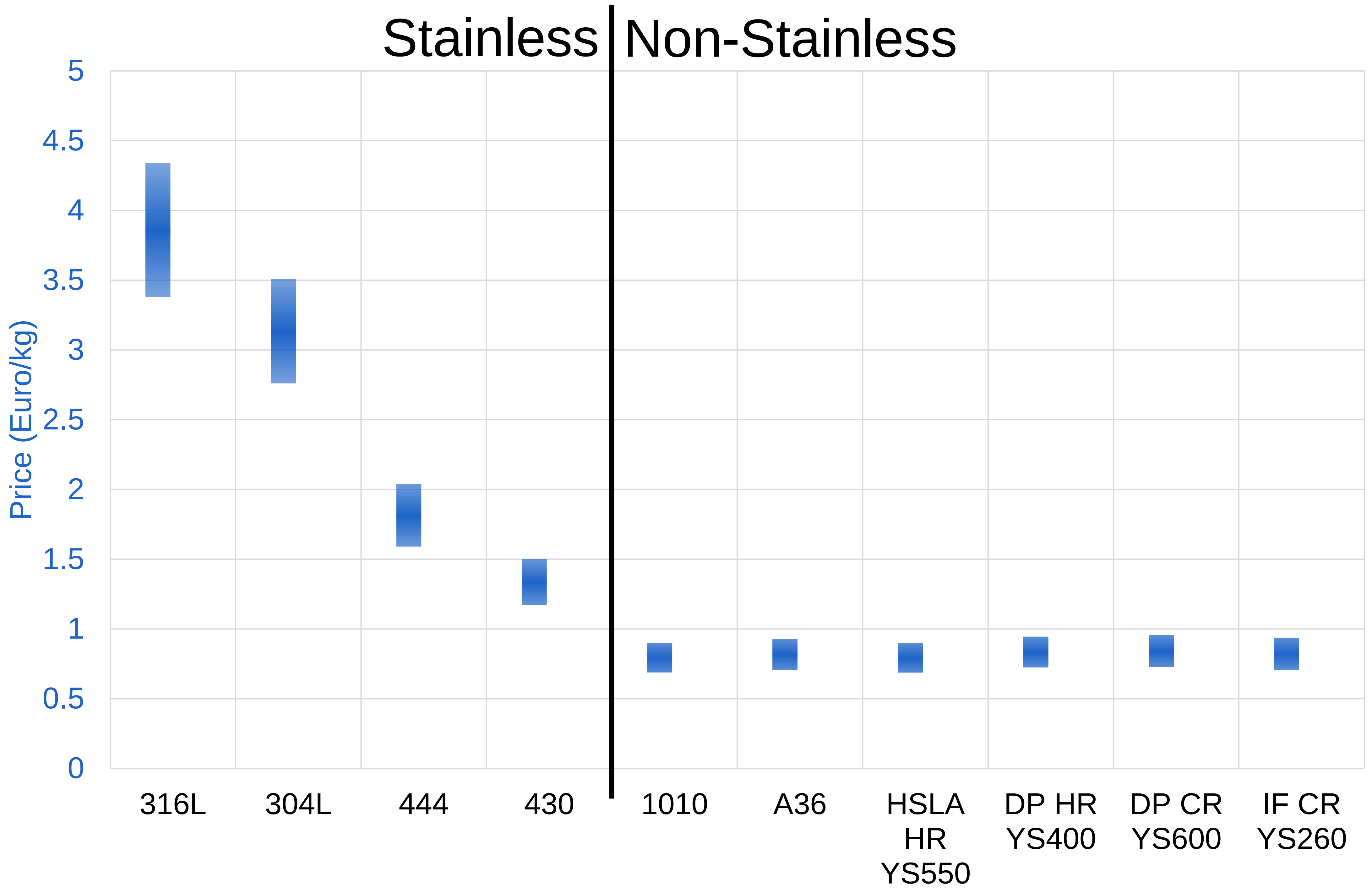

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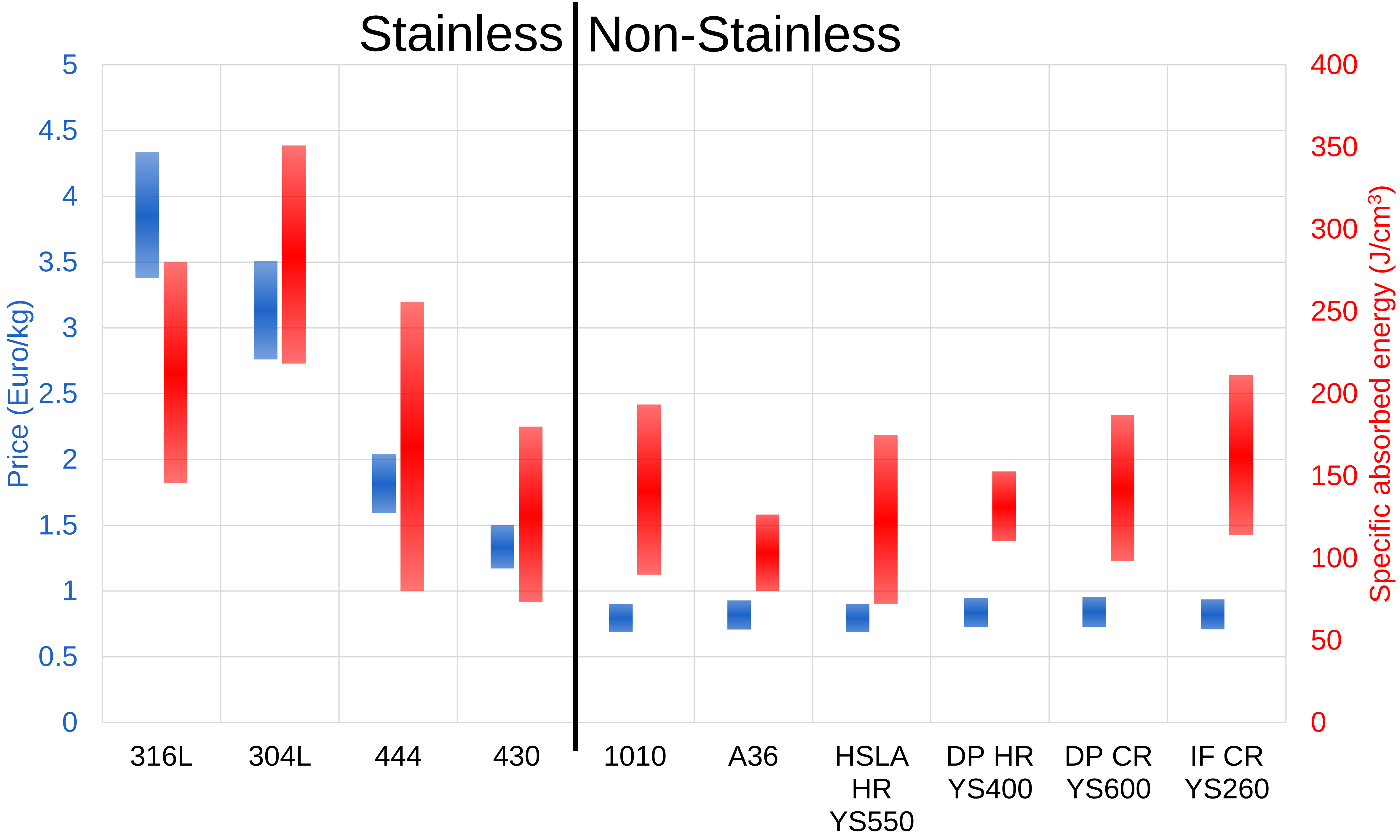
OVERVIEW OF STEELS POTENTIALLY TO BE USED AS THE BEAMPIPE MATERIAL



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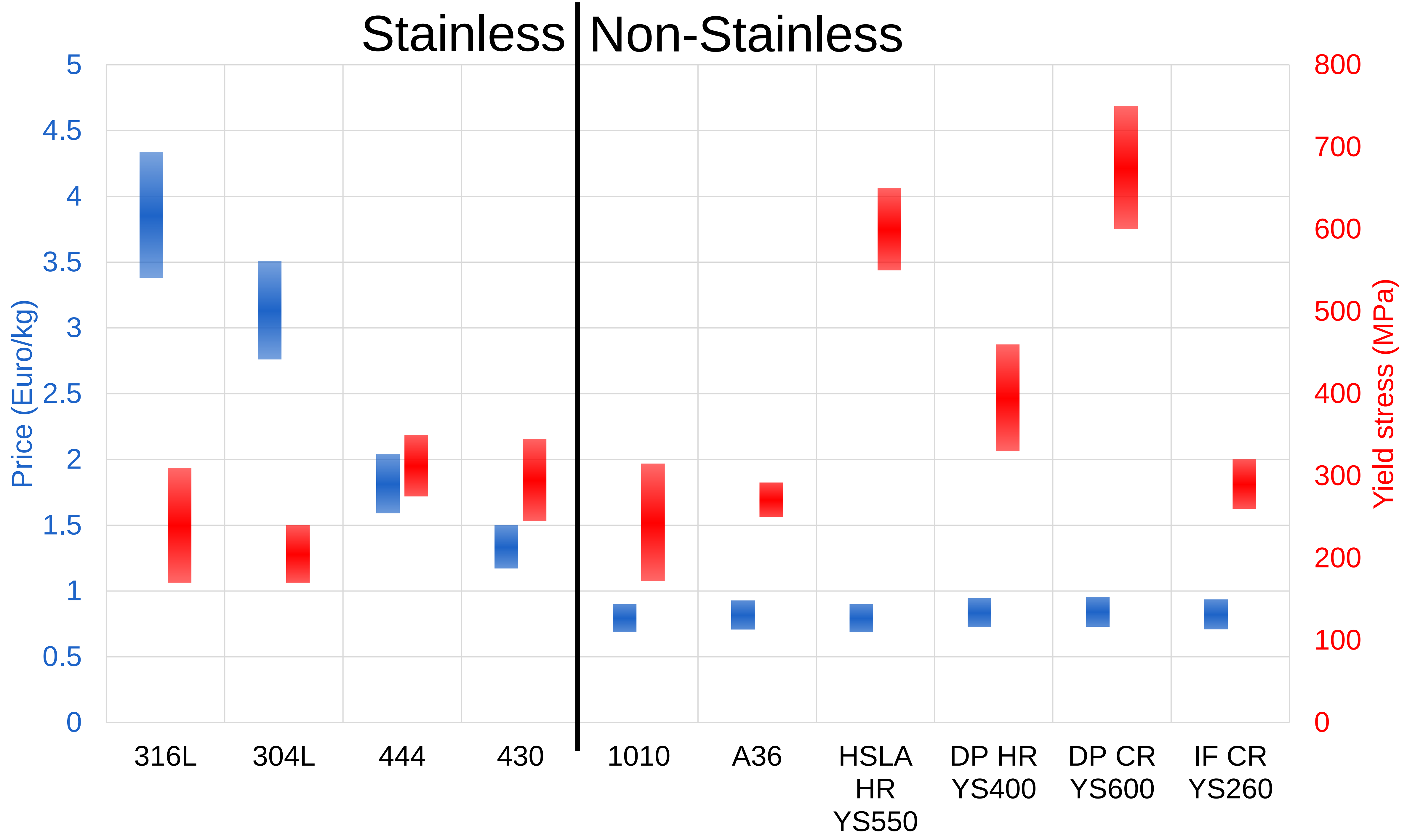

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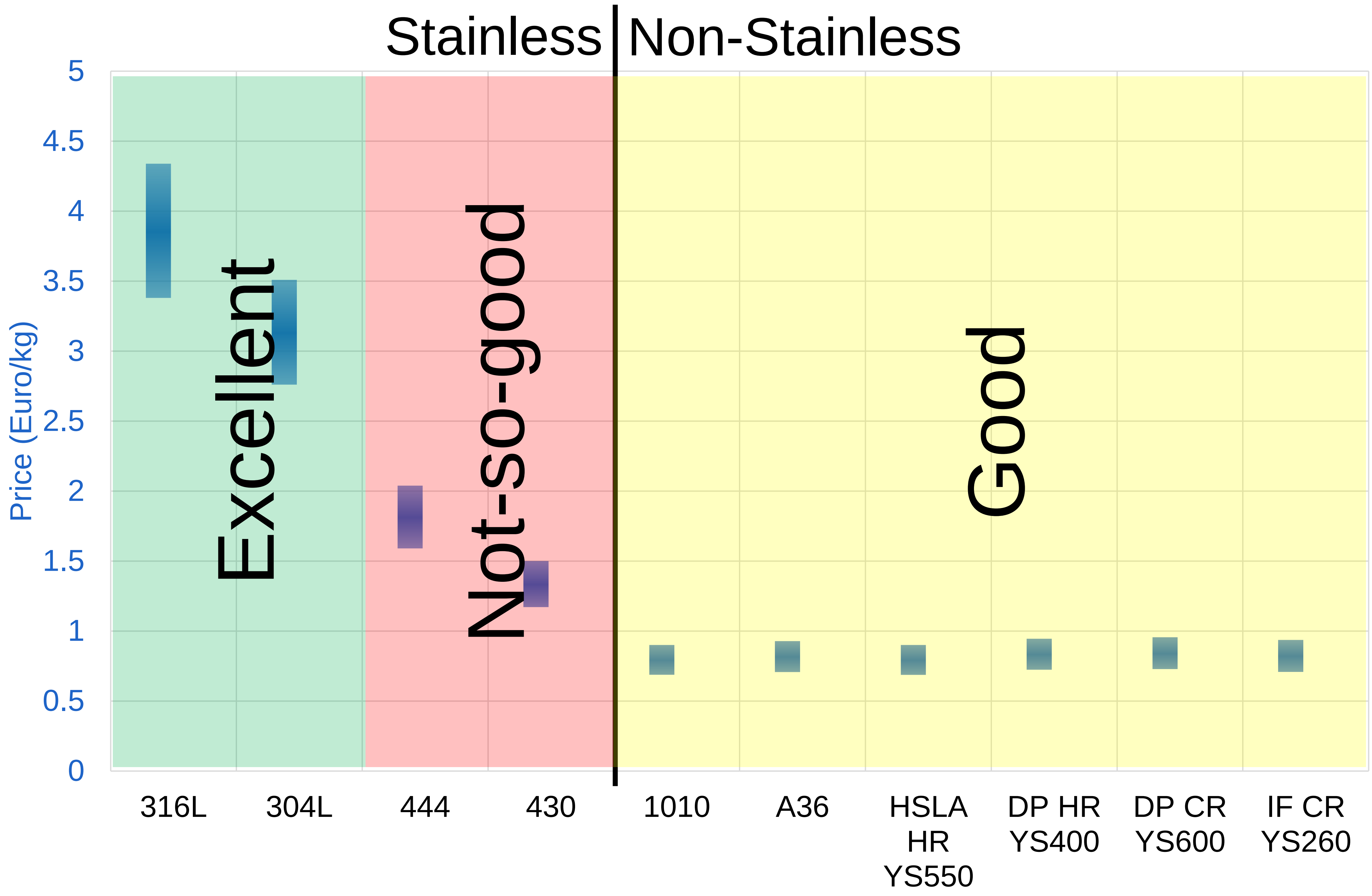

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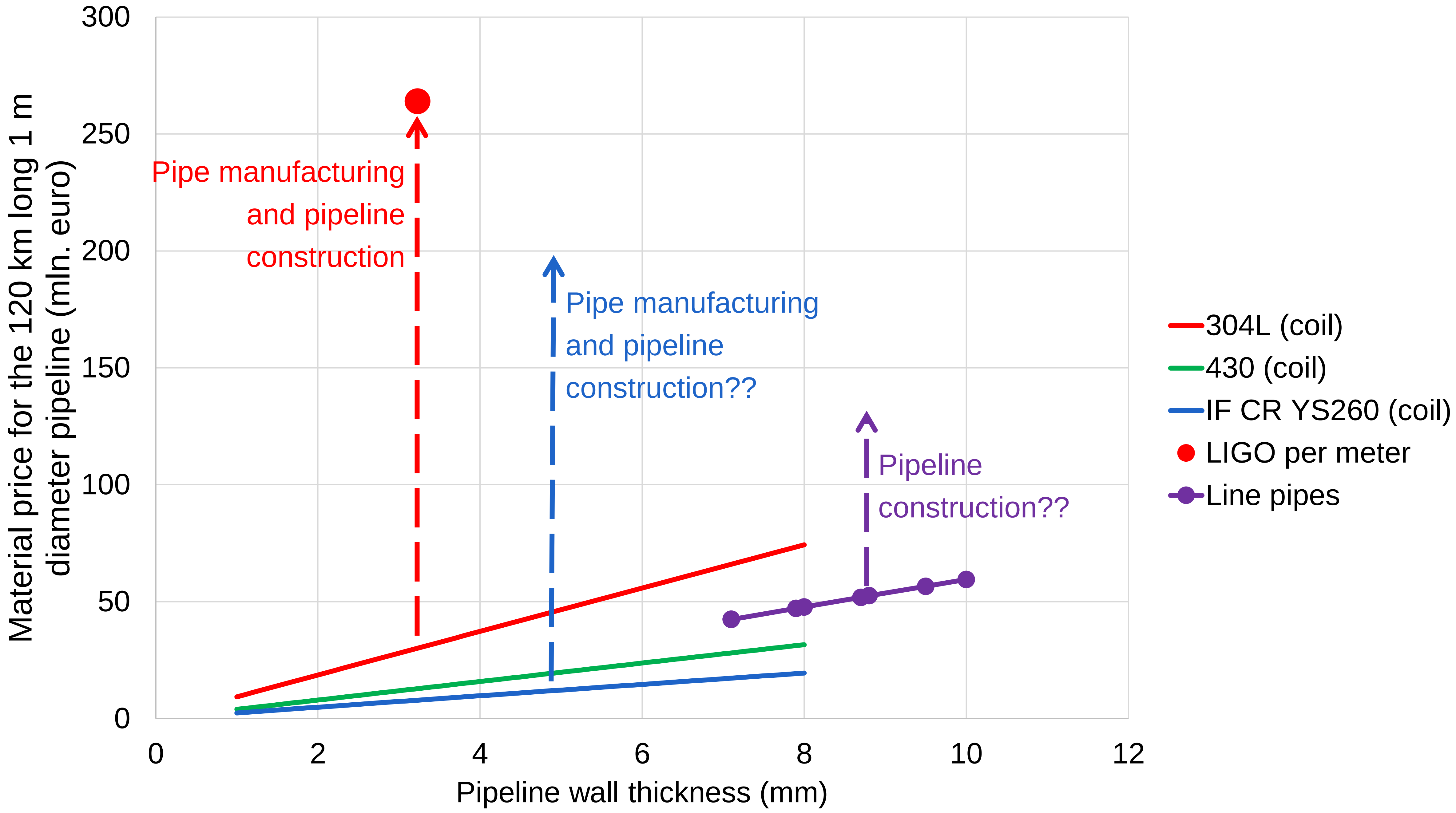

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OVERVIEW OF STEELS POTENTIALLY TO BE USED AS THE BEAMPIPE MATERIAL

Austenitic stainless steel alternatives (to reduce the cost)

Ferritic stainless steel

Formability of welded joints?

Non-stainless steel

Cleaning?

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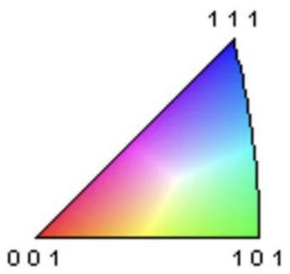
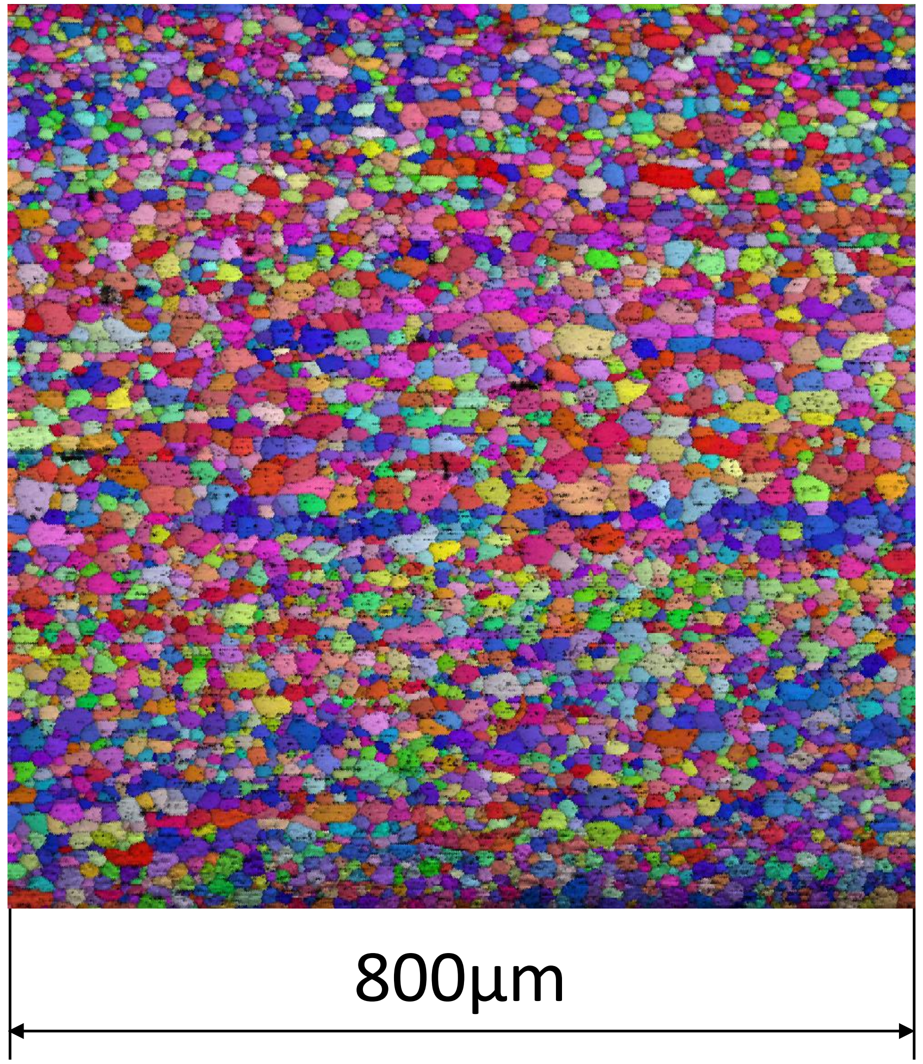
FERRITIC STAINLESS STEEL WELDED JOINT FORMABILITY

- The immediate task is to produce pre-prototypes of the ET beam pipe, smaller diameter pipe sections to be manufactured in CERN
- The pre-prototypes are longitudinally welded corrugated pipes, corrugations are applied by cold forming of the welded pipe
- AISI 430 FSS welds failed by brittle cracking during the cold forming
- Grades 444 and 441 demonstrated better performance but some damage still occurred
- Change of the welding process from TIG to laser welding apparently led to satisfactory results
- **Metallurgical aspects of the FSS welding in these challenging conditions must be understood**

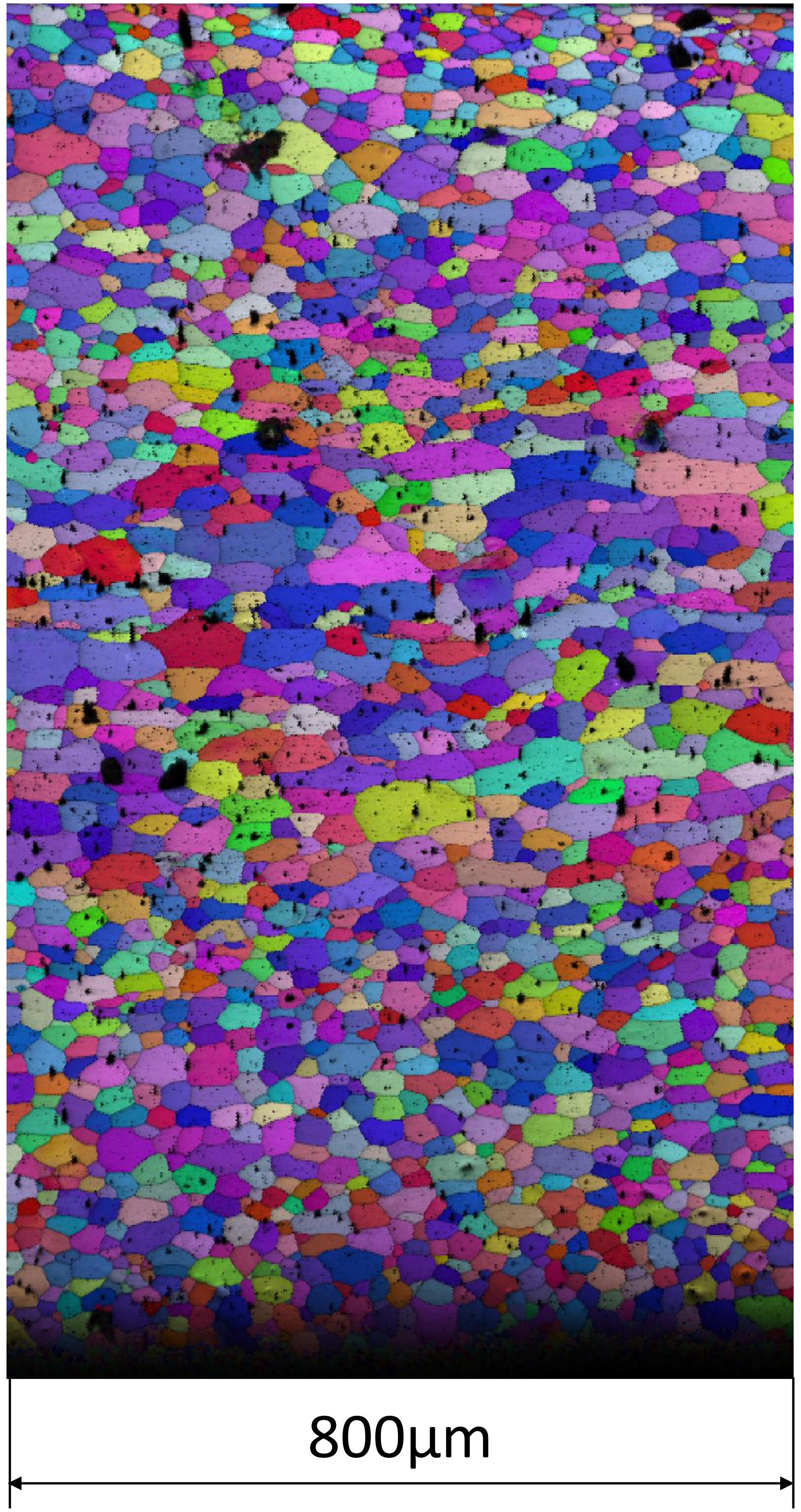
BASE METAL



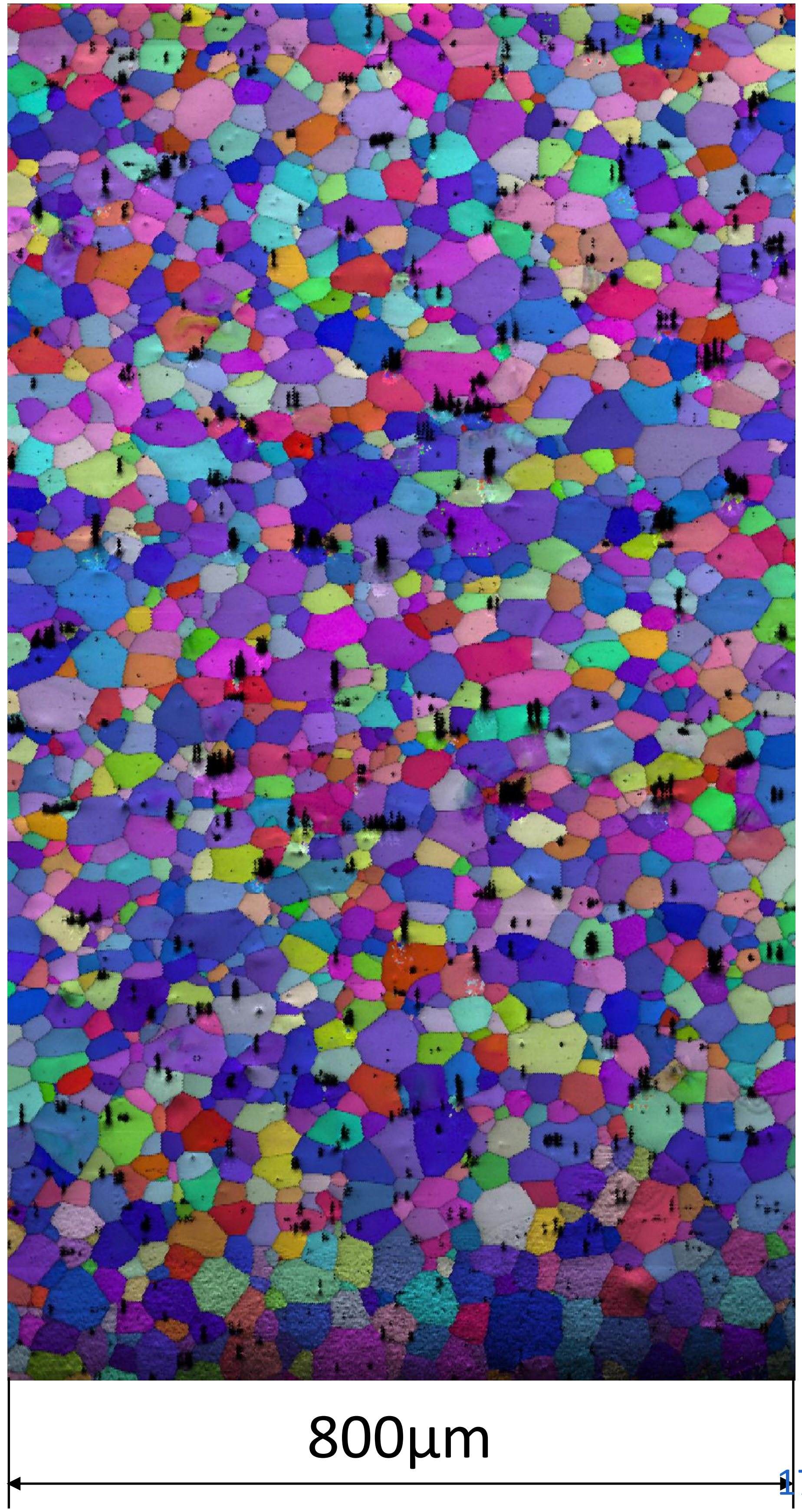
430

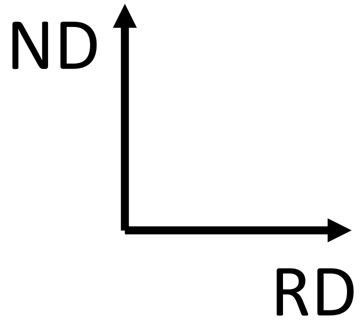


444



441





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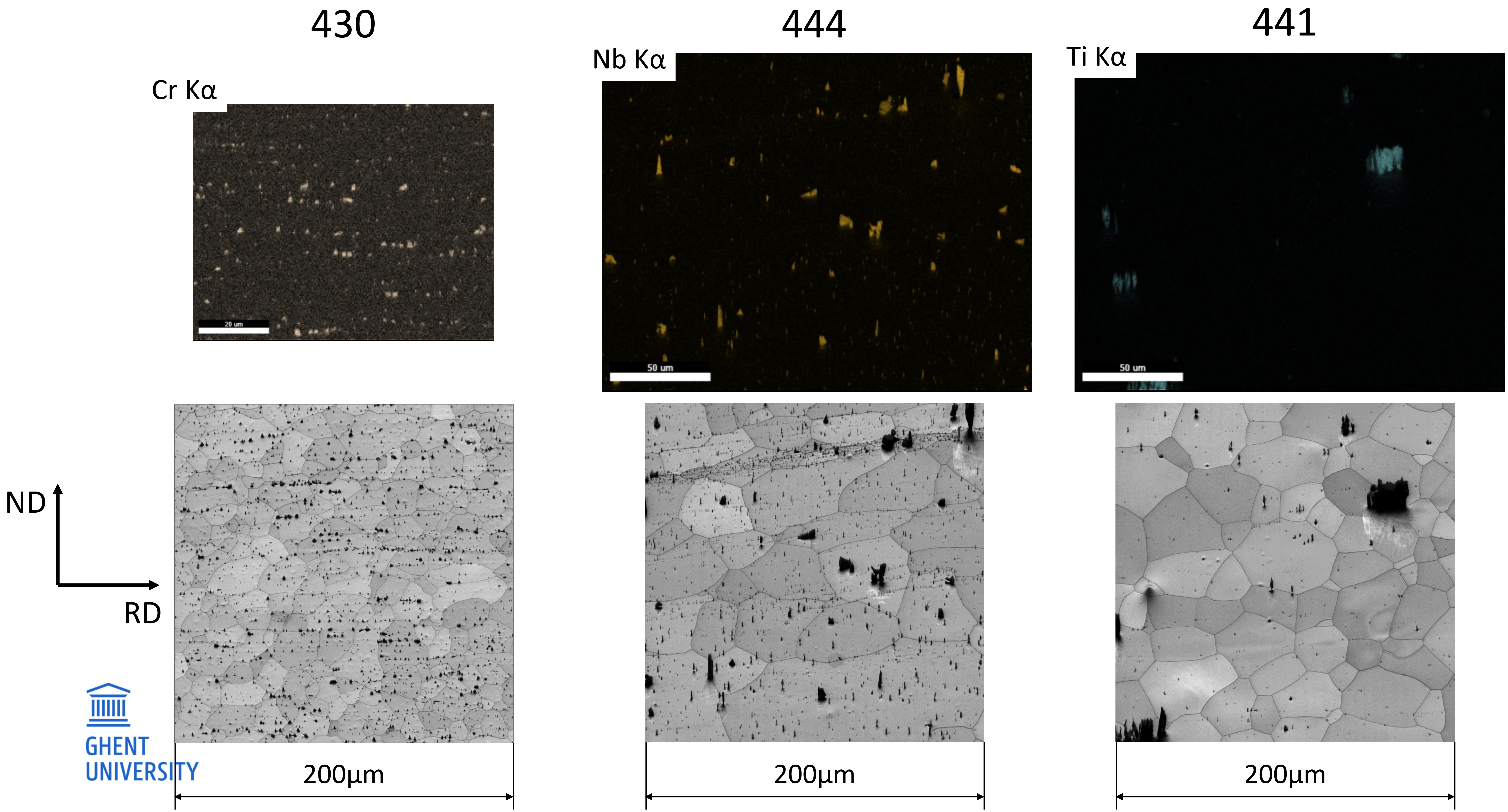
BASE METAL



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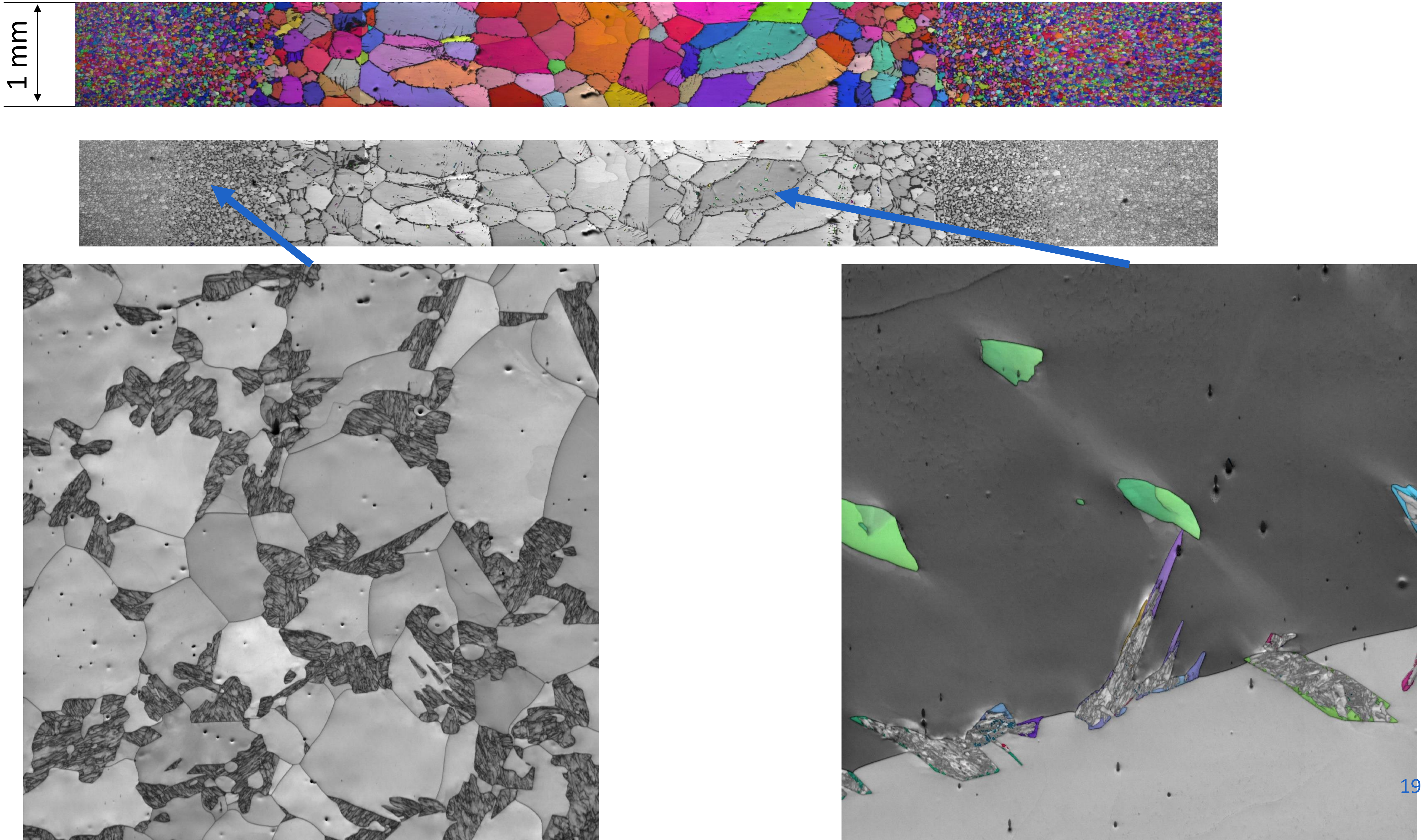
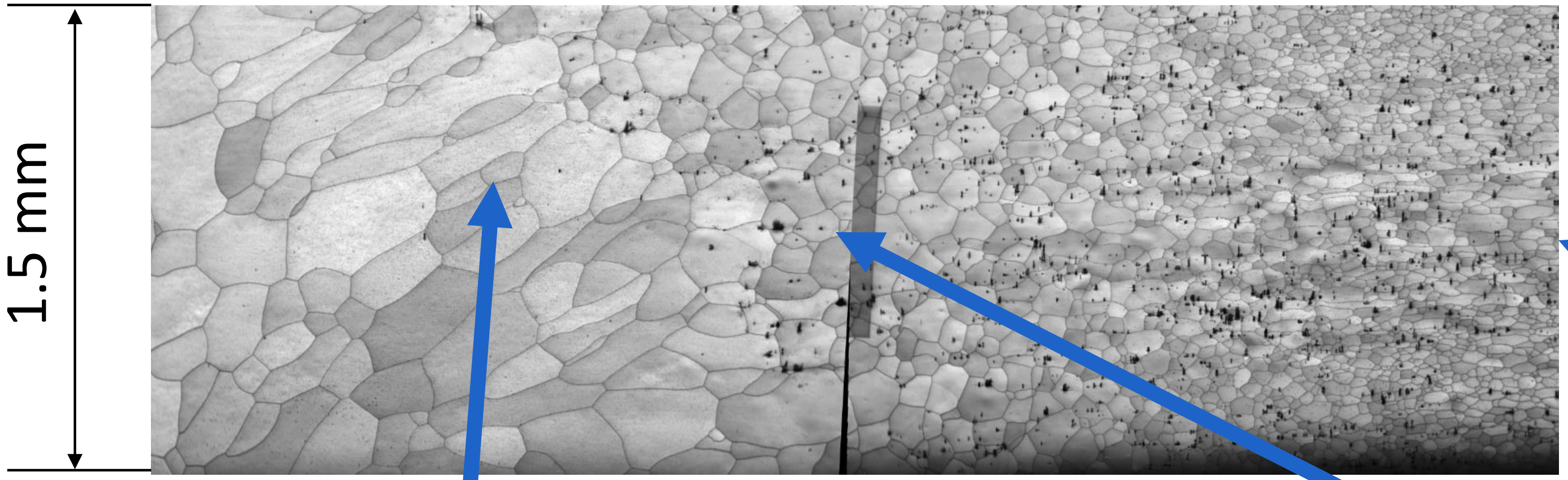
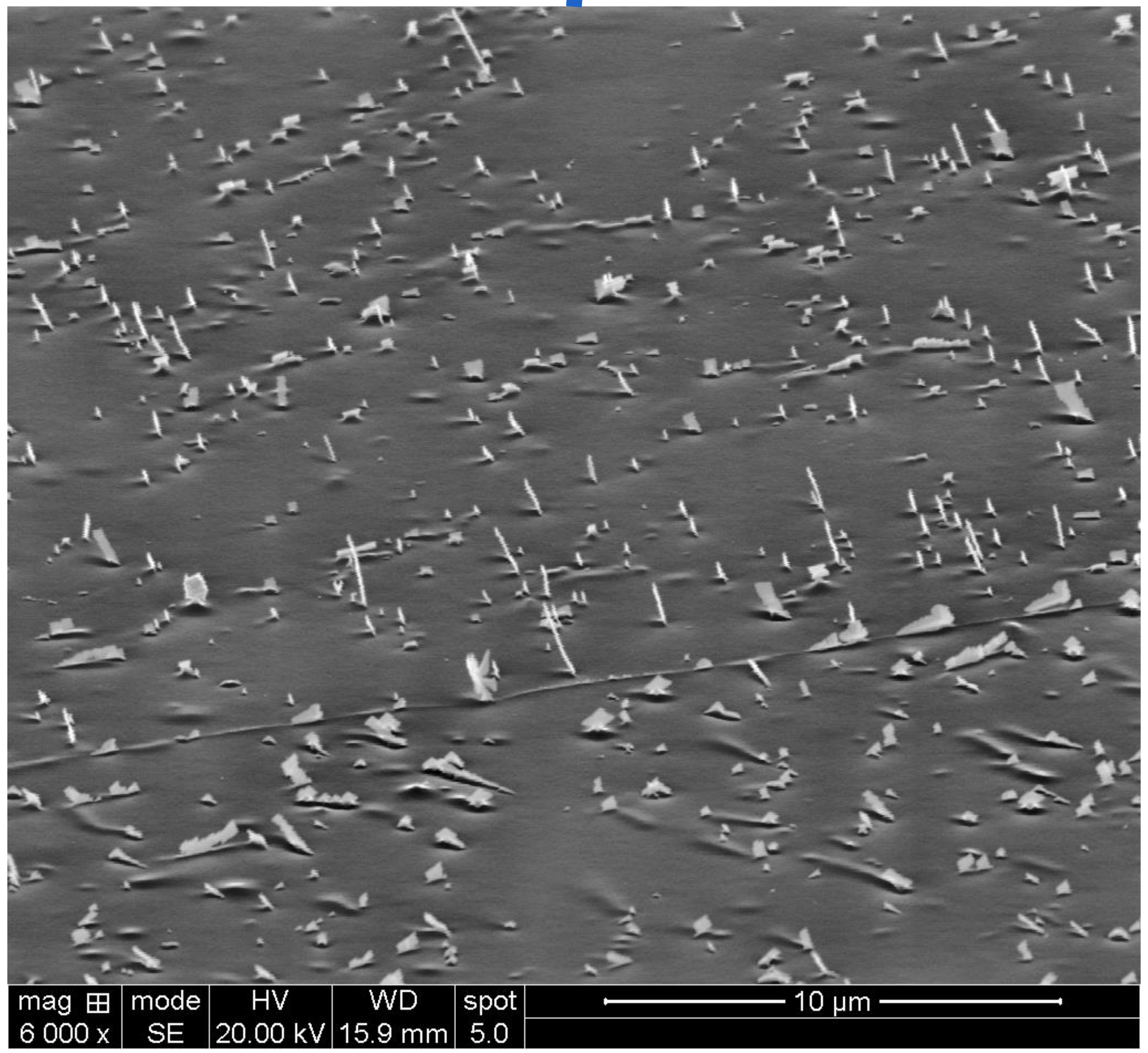
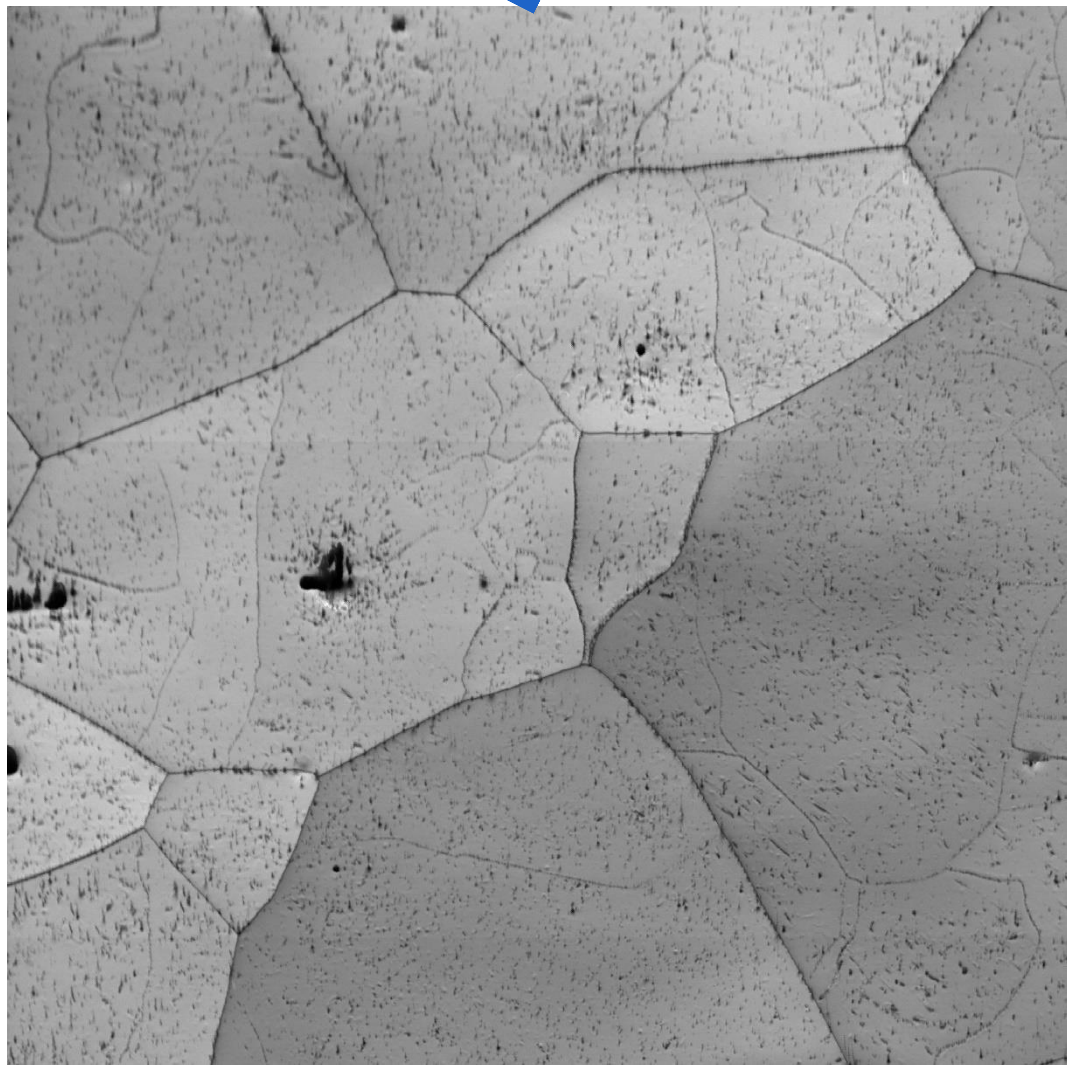
430 TIG WELDING JOINT

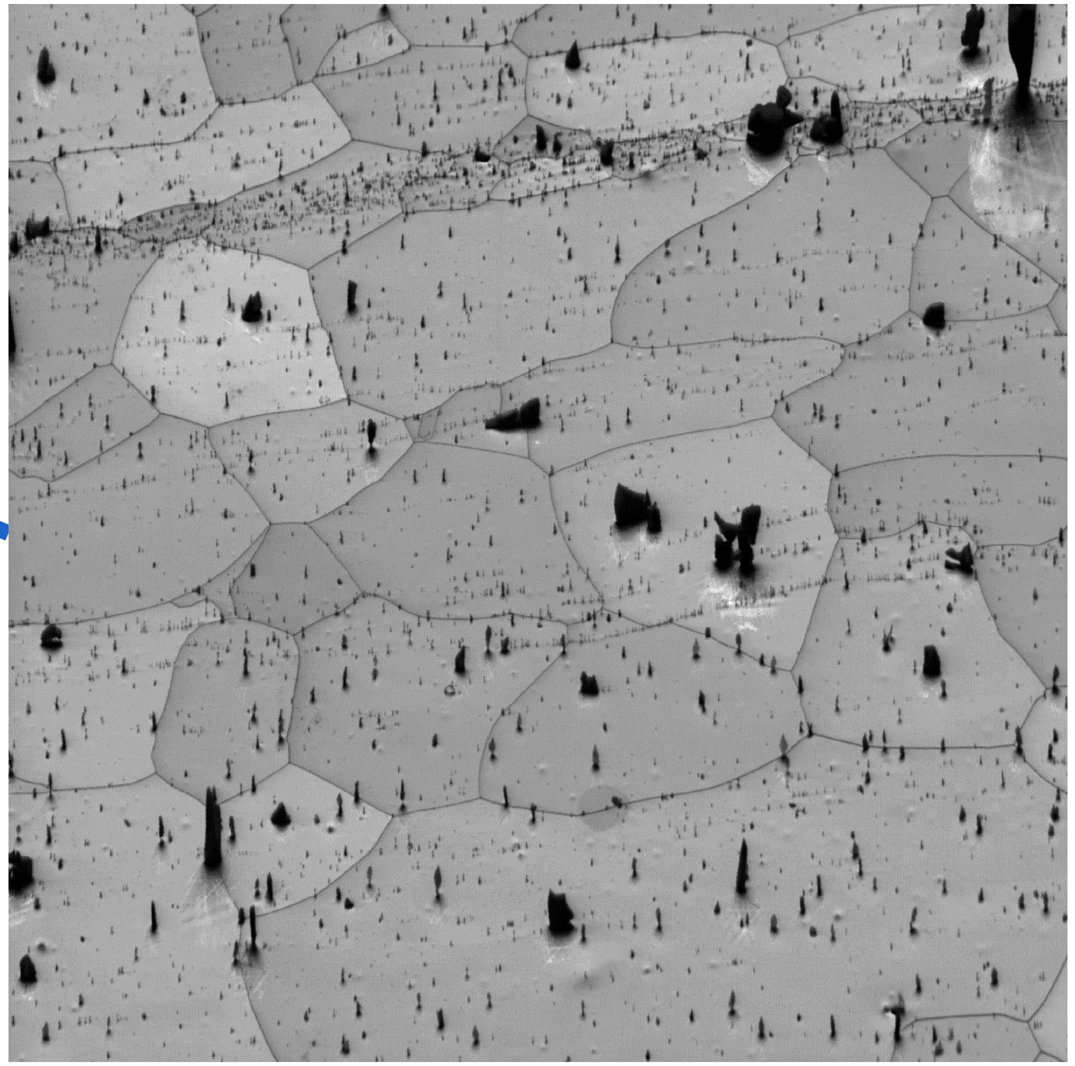


444 TIG WELDING JOINT

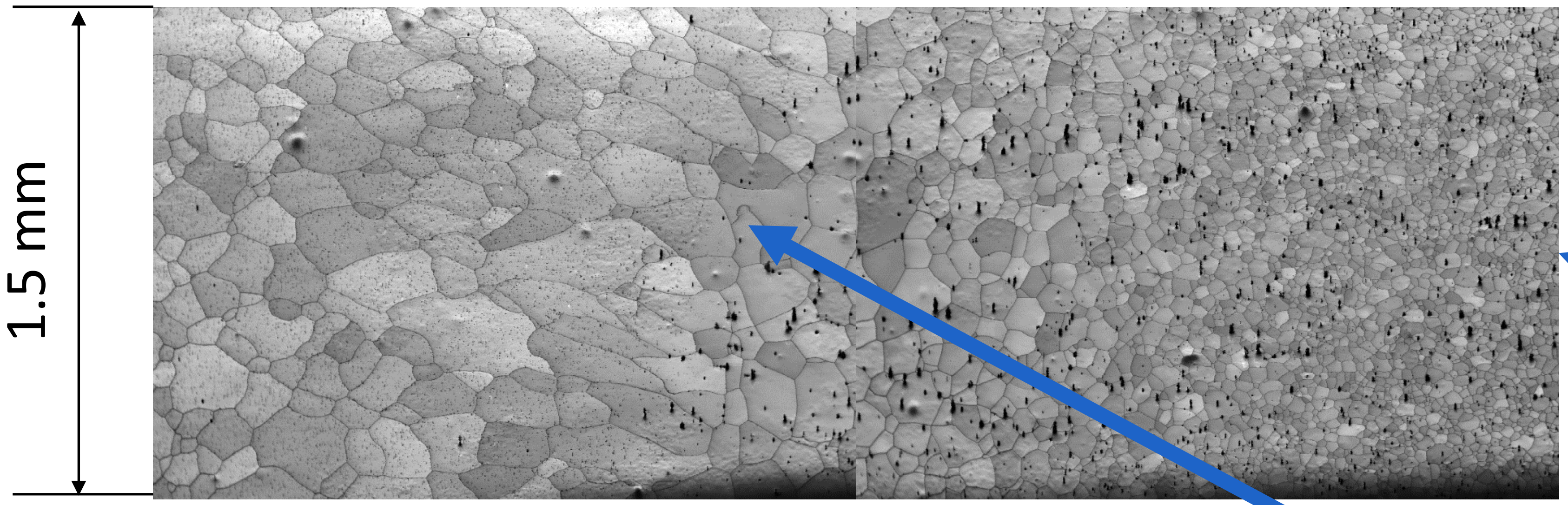


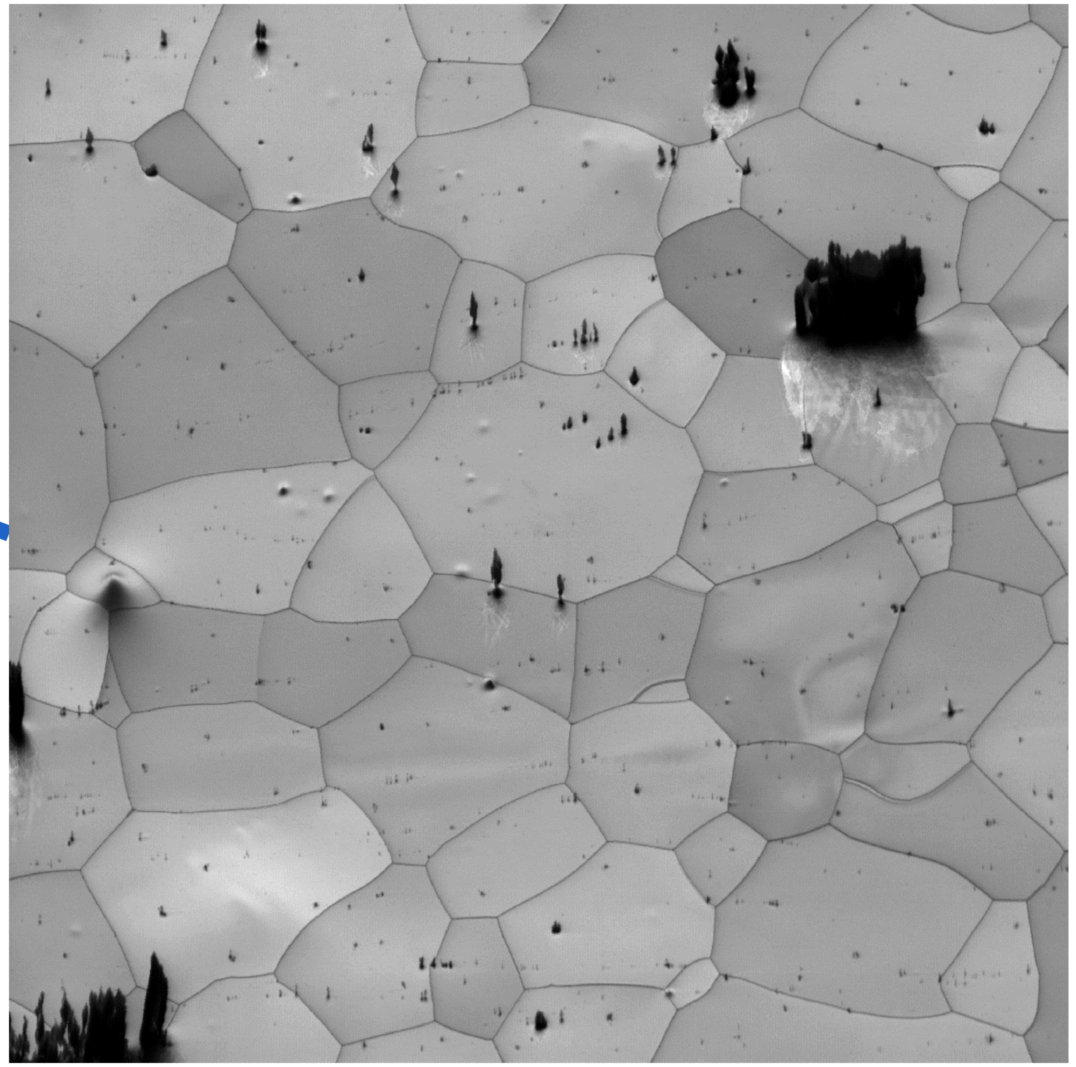


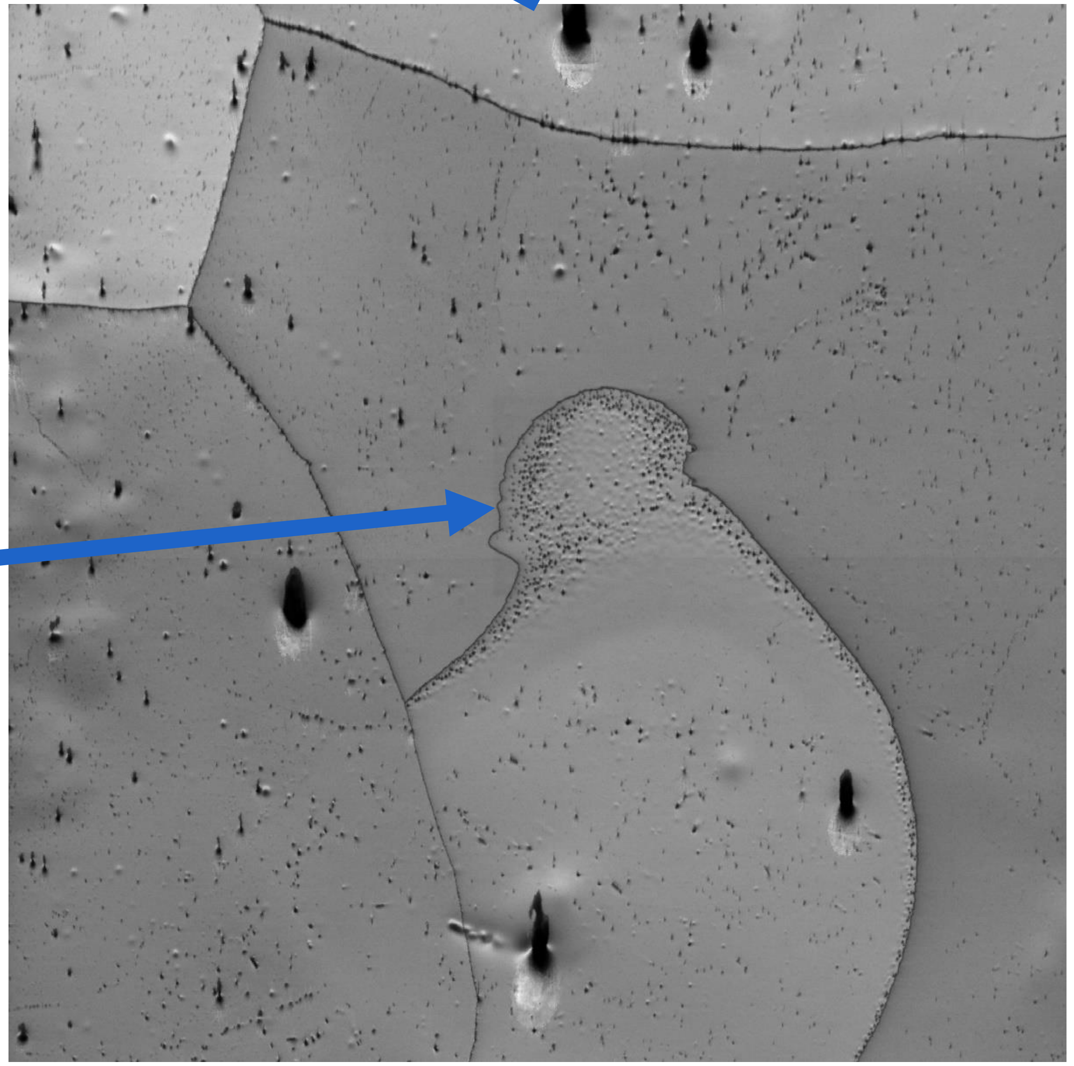


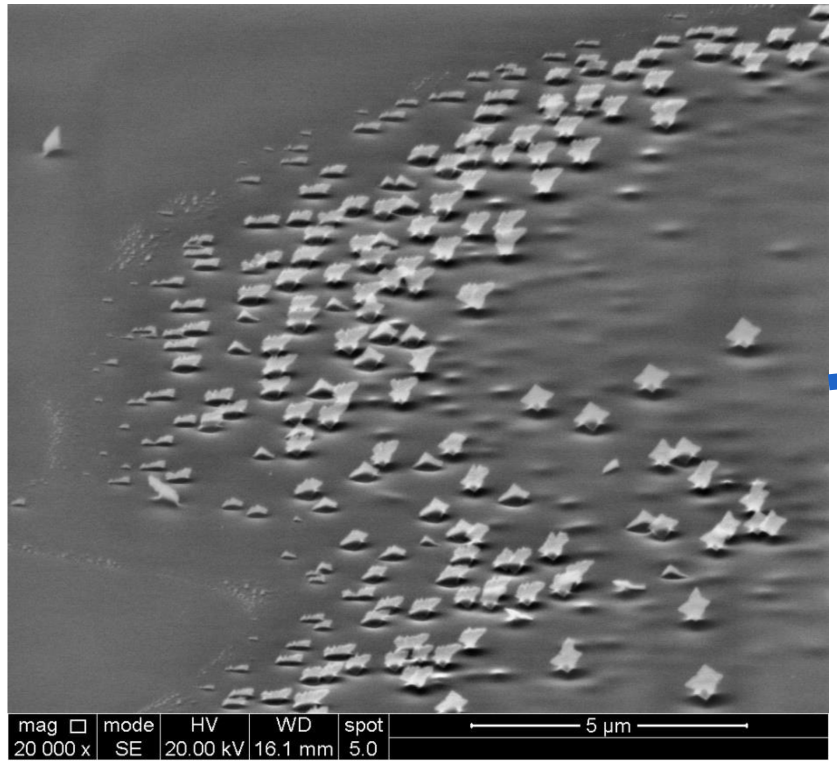


441 TIG WELDING JOINT









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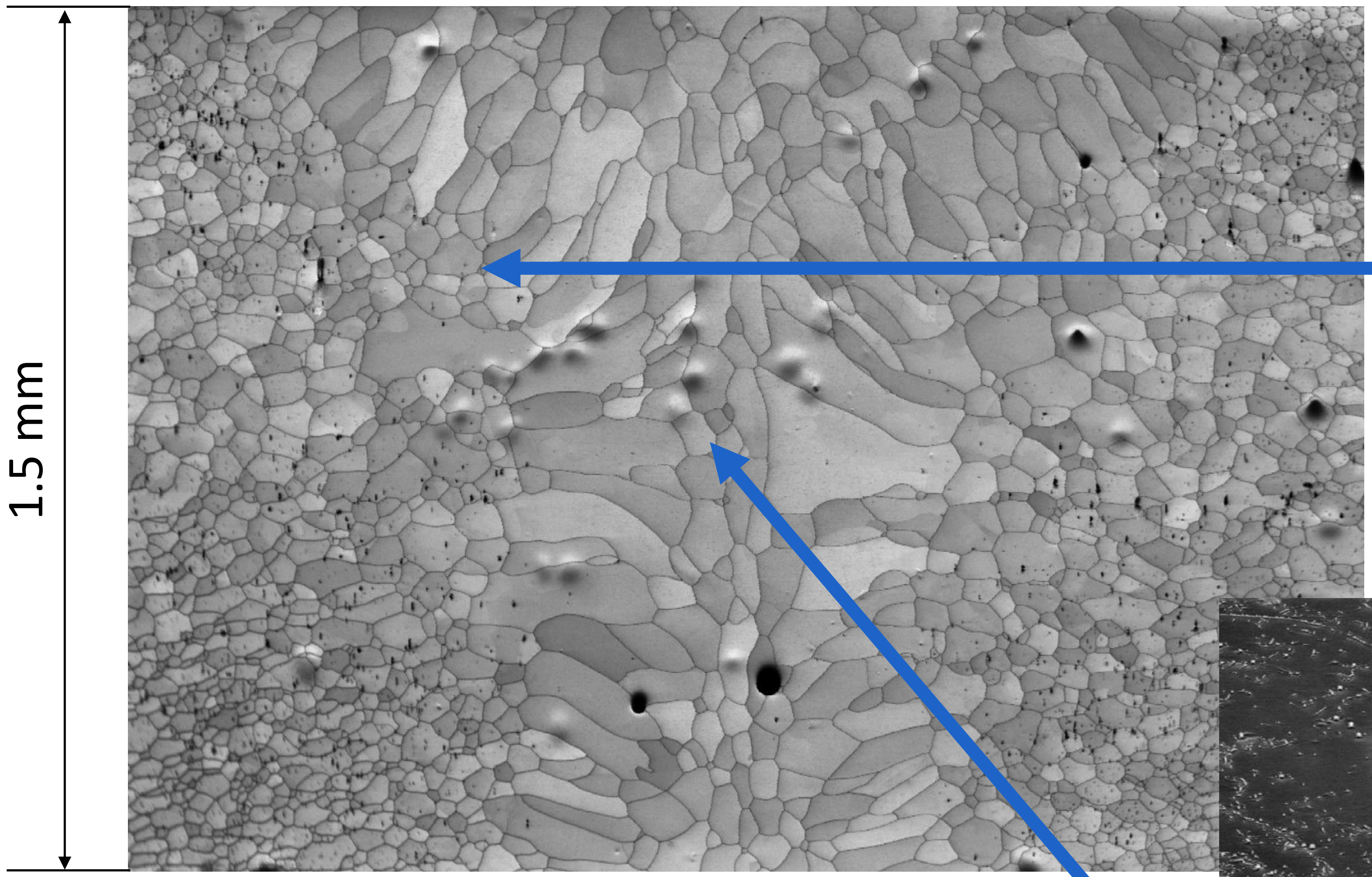
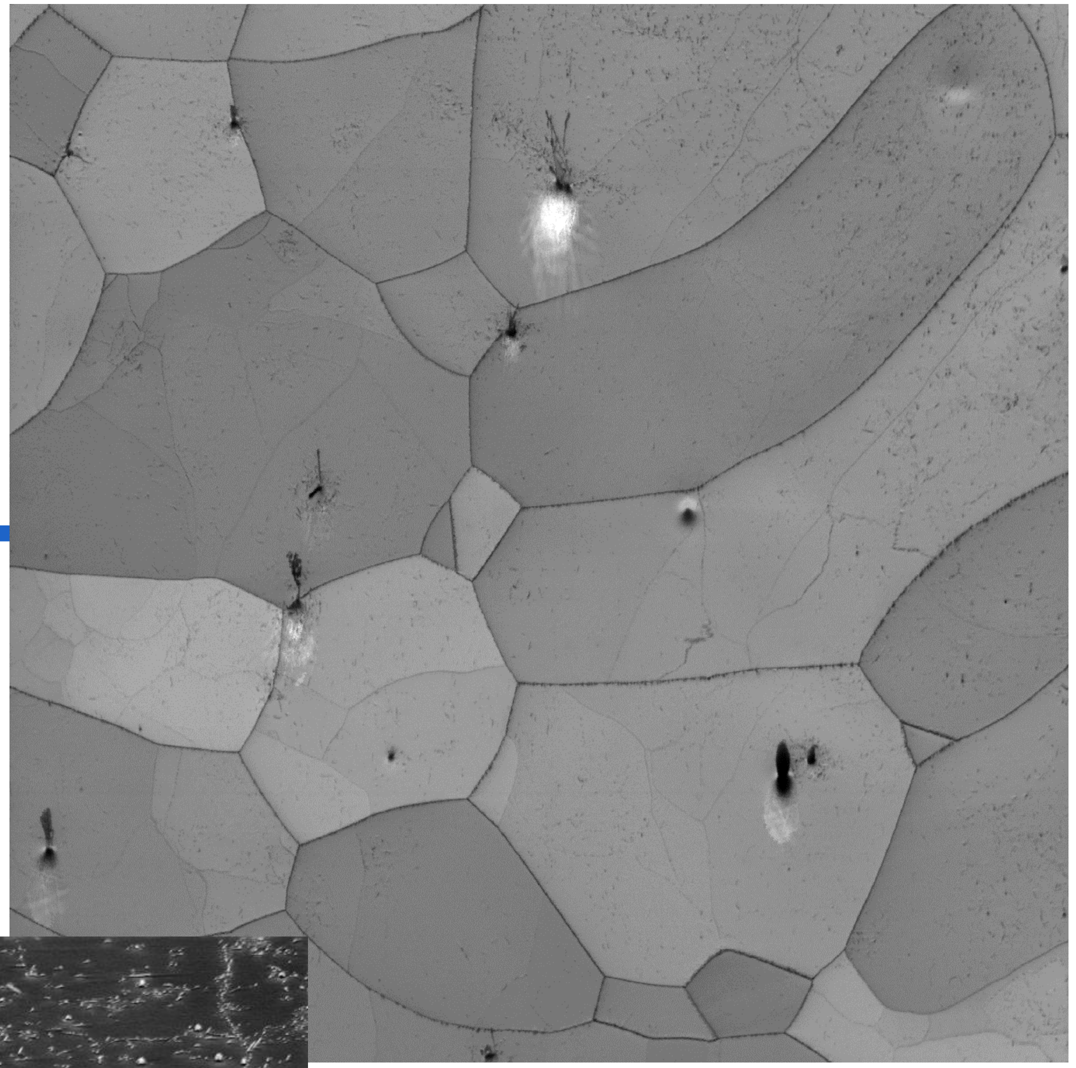
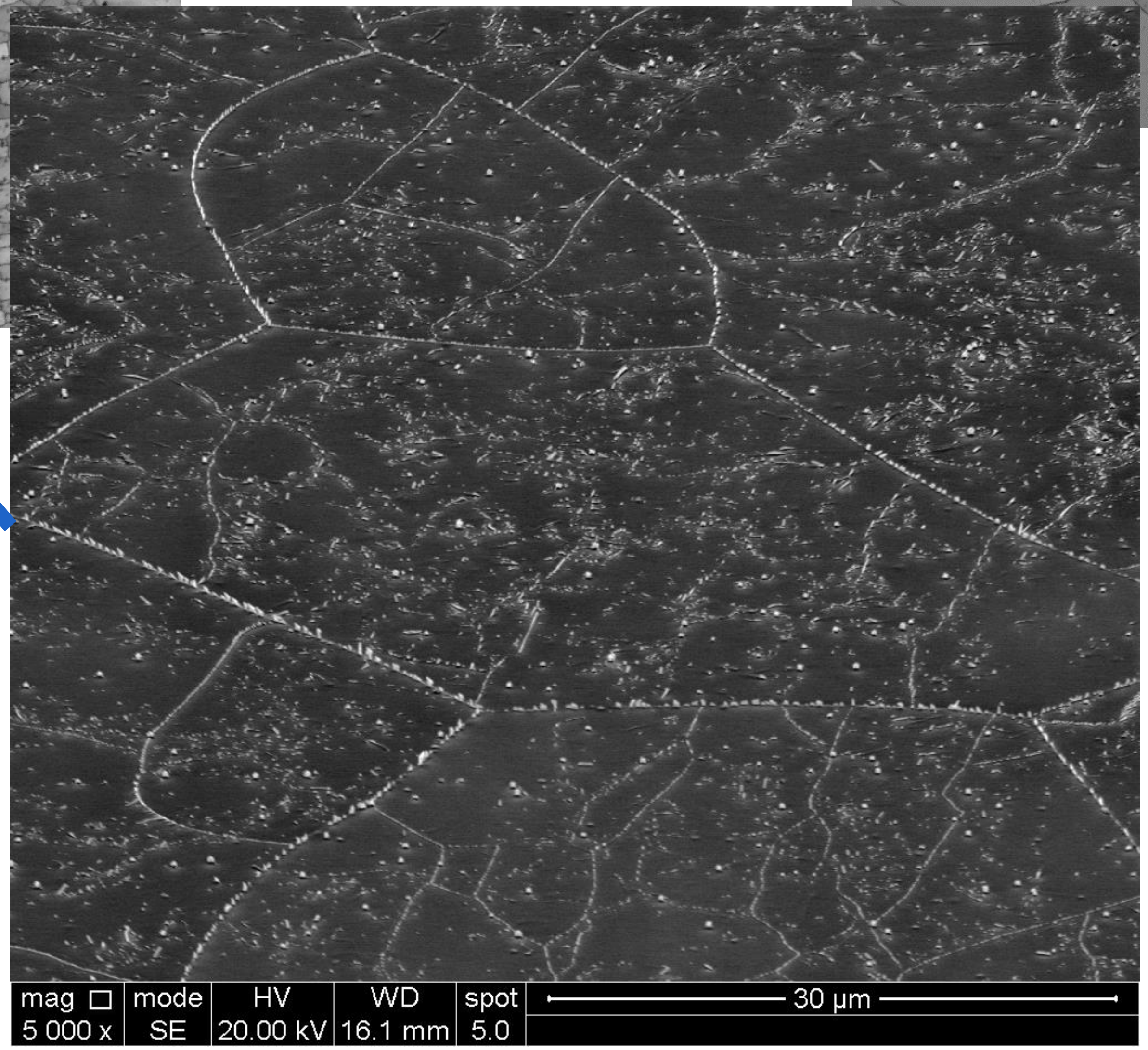
444 LASER (PULSED) WELDING JOINT







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BASIC WELDING HEAT TRANSFER MODEL

Tungsten Inert Gas (TIG) welding parameters

(aka Gas Tungsten Arc Welding (GTAW), an arc welding process that produces the weld with a non-consumable tungsten electrode)

Pulsed
I =40 A to 85 A
Pulse time = 0,15 s
V = 12 V
Speed = 130…145 mm/min

=> Heat input ≈ 185 J/mm

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BASIC WELDING HEAT TRANSFER MODEL

[N.N. Rykalin (1951)]

$$T(t) = \frac{Q}{d\sqrt{4\pi\lambda c\rho t}} \exp\left(-\frac{r^2}{4at} - bt\right) + T_0$$

$$r = \frac{\sqrt{\left[\frac{\lambda(T_p - T_0)d}{0{,}121Q}\right]^2 + 8ba} - \frac{\lambda(T_p - T_0)d}{0{,}121Q}}{2b}$$

$$a = \frac{\lambda}{c\rho} \qquad b = \frac{2\alpha}{c\rho d}$$

T	Temperature (°C)	
T_0	Initial temperature (°C)	
t	Time (s)	
Q	Heat input $\left(\frac{J}{m}\right)$	180000
d	Thickness (m)	0.0015
ρ	Density $\left(\frac{kg}{m^3}\right)$	7800
λ	Mean thermal conductivity $\left(\frac{W}{m\cdot K}\right)$	25
c	Mean specific heat capacity $\left(\frac{J}{kg\cdot K}\right)$	420
α	Mean heat transfer coefficient $\left(\frac{W}{m^2\cdot K}\right)$	180
r	Distance between the heat source and the modelled point (m)	0.00613

With the peak temperature of 1350°C

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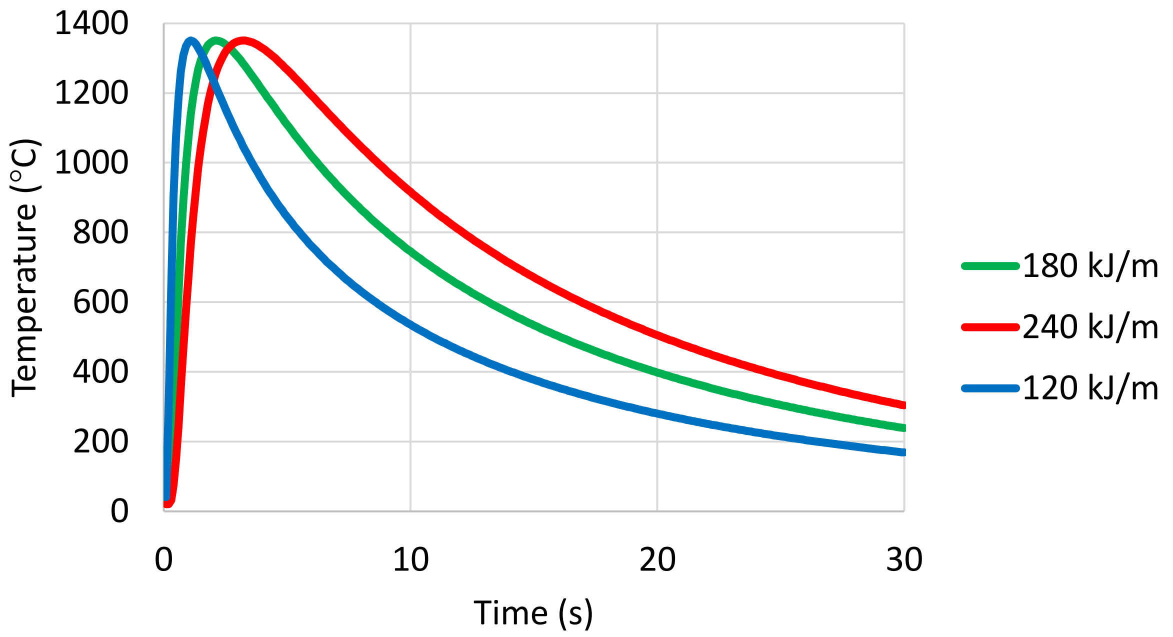
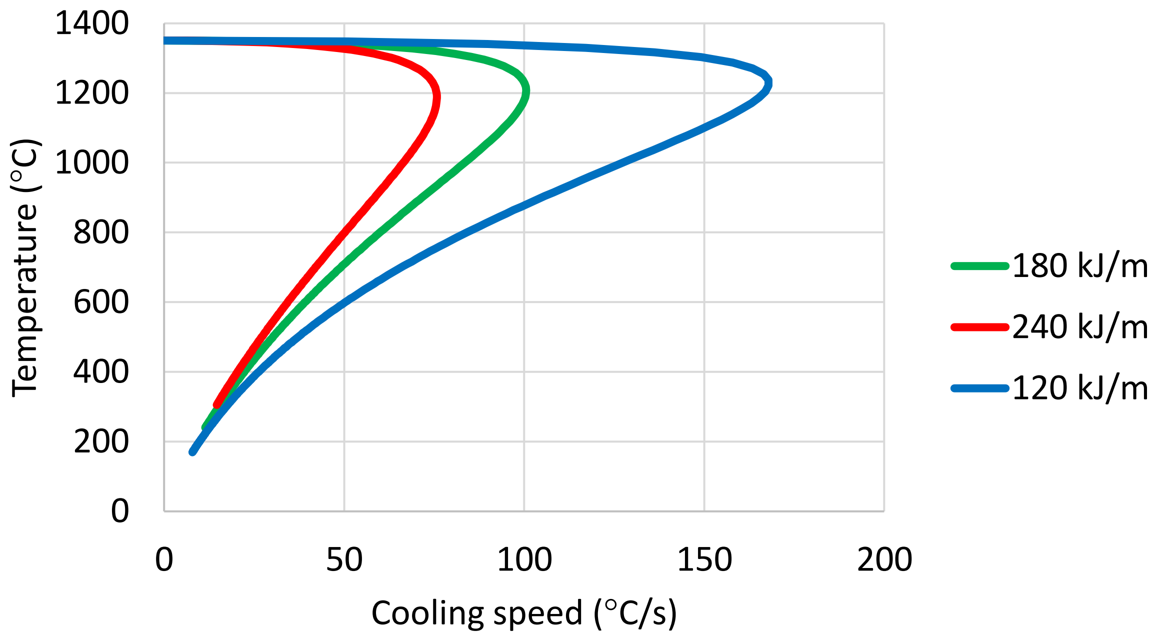
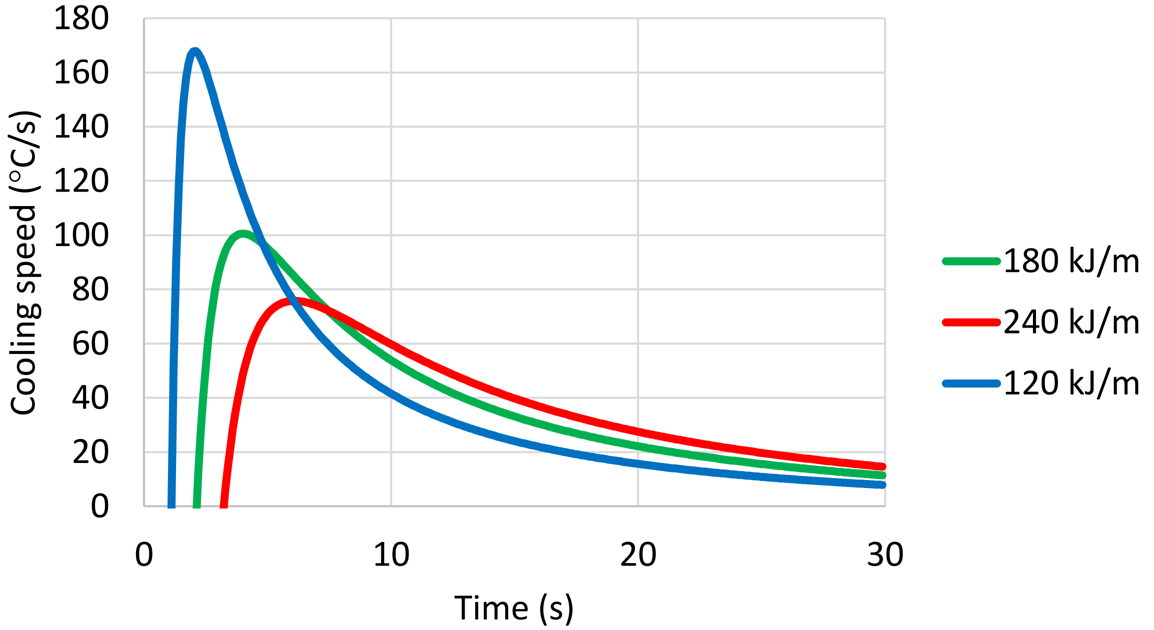
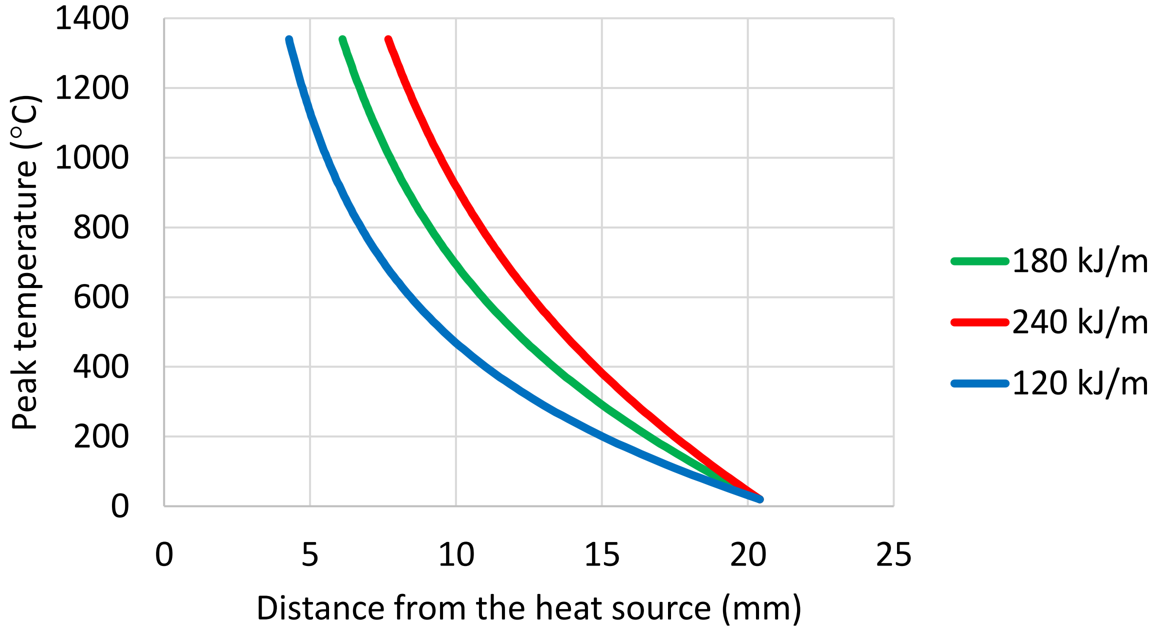
BASIC WELDING HEAT TRANSFER MODEL

180 kJ/m – heat input estimated from the welding parameters, 240 and 120 kJ/m – arbitrary higher and lower heat inputs









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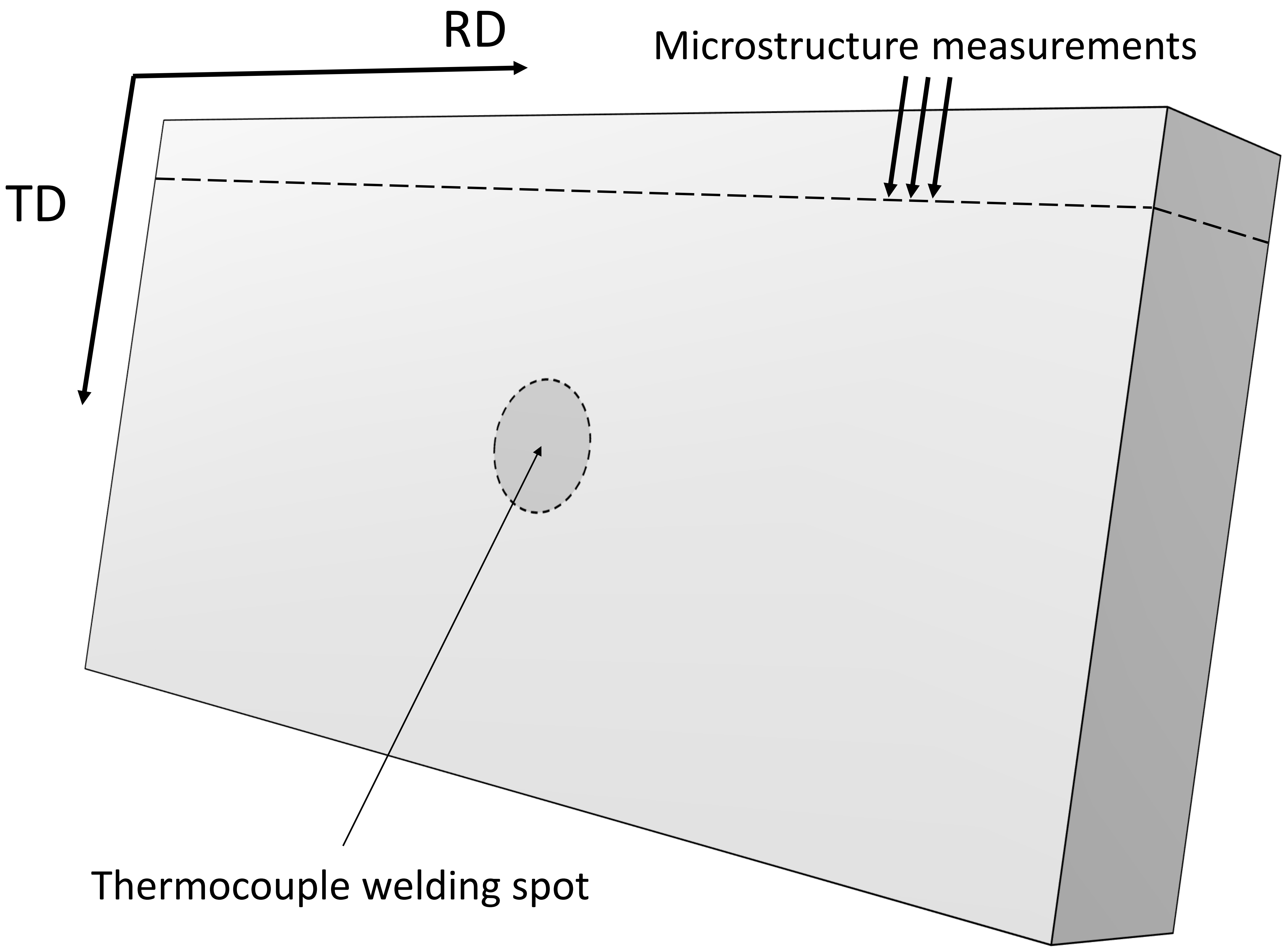
DILATOMETER SIMULATIONS

Dilatometer specimen:

10 mm × 5 mm ×

sheet thickness (1.5 mm)



Dilatometer measures dimensional changes in material as a function of temperature.

It can implement complex temperature-time programs with high heating and cooling rates using induction heating and cooling by inert gas stream.

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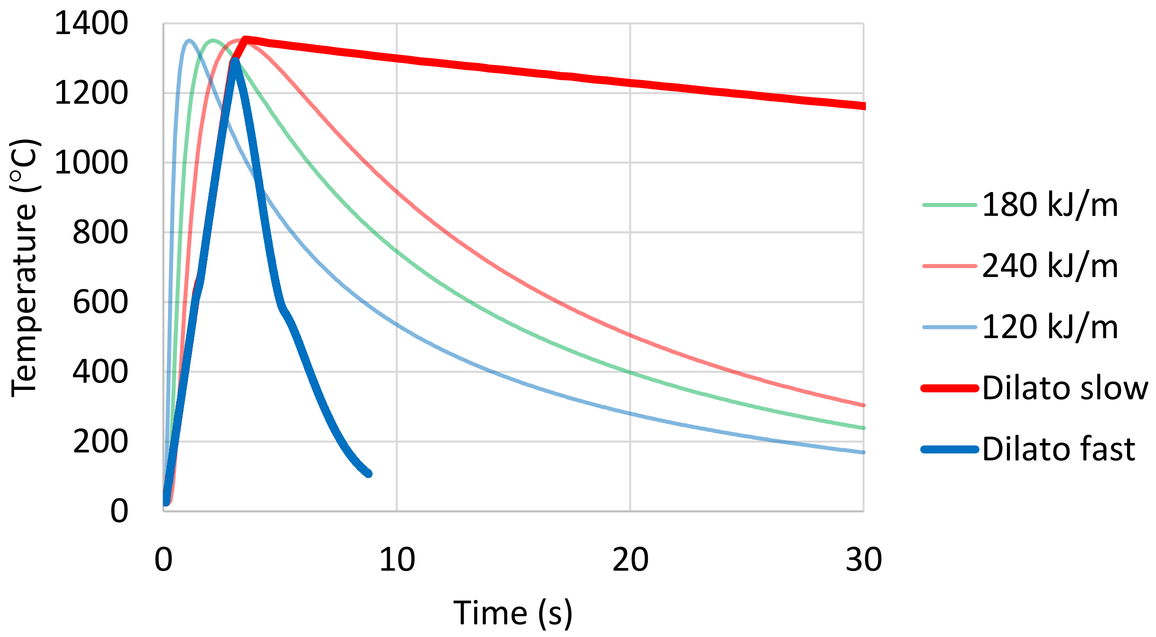
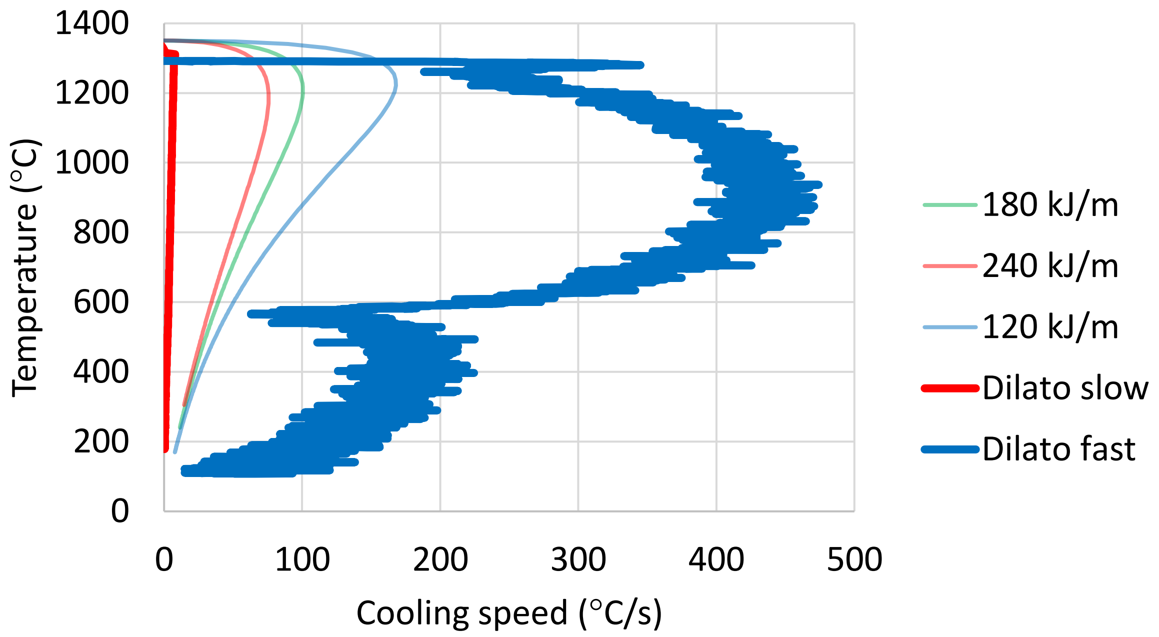
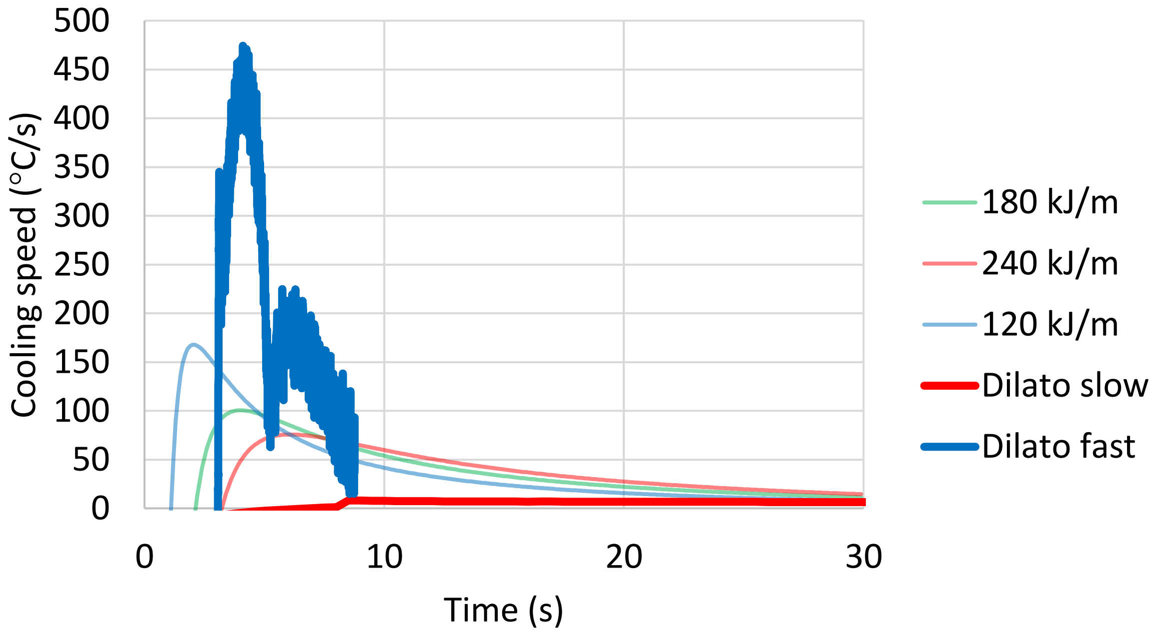
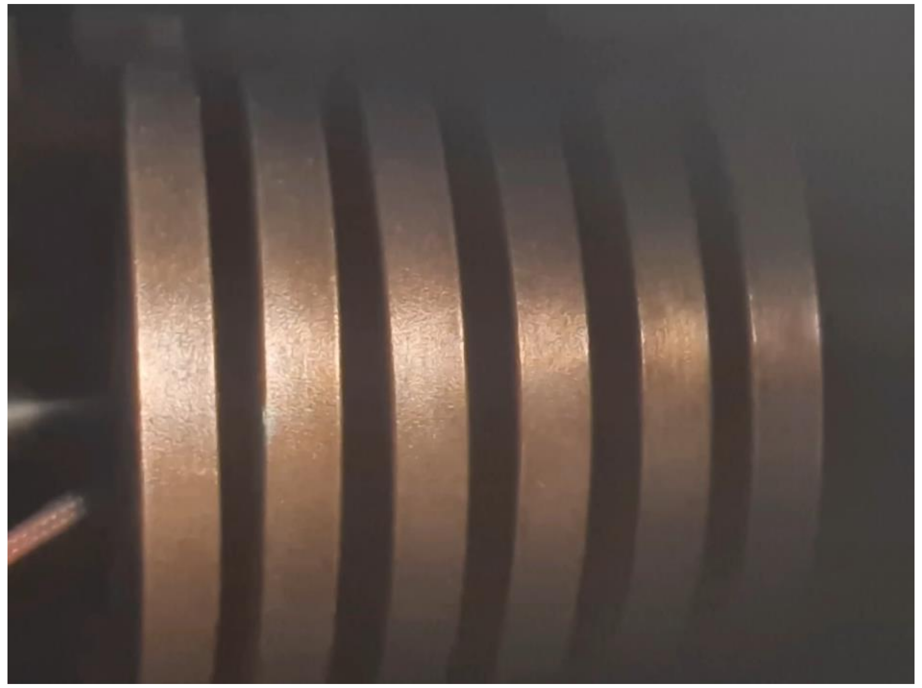
DILATOMETER SIMULATIONS

Two treatments: much faster and much slower cooling rates compared to the model estimation









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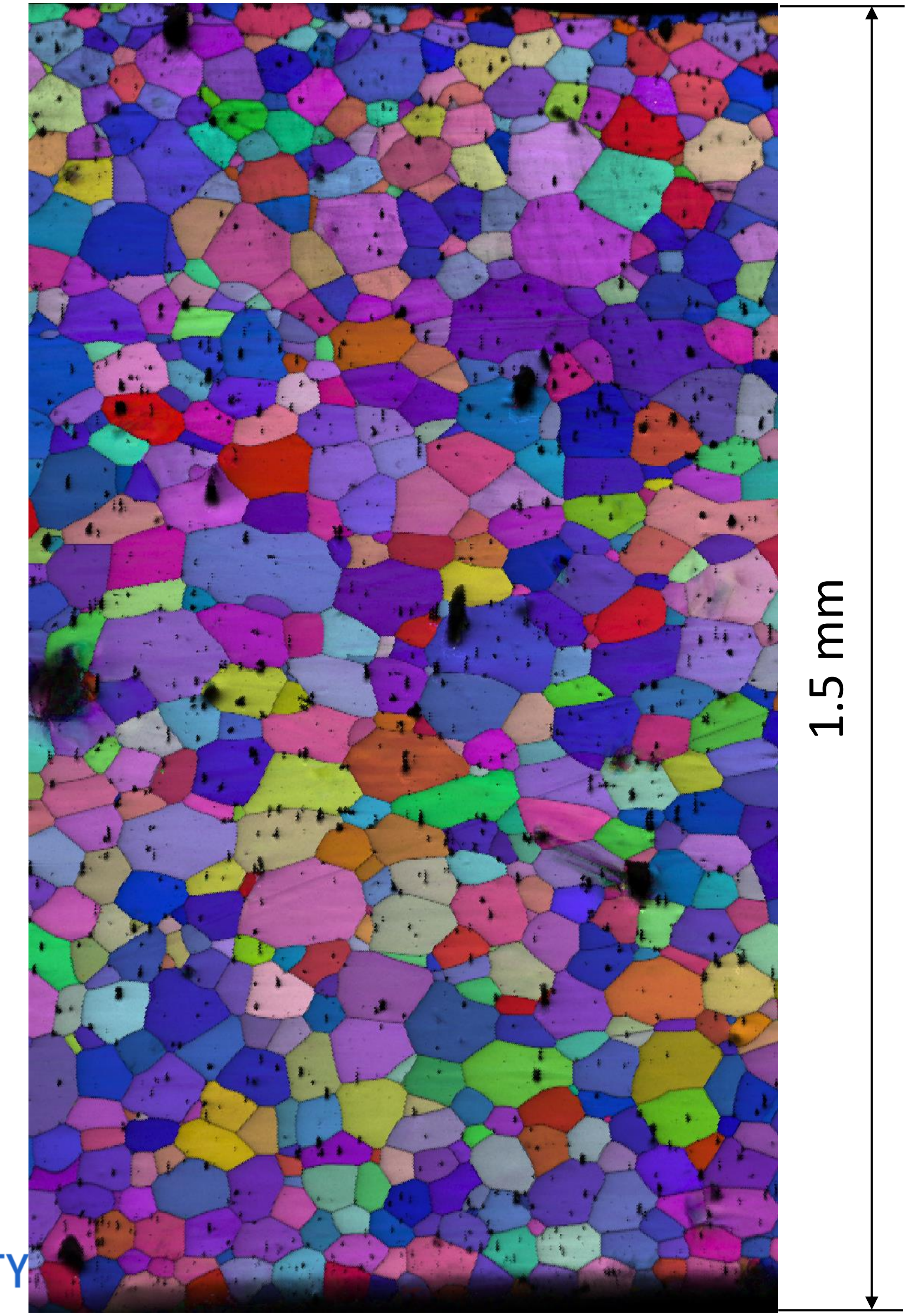
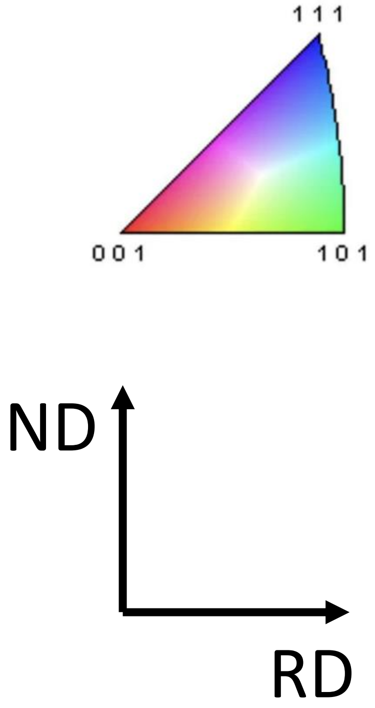
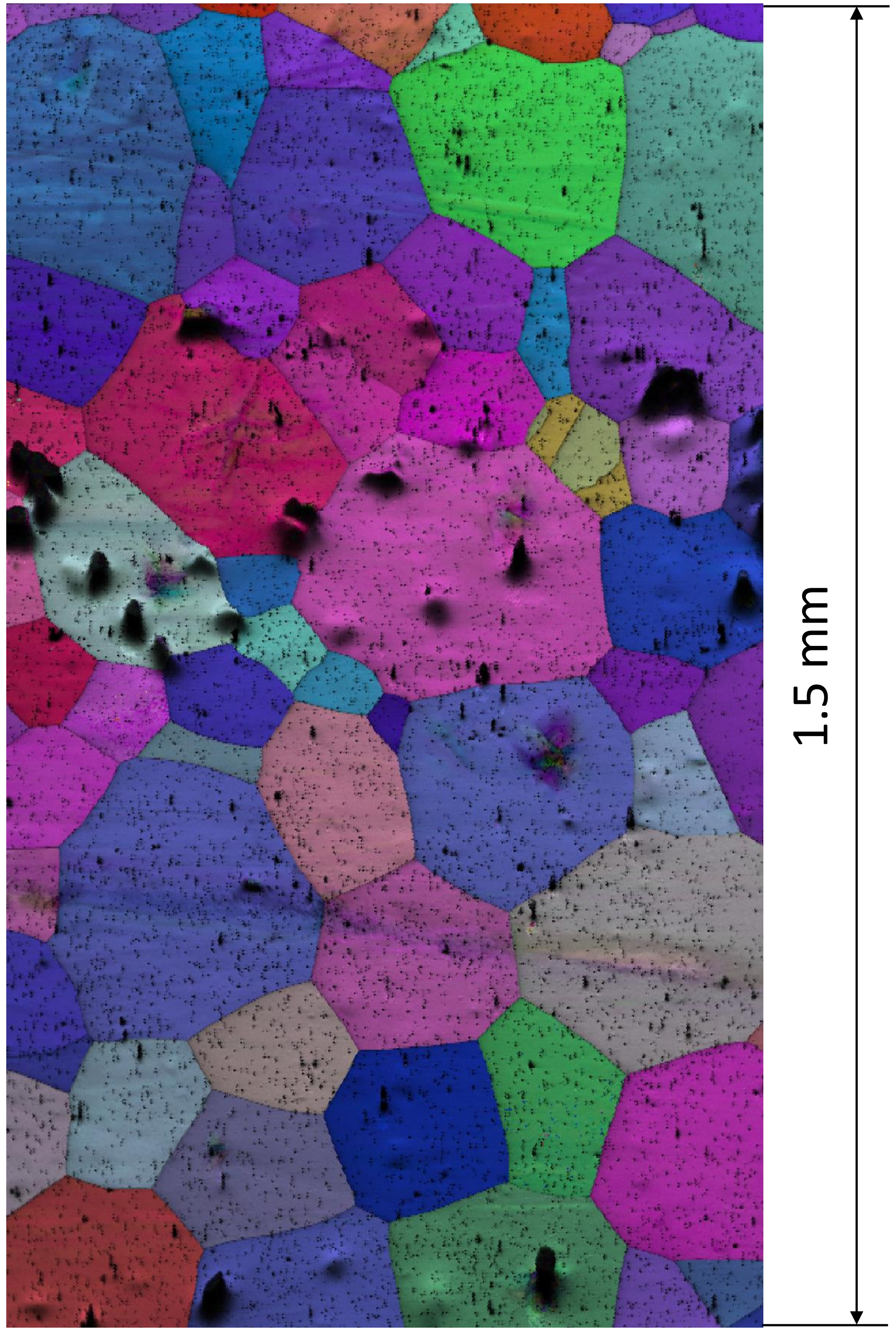
444 DILATOMETER SIMULATIONS

Fast dilatometer treatment



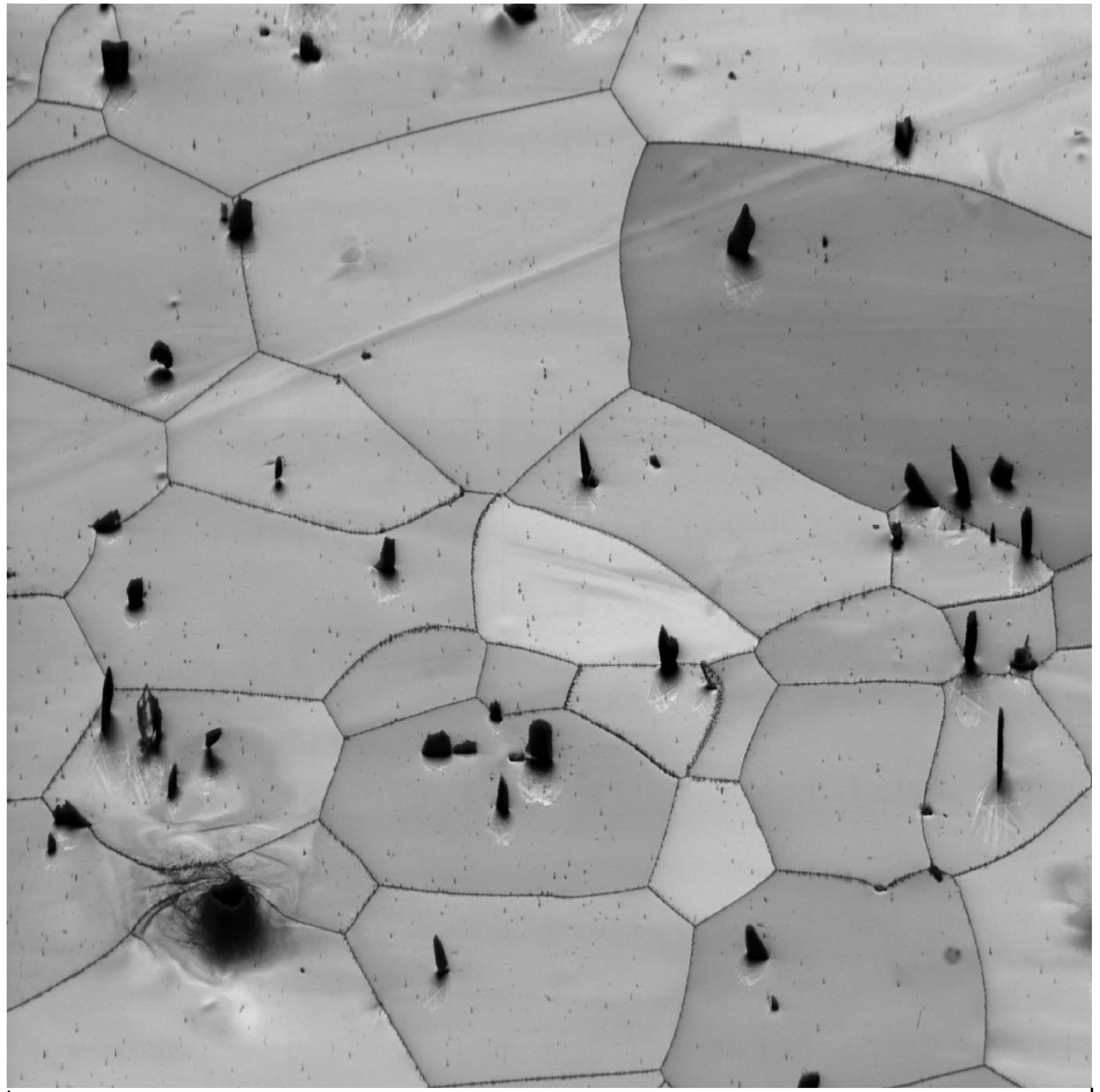


Slow dilatometer treatment



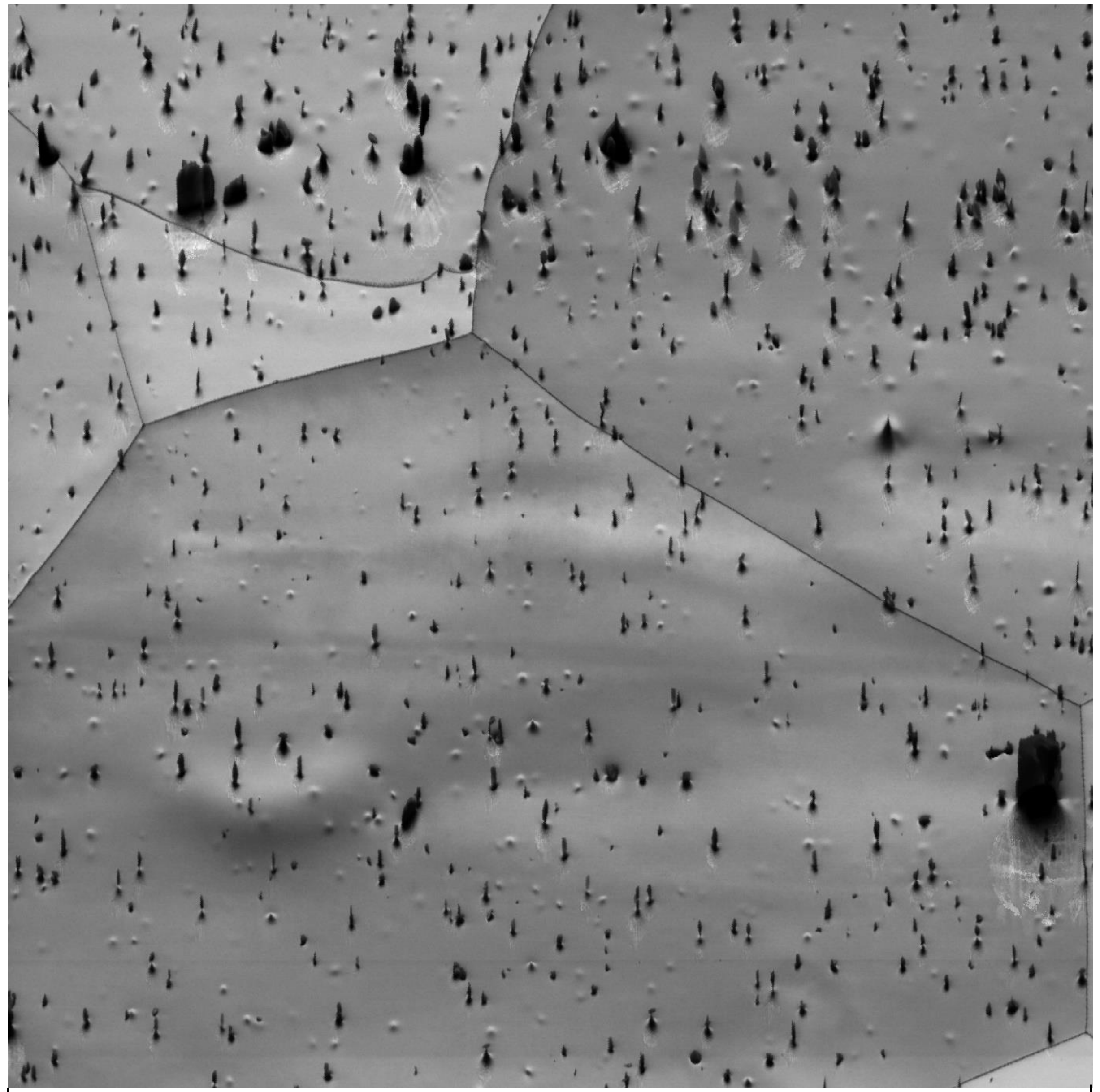
444 DILATOMETER SIMULATIONS

Fast dilatometer treatment



200μm

Slow dilatometer treatment



200μm

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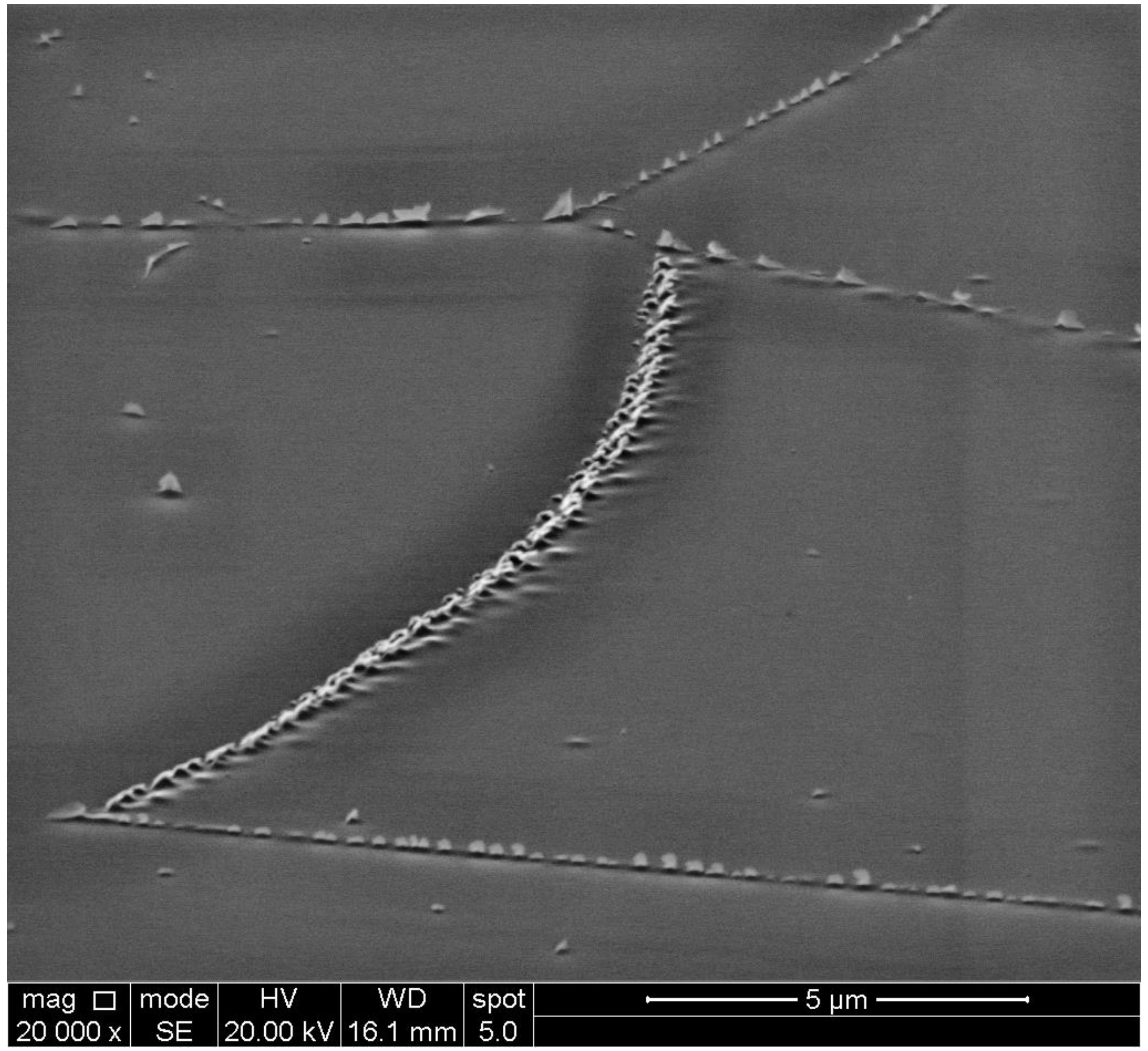
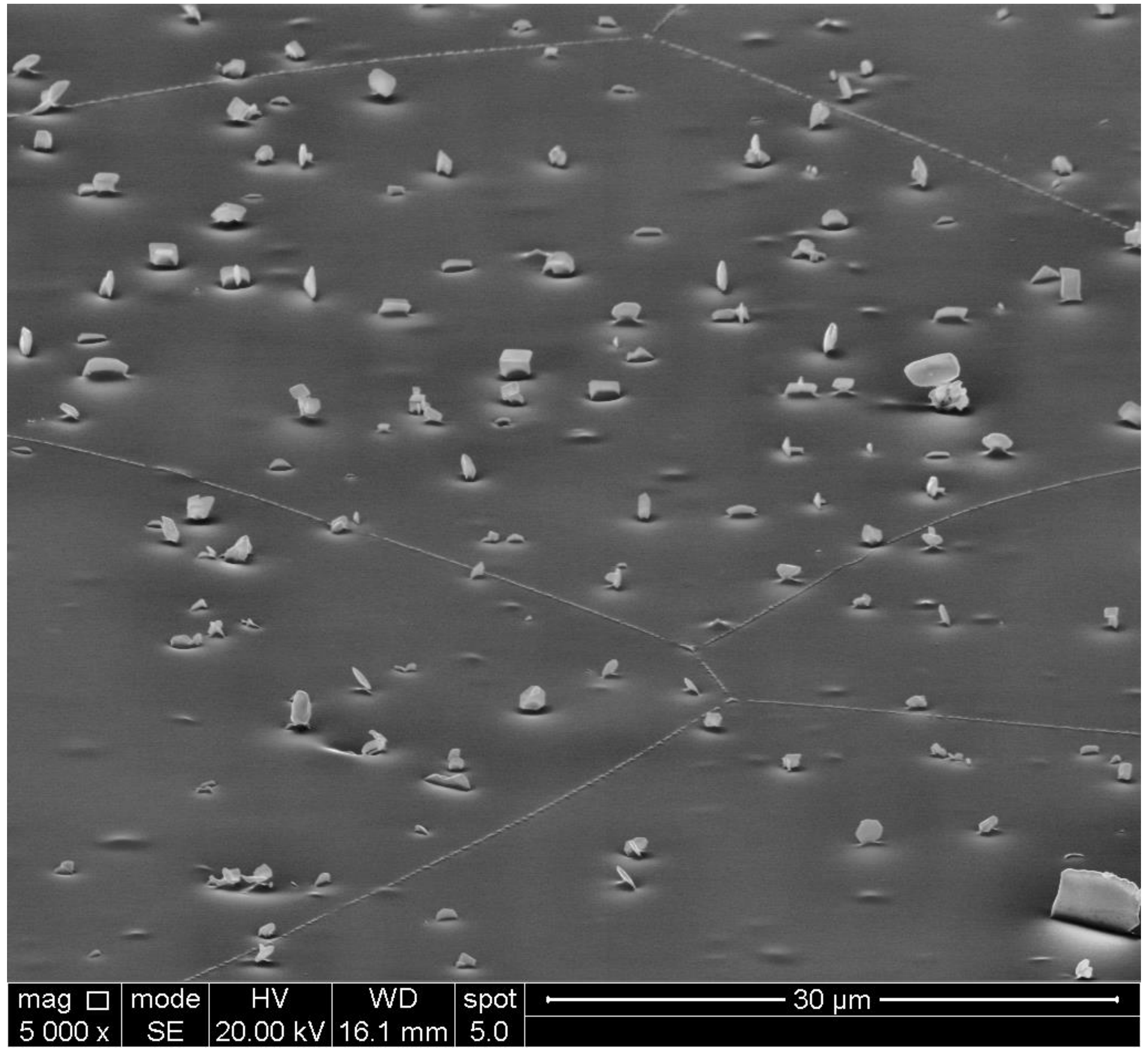
444 DILATOMETER SIMULATIONS

Fast dilatometer treatment



Slow dilatometer treatment



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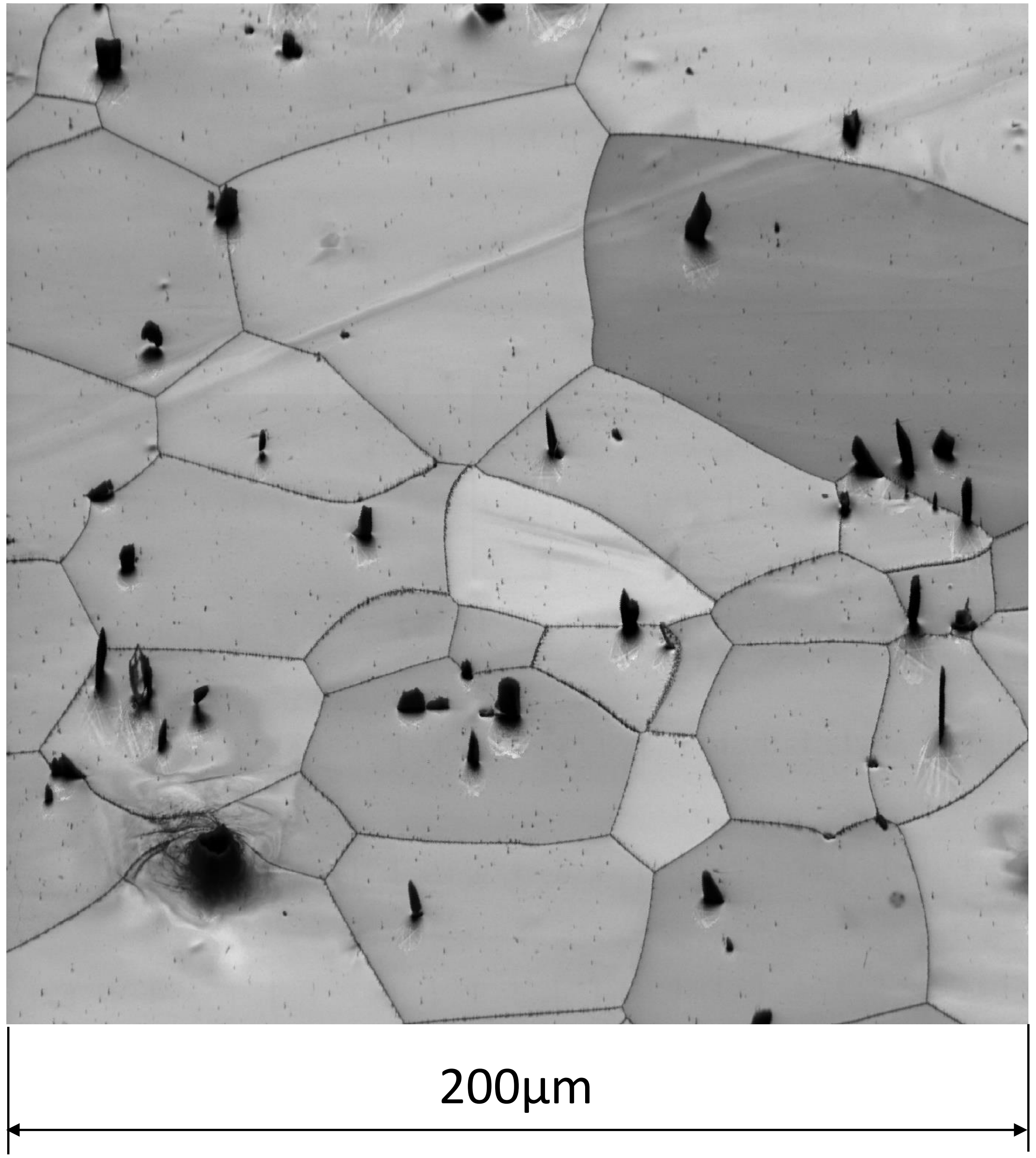
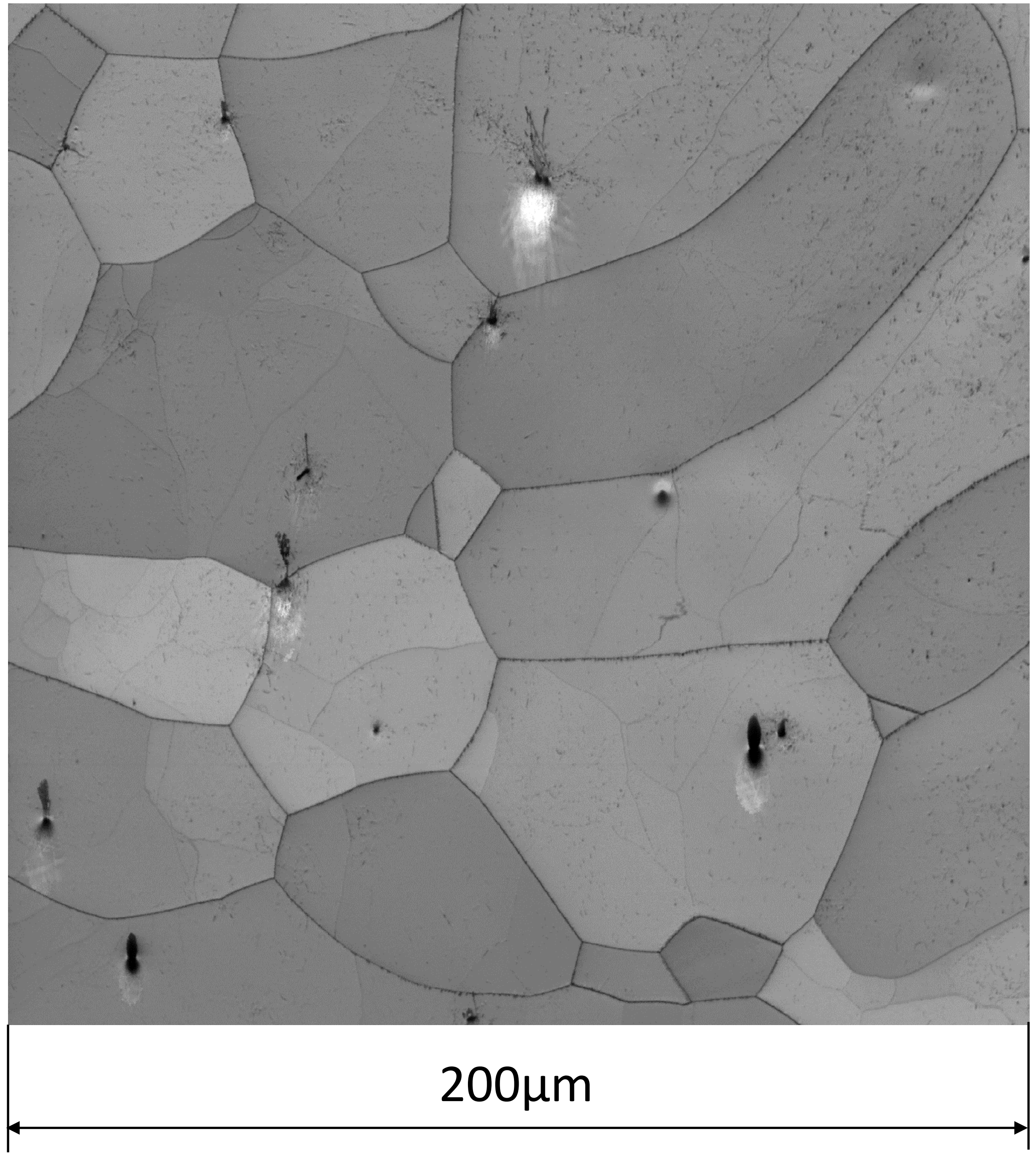
444 DILATOMETER SIMULATIONS

Fast dilatometer treatment



Lazer welding HAZ



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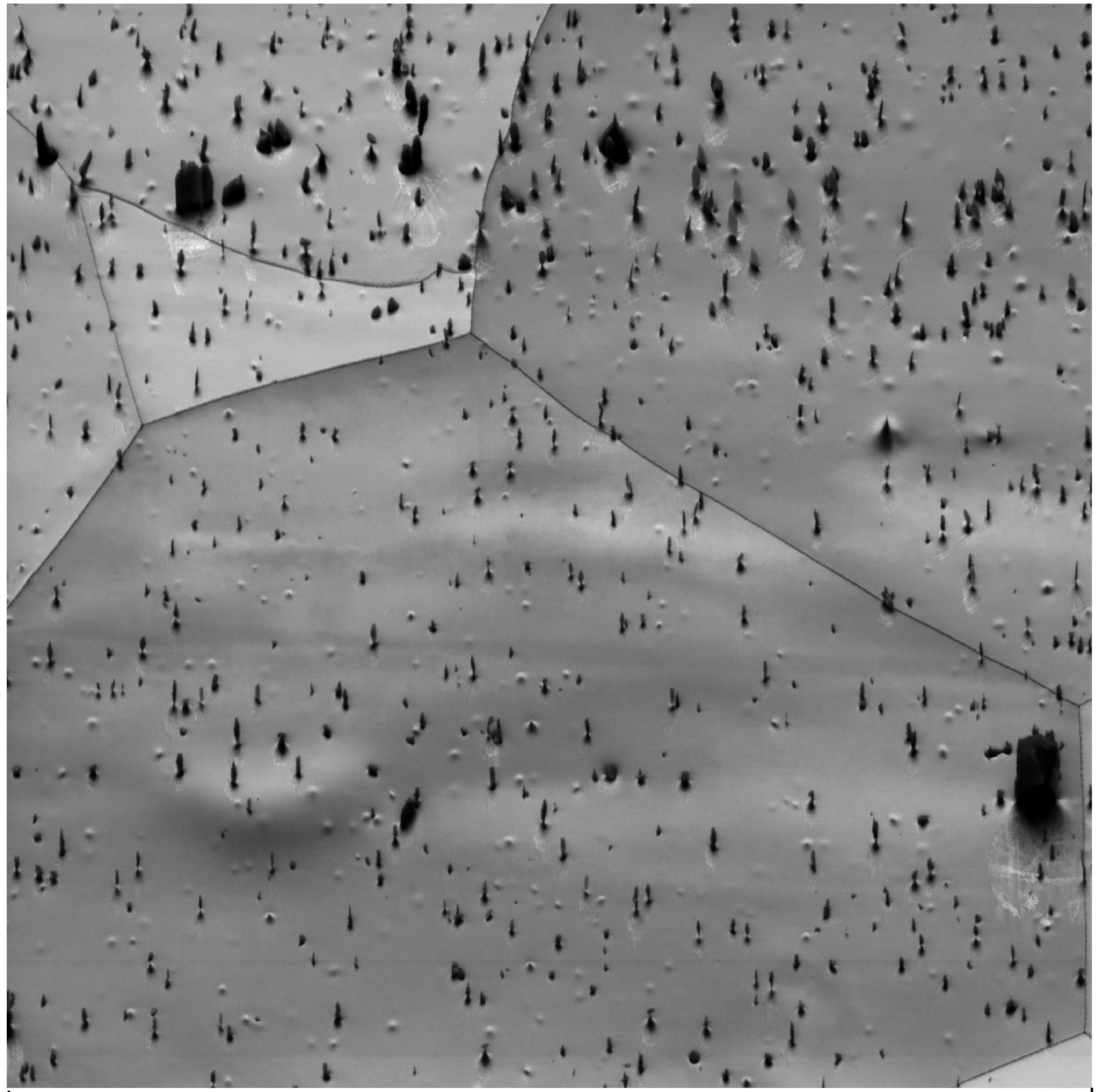
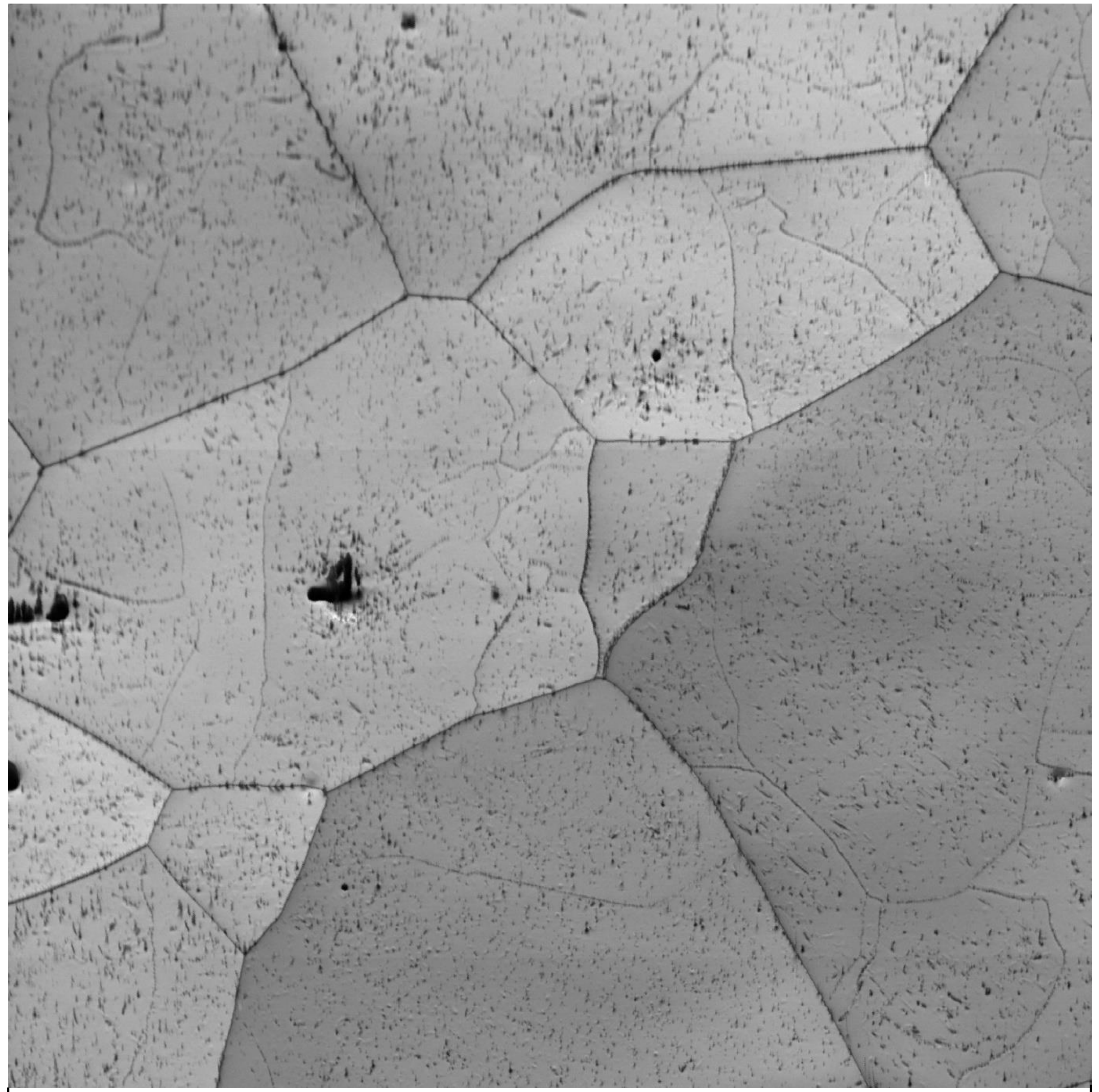
444 DILATOMETER SIMULATIONS

Slow dilatometer treatment



200µm

TIG welding HAZ



200µm

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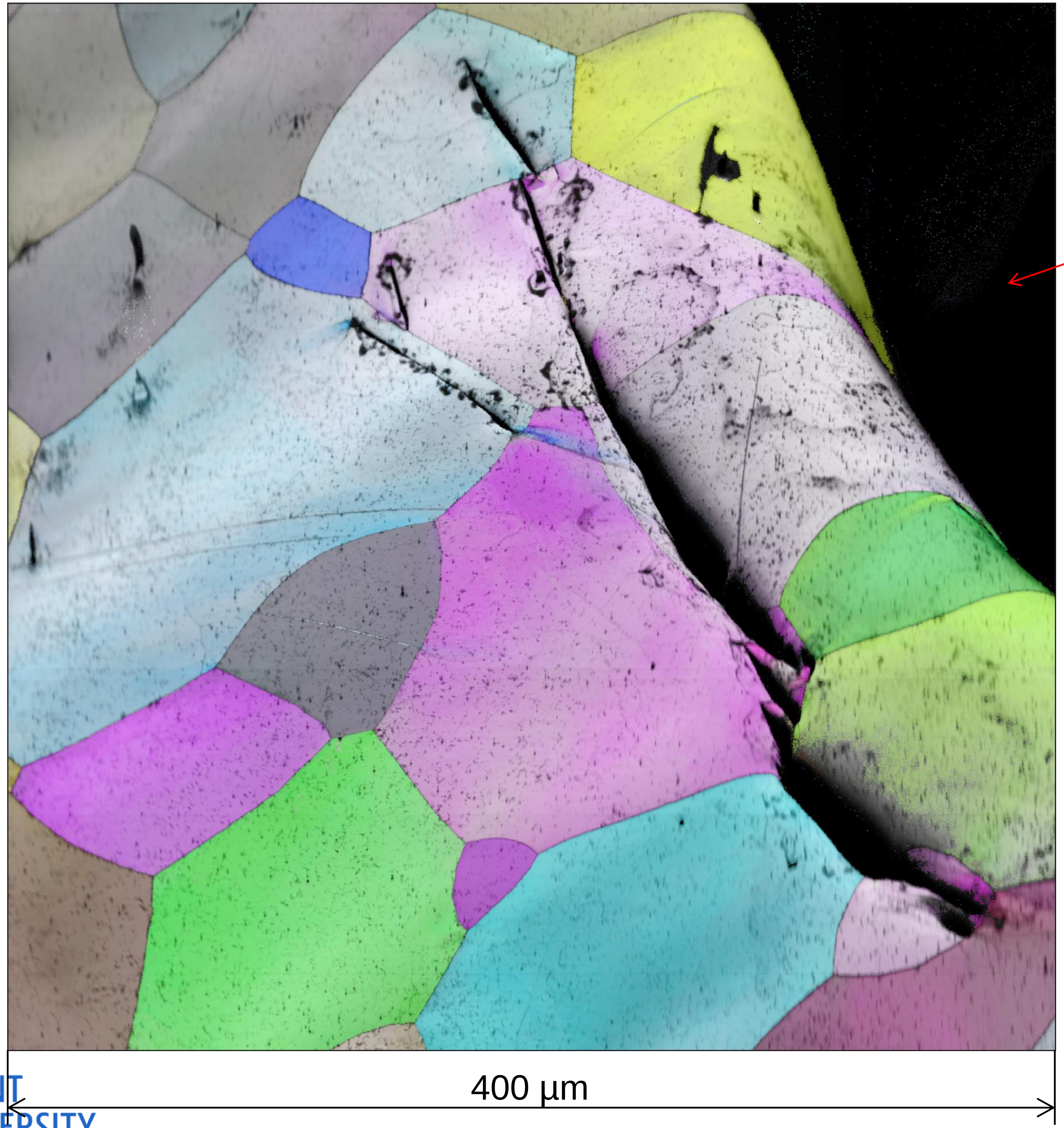
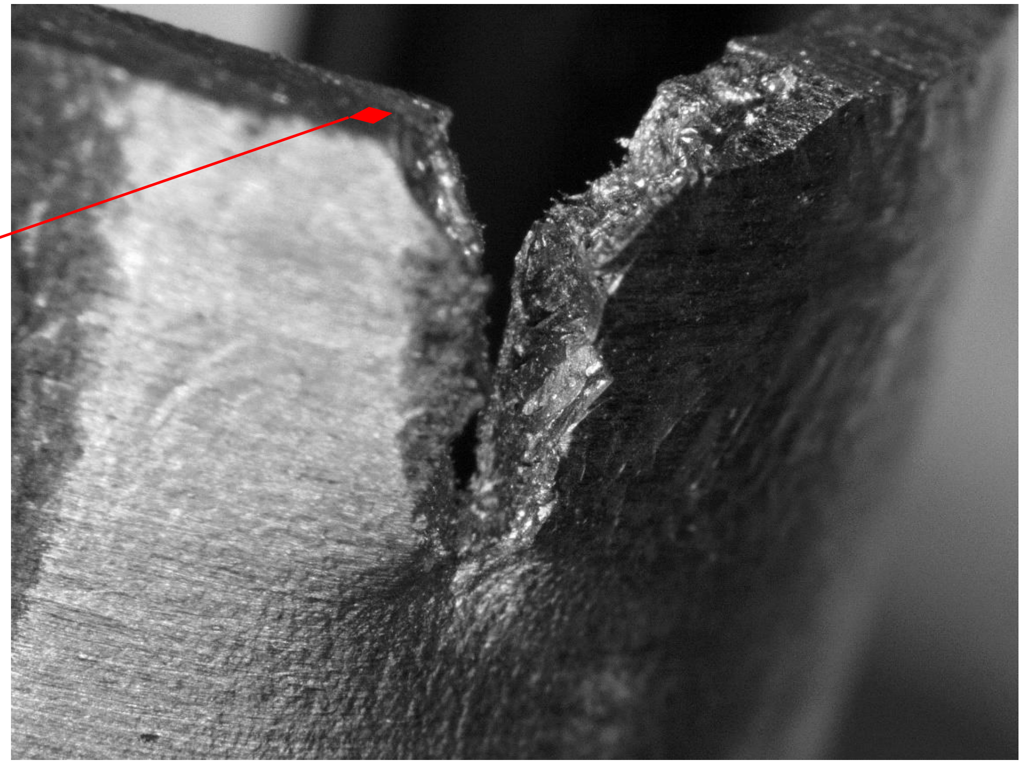
CORRUGATED 444 TIG WELD WITH FAILURE





Since the fracture is (quasi-)brittle, there are secondary cracks which can be used to analyse the fracture characteristics. Therefore, electropolishing was used to prepare the sample (it doesn’t blunt the edges of the secondary cracks too much).

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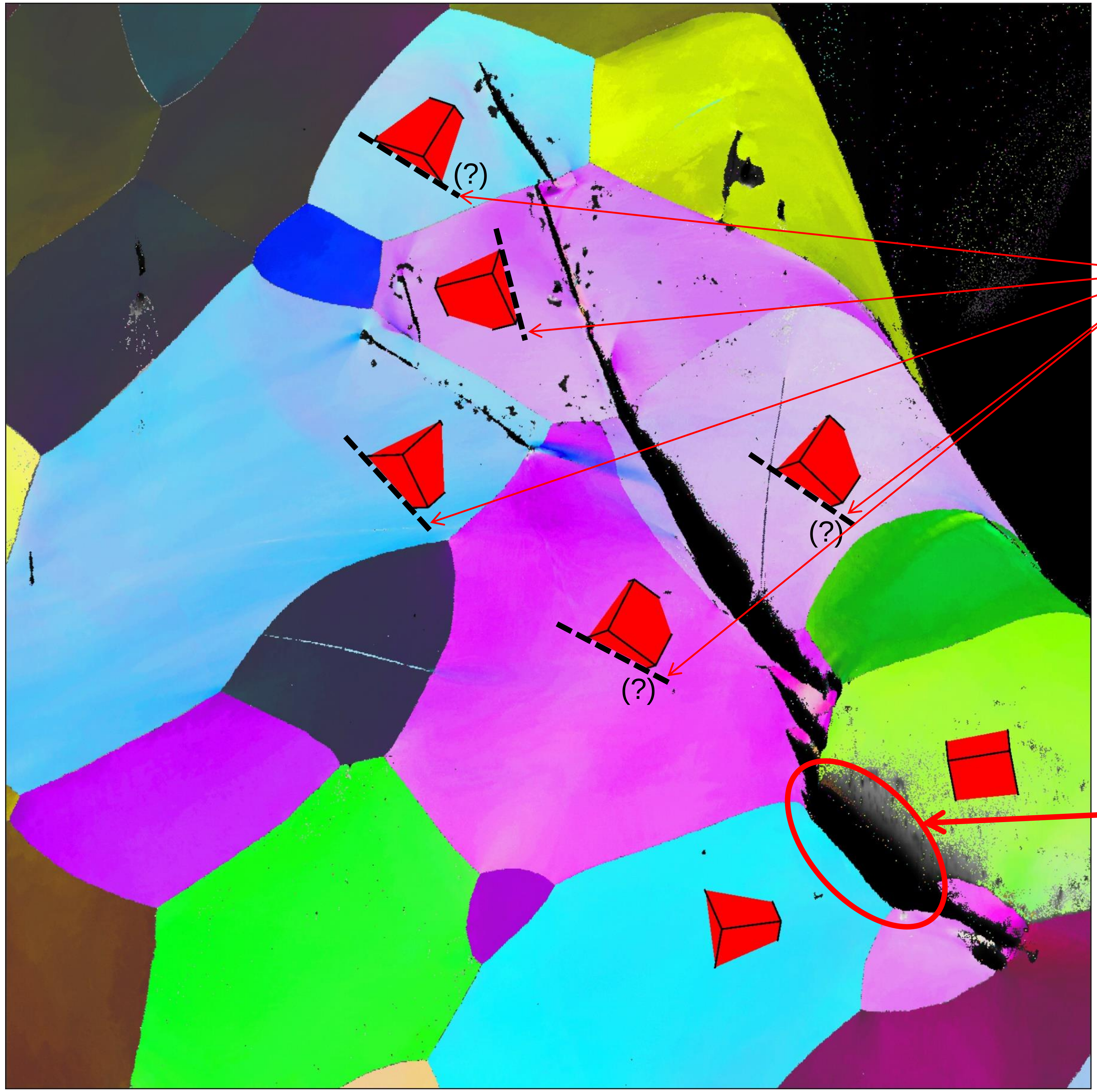
CORRUGATED 444 TIG WELD WITH FAILURE



Intragranular fracture corresponds to the {001} cleavage planes (cube face)

Intergranular fracture is also present

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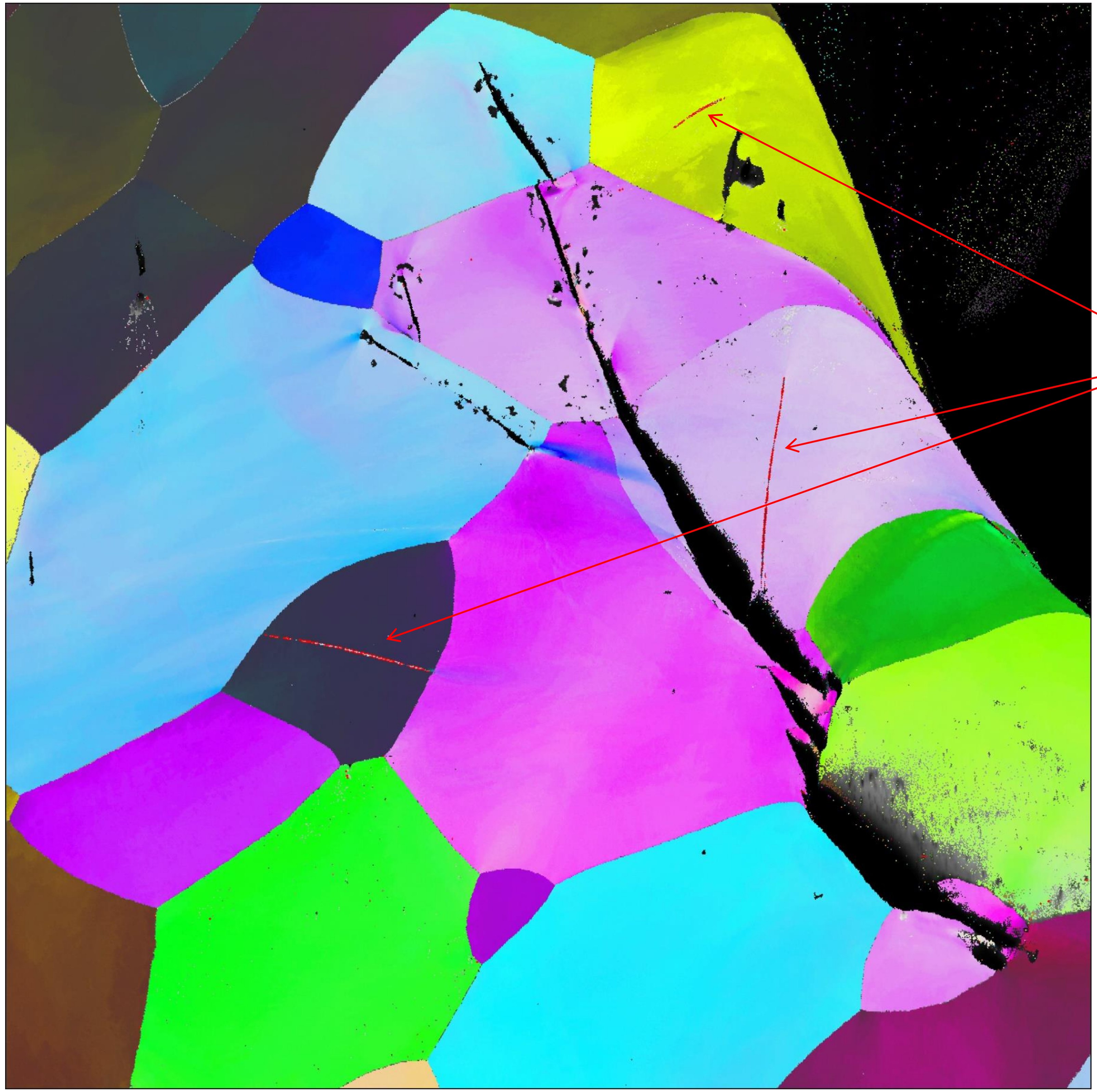
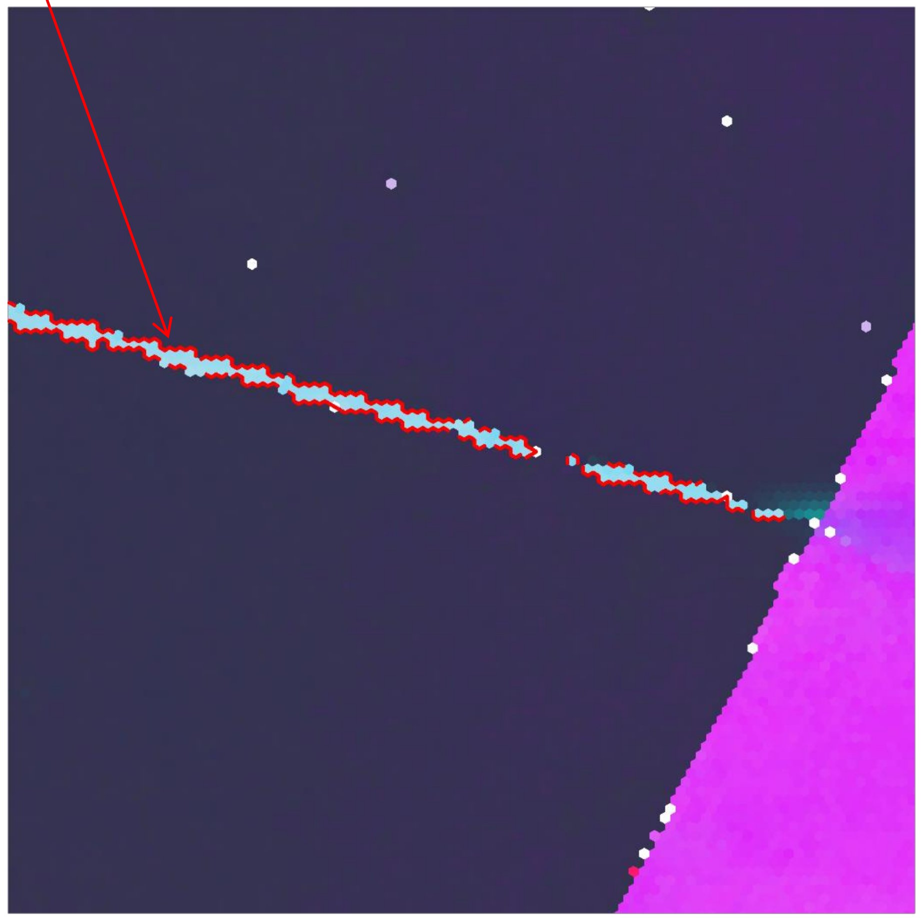
CORRUGATED 444 TIG WELD WITH FAILURE

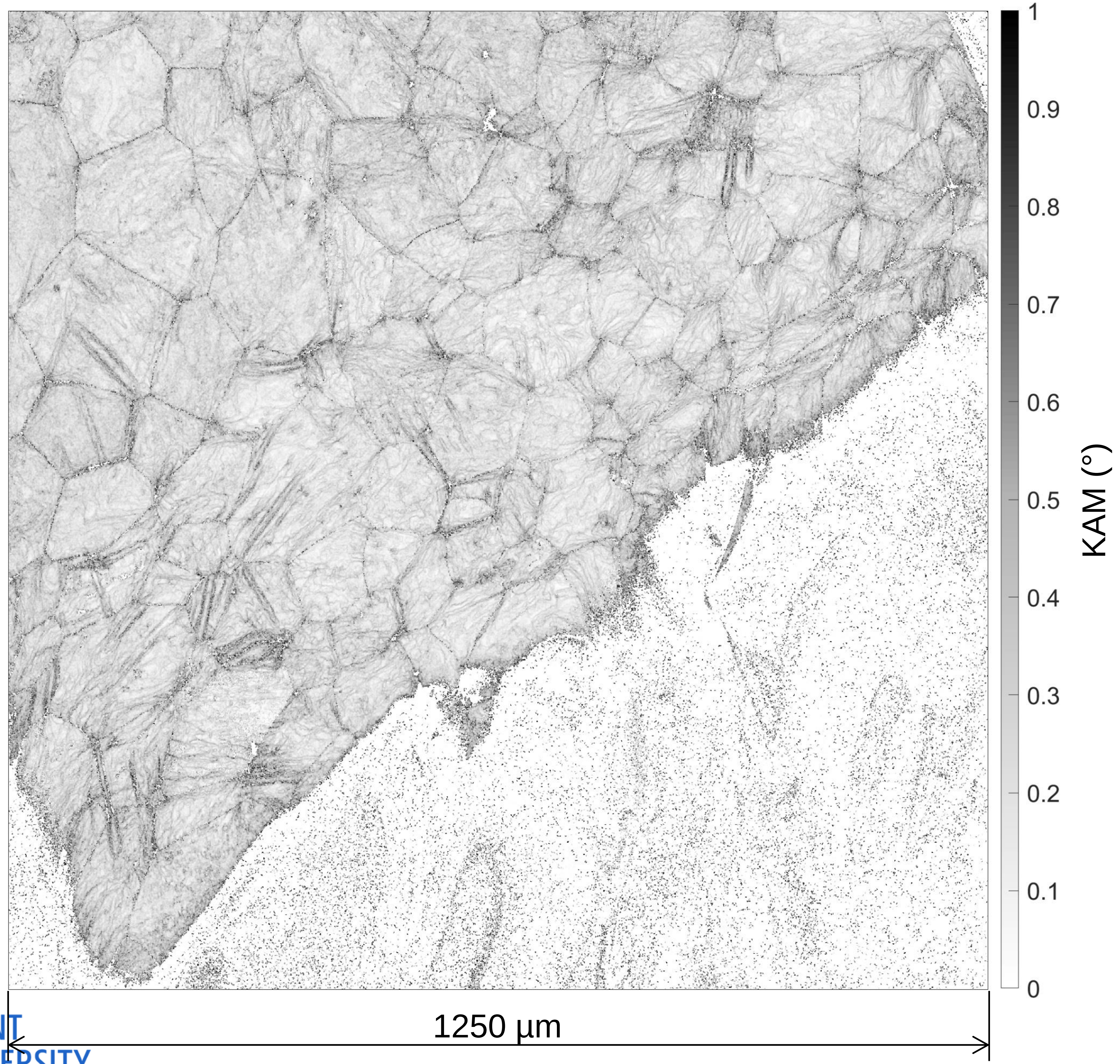


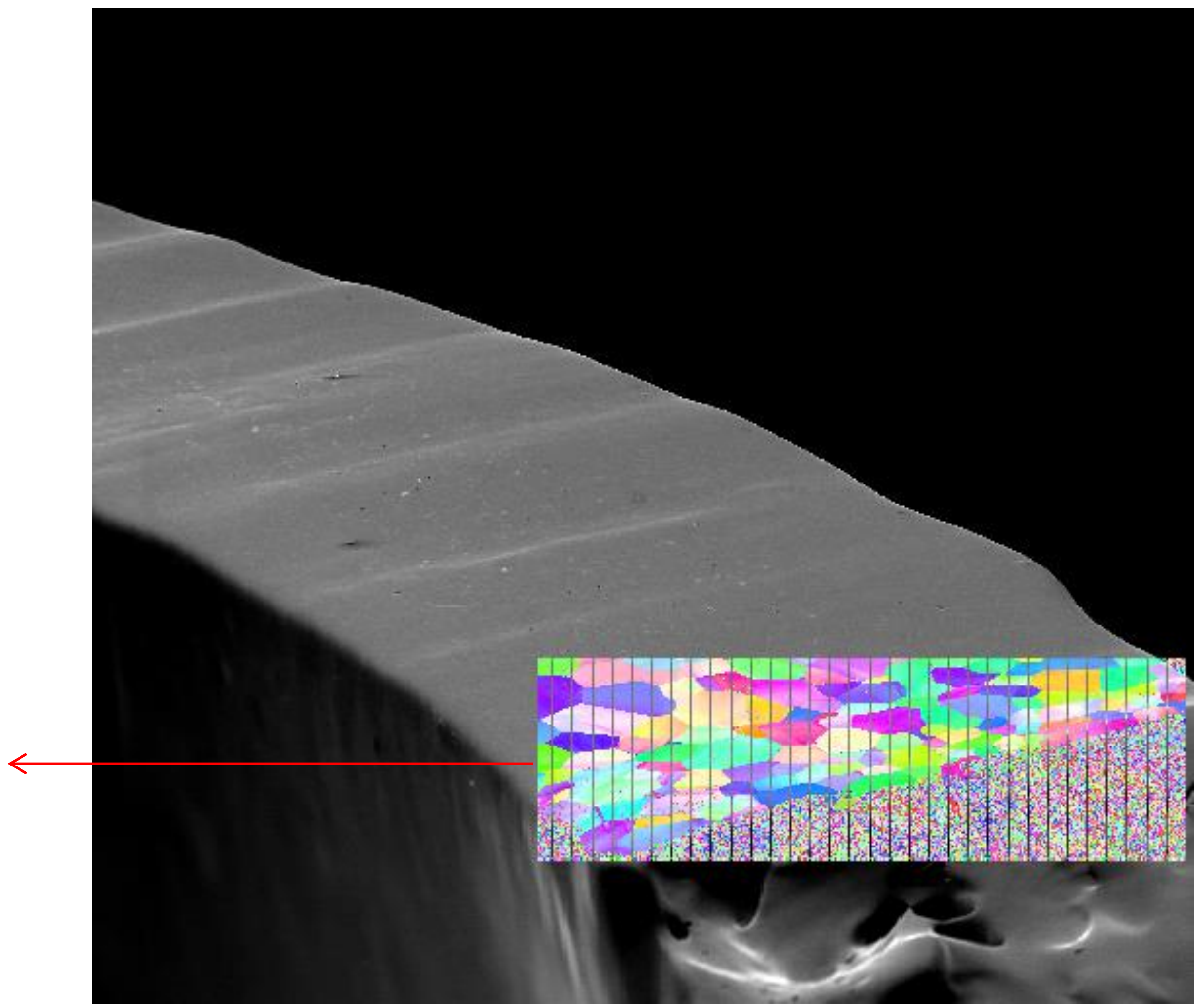
(Deformation) twinning detected

$\Sigma 3$ CSL boundaries



CORRUGATED 444 TIG WELD WITH FAILURE





Strain heterogeneities (shear/deformation bands, twins) formed during the cold forming in combination with the grain boundary precipitation could provide conditions for cleavage fracture *initiation*.
Cleavage fracture *propagation* is then easy due to the large grain size.

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COMMENTS – FSS WELD FORMABILITY

- Unlike grade 430, grades 444 and 441 never transform to austenite
- The microstructure of 444 and 441 steels is therefore defined by the ferrite grain size and Nb and Ti –based precipitation which occurs both inside ferrite grains and along their boundaries
- It doesn’t appear feasible to completely supress the grain boundary precipitation by quenching
- Therefore, the only way to improve the weld toughness (given any post-heat-treatment is not practical) is to reduce the grain size (which was to a significant extent achieved by laser welding).
- Finer grain size should
    - Improve the resistance to cleavage fracture propagation,
    - Reduce the propensity to form strain heterogeneities.

CONCLUDING COMMENTS

- Collaboration between the Materials Science and Technology group of UGent and the Materials sector of CERN has been established
- The work so far has been focused on the welding technology optimization to allow the manufacturing of the ferritic stainless steel pre-prototype
- The results suggest that the use of very low heat input welding technique (laser) and stabilized FSS grades 444 or 441 allows to achieve good enough formability of the welds to withstand the corrugation forming process, and therefore the FSS pre-prototype can be manufactured identically to the other two
- That said, if the FSS becomes the material of choice, corrugation should probably be avoided (and stiffener rings should be used instead)
- Another important activity is to search for and to work with industrial partners who are to help with the pilot sector manufacturing

Thank you!

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