2019年度水化学部会
March 6th 2020

Research Summary

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Outline

1. MC research, NTHU (2010 Feb. – 2012 Aug.)

2. RA research, NTHU (2013 Sept. – 2015 Jan.)

3. DC and Postdoc research, KU (2015 Apr. – 2018 Mar./ 2018 Oct. – Present)

4. Future Prospective toward Fusion Energy Research

MC and RA Research, NTHU

MC & RA Research

MS research

Objectives:

Evaluate the efficacy of ZrO_2 inhibitive protective coating (IPC) on 304SS-Alloy82 welds under oxygenated hot water via CBB method

Results:

1.Crack sites match high hardness and residual stress; some were arrested or shifted as crack advancing to fusion boundary

2.Uneven coating promotes localized corrosion

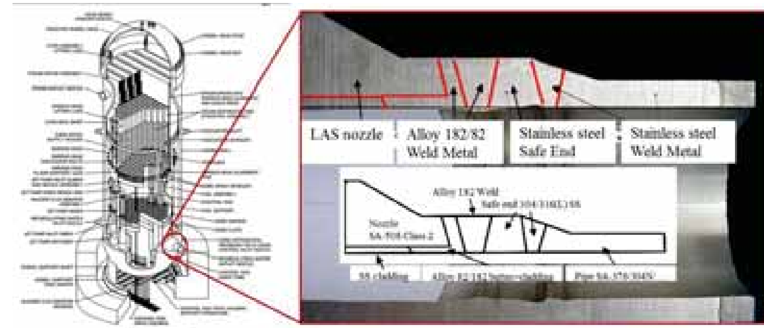
RA research

Objectives:

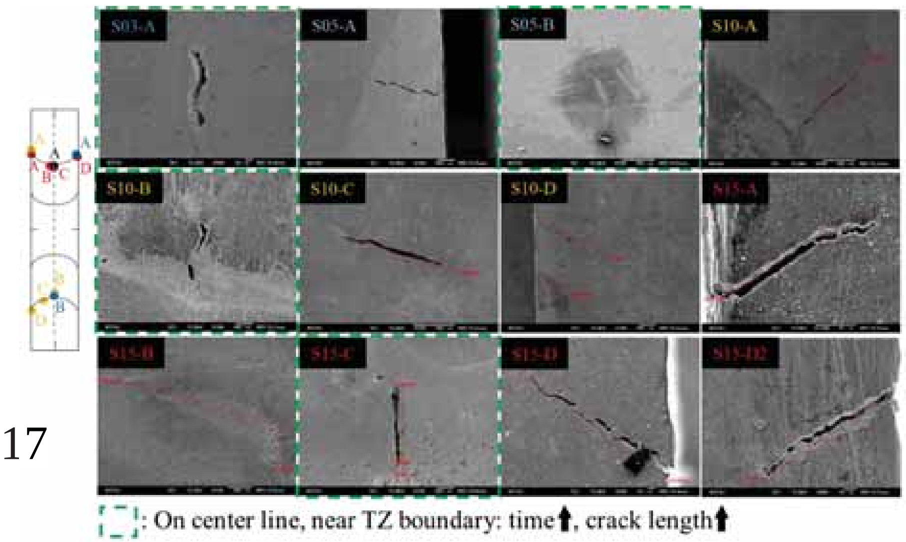
Elucidate incipient oxidation mechanism of In617 and Haynes 230, candidate steels for HTGR, under open air condition

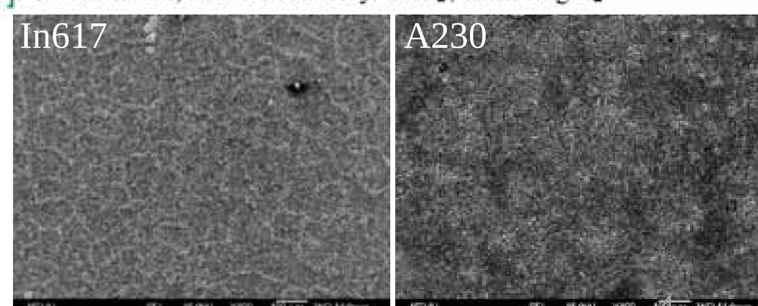
Results:

The oxide ridge above grain boundary of Haynes 230 is less obvious than In617, showing a better oxidation resistance



304 SS- A82 safe end weld in BWR recirculating piping system





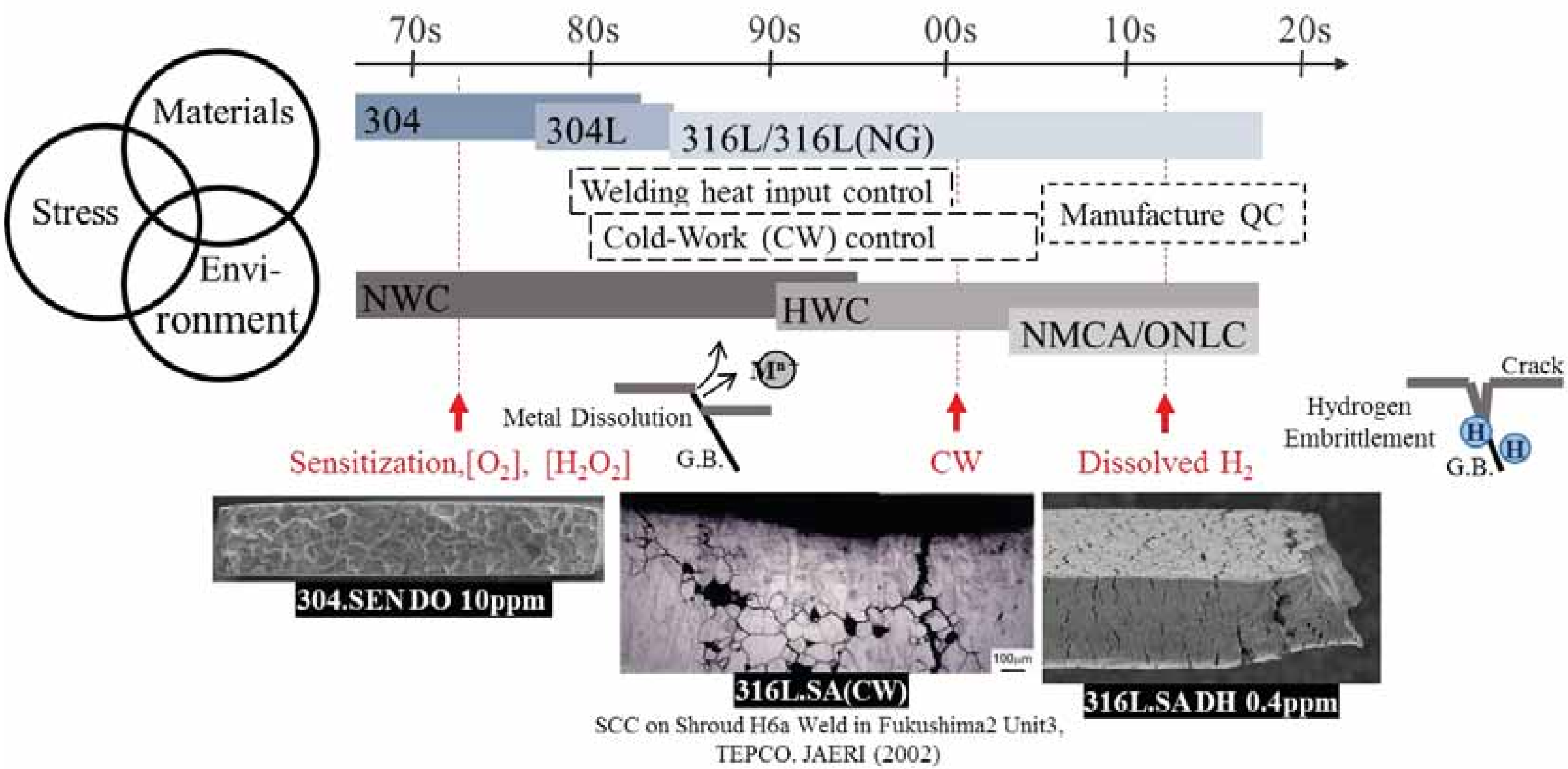
Surface morphology of In617 and Haynes 230 oxidized at 1000^{o}C, 360hr, open air

DC and Postdoc Research , KU

Background: SCC history

Backgrounds:
Current austenitic stainless steels and Ni-based alloys used in nuclear power plants suffer SCC under oxygen- (and) hydrogen-dissolved hot and pressurized water. Further, solution-annealed (SA) 316L showed SCC in hydrogenated water, and fracture surface resembles hydrogen embrittlement (HE).

Objective:
Access SCC on SA-316L (and other steels) under different water chemistries.



Brief history of SCC and major factors occurred in LWRs

Experimental

Materials:

wt%	Fe	Cr	Ni	C	Mo	Mn	Si	S	P
304	bal.	18.14	8.06	0.06	-	0.79	0.48	0.008	0.033
304L	bal.	18.43	9.71	0.03	-	0.99	0.59	0.002	0.031
316L	bal.	17.41	12	0.022	2.18	1	0.72	0.004	0.027
310S	bal.	24.76	19.17	0.02		0.8	0.7		0.022

*310S: a low carbon grade, high Ni content ASS

Flowchart:

304(L),**316L**,310S

↓

SA:1050°C,1h,W.Q.

↓

SEN:700°C,100h,W.Q.@316L,310S
650°C,124h,W.Q.@304(L)

↓

polishing/grinding

#1200-#4000 ↓ 3 µm -0.25µm

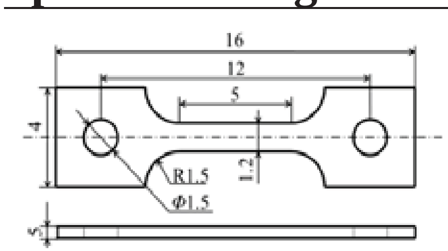
SSRT in HW, PW, SCW water

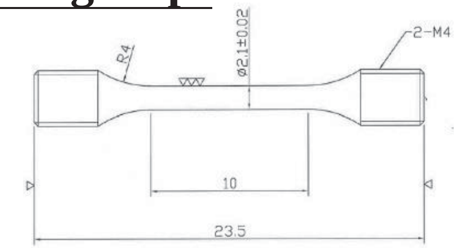
↓

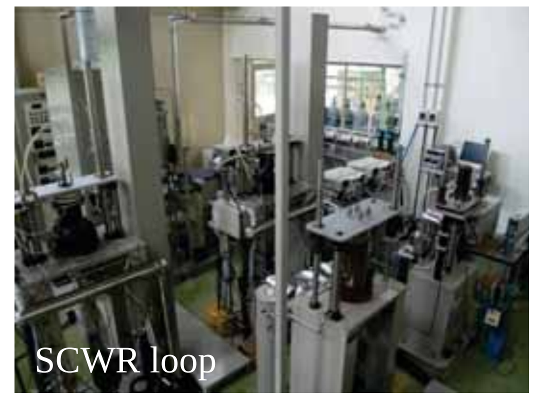
σ-ε curve, SEM, EBSD

*Heat treatment:
SA: Solution-Annealing
SEN: Sensitization

Specimen design and testing loops:

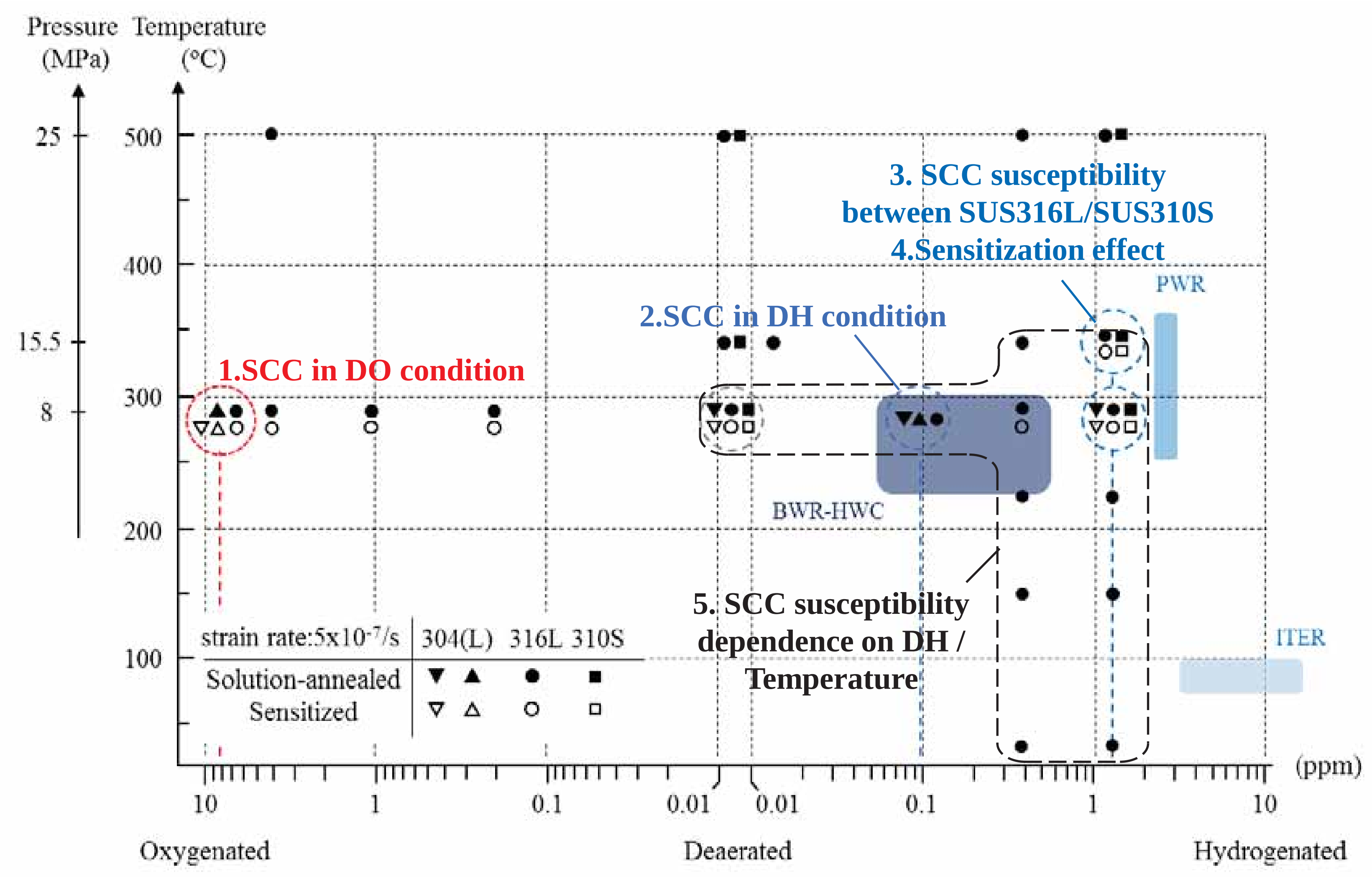






Parameter	HW loop	SCWR loop
Temperature (°C)	25-288	288-500
Pressure (MPa)	7.8-8	15.5 – 25
Flow Rate (L/h)	0.75-2	1.4 - 1.6
Cond. (uS/cm)	<0.1	
Strain rate (s^{-1})	$5x10^{-7}$	
Water condition (ppm)		
DO	-	10,8,4,1,0.2
DH	0.1,0.4,1.4	0.4,1.4
Deaerated	DO,DH < 0.1	

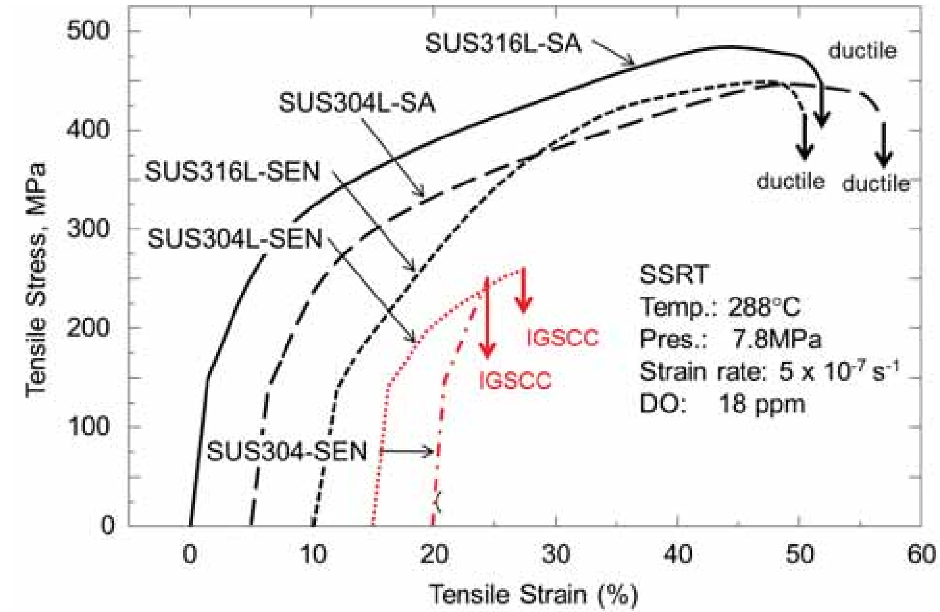
Experimental Conditions



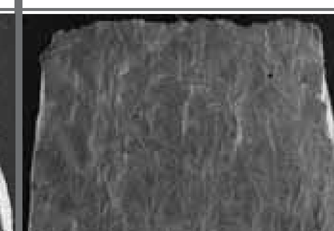
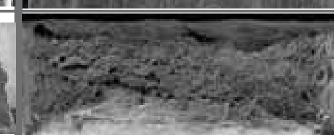
1.SCC in DO condition

1. <u>SCC in DO (10ppm) condition</u>
   - Low carbon (304 -> 304L)
   - Add Mo (304L->316L)
   - SA heat treatment (SEN->SA)

   Can decrease SCC susceptibility

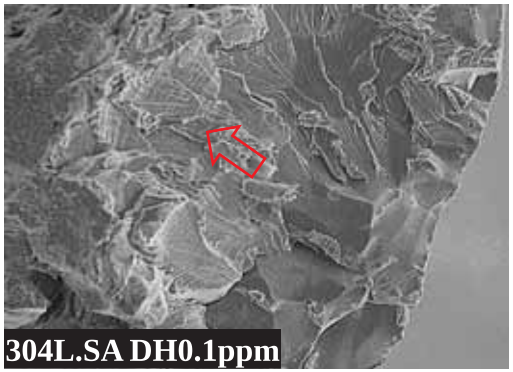


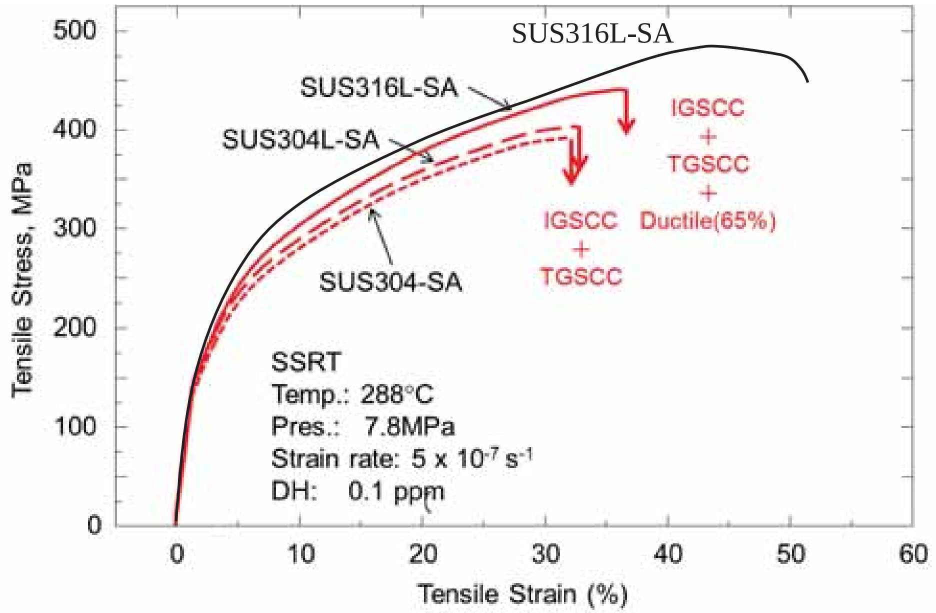
SCC susceptibility decreases ➡

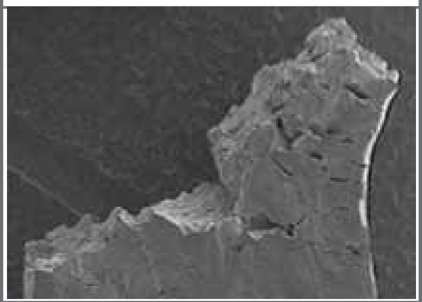
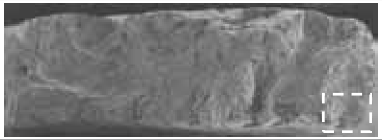
Material	304.SEN	304L.SEN	304L.SA	316L.SA	316L.SEN
Side Surface					
Fracture Surface					
IG+TG [%]	100	99	0	0	0

2.SCC in DH condition

2. SCC in DH (0.1ppm) condition
   - Fracture: IG initiation-TG propagation
   - dissolved H_2 shifts SCC mechanism



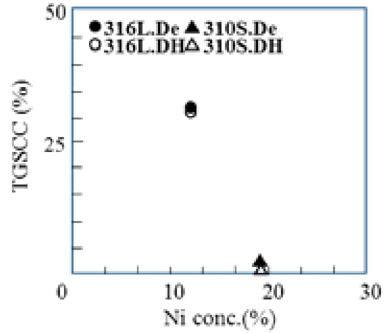


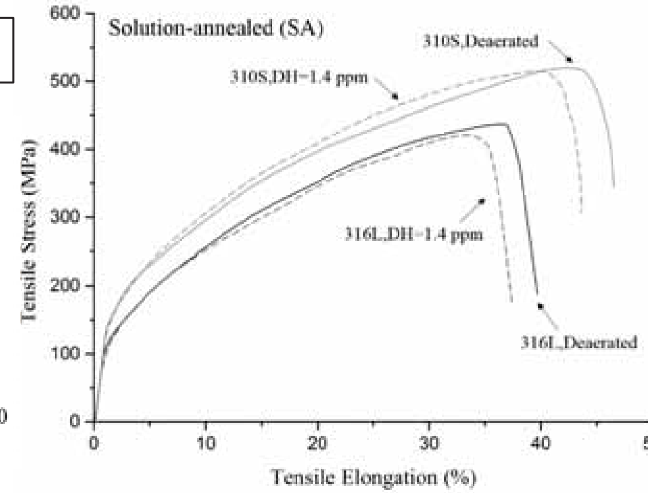
Material	304.SA	304L.SA	316L.SA
Side Surface			
Fracture Surface			
IG+TG [%]	99	98	32

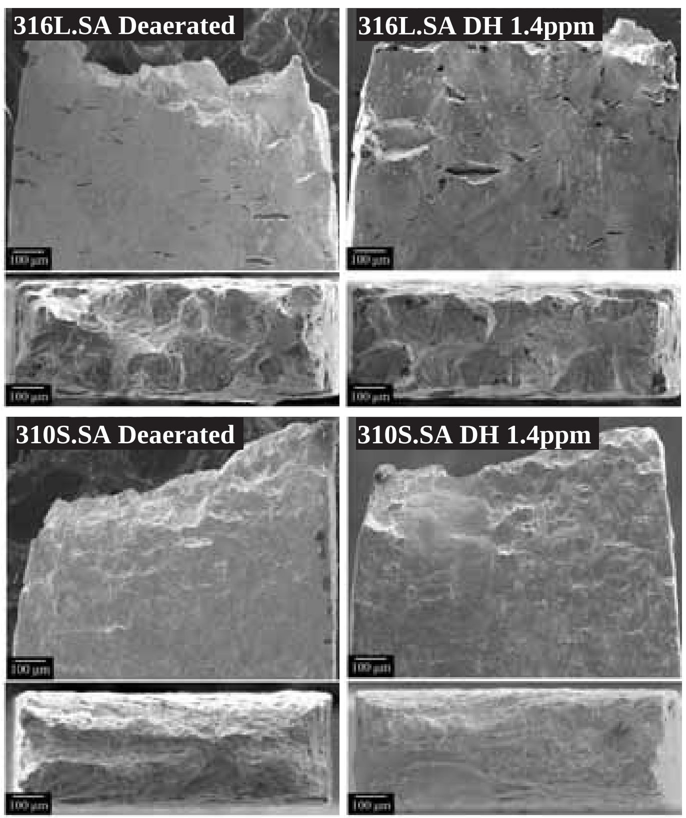
3. SCC susceptibility between SUS316L/SUS310S

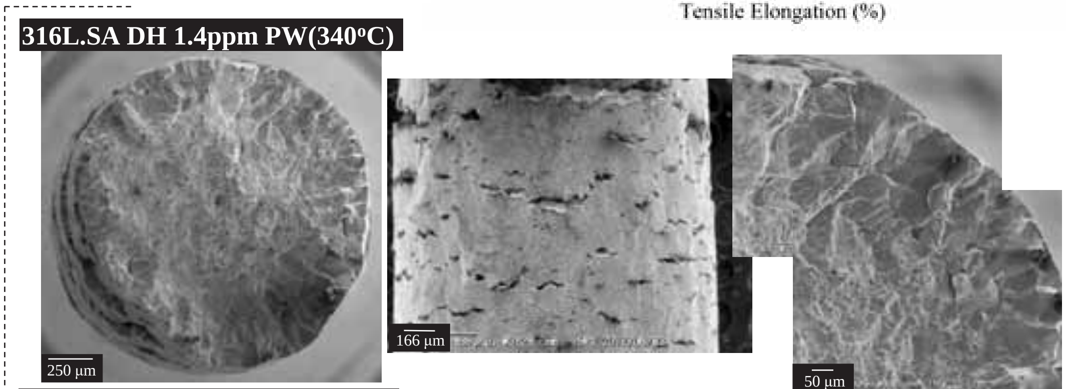
3. SA-310S in HW and PW at DH=1.4ppm
  - Ni effect: increase Ni content could decrease SCC susceptibility

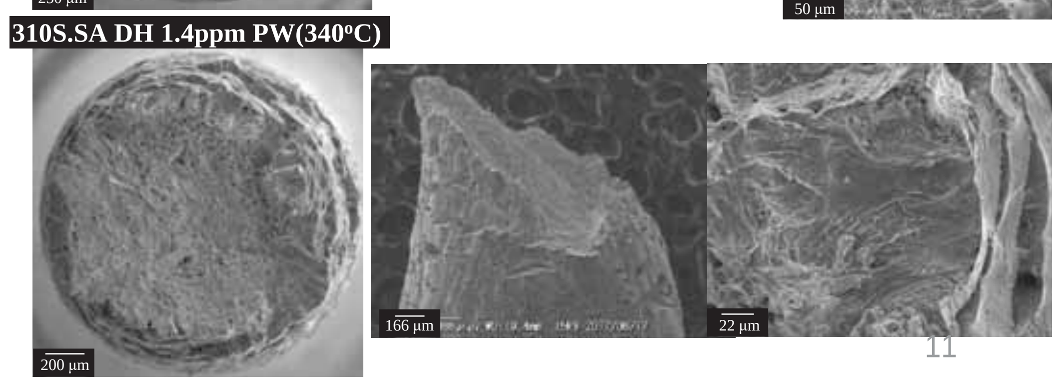
SSRT in HW







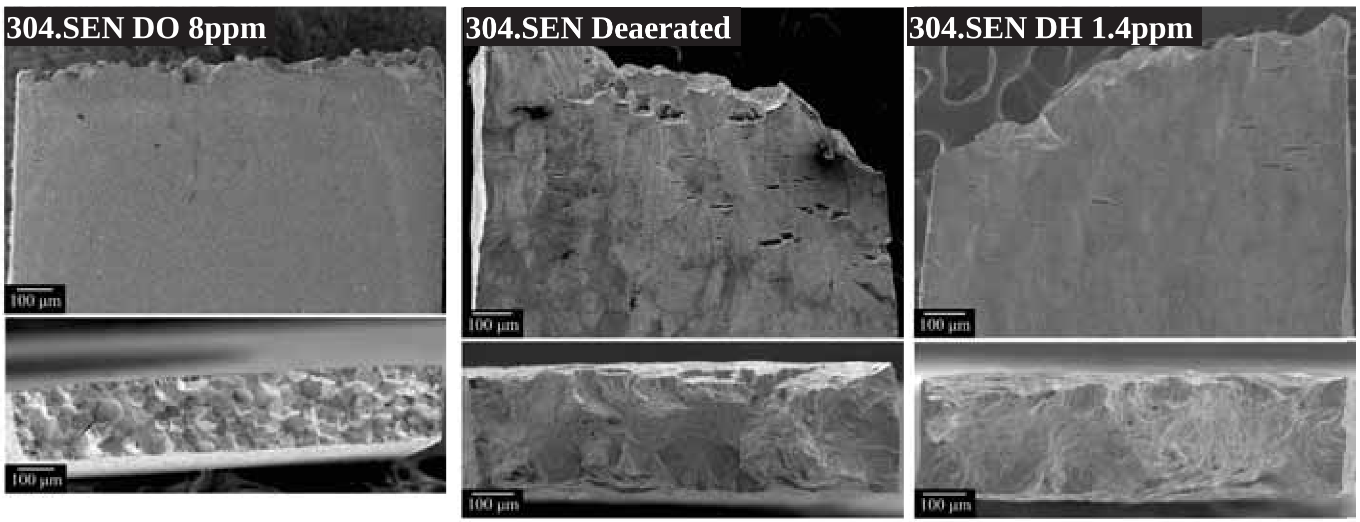


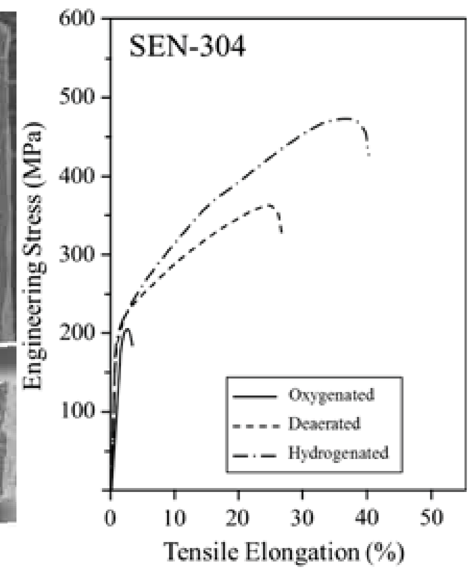


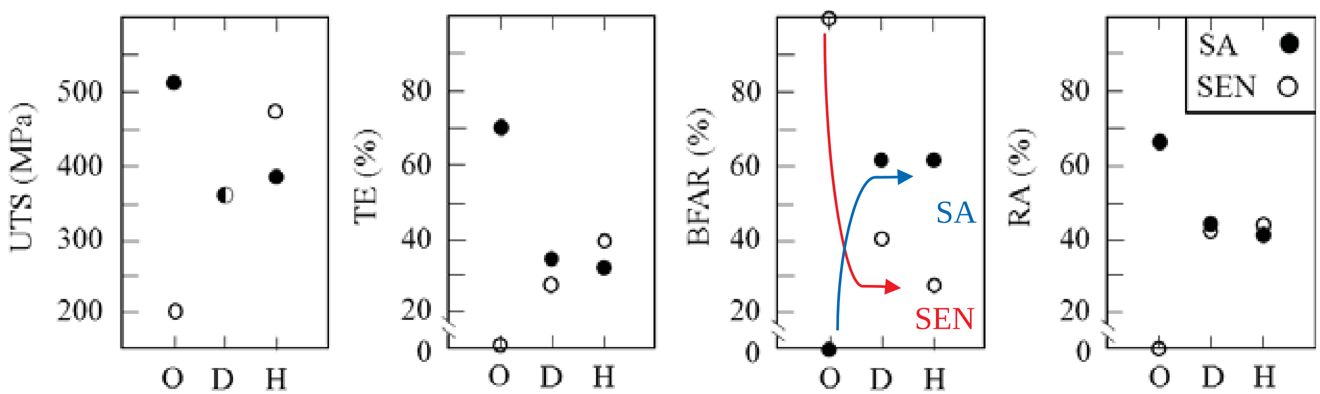
4. Sensitization effect

Confidential

4. SEN-304 at DH=1.4ppm
   - SCC susceptibility in DH condition is smaller than in DO.
   - Carbide could traps hydrogen, hence less hydrogen being trapped at dislocations



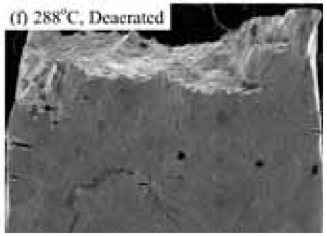
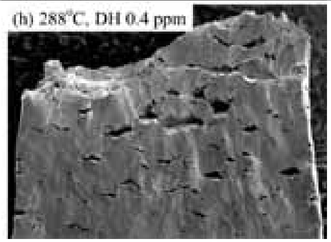
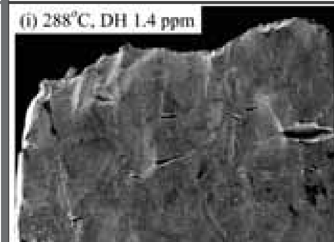
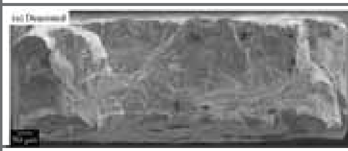


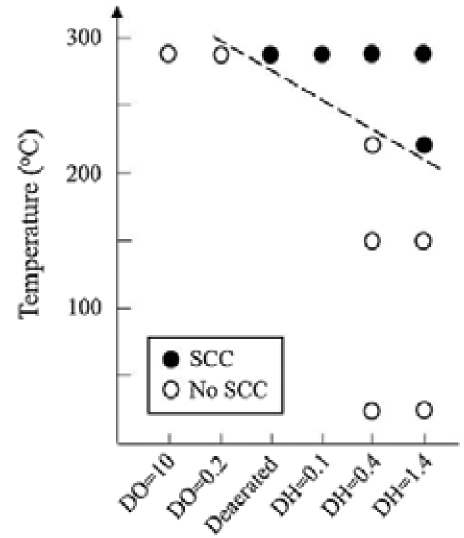


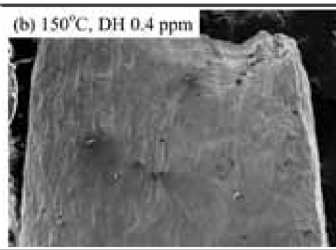
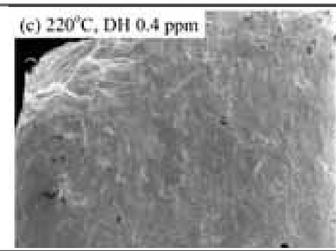
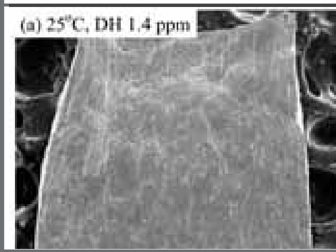
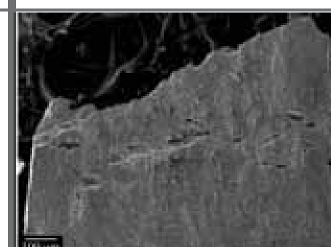
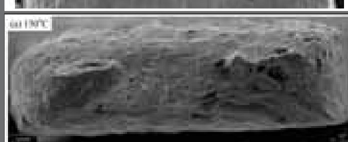
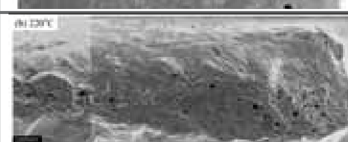
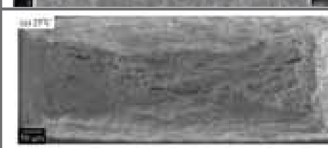
Summary of mechanical properties of SA and SEN 304 tested in oxygenated, deaerated and hydrogenated HW

5. SCC susceptibility dependence on DH / Temperature – SCC Mapping

5. SA-316L in HW (RT-288°C) with various DH content

Condition	288°C.Deaerated	288°C.DH=0.4	288°C.DH=1.4
Side Surface			
Fracture Surface			
IG+TG[%]	32	41	32

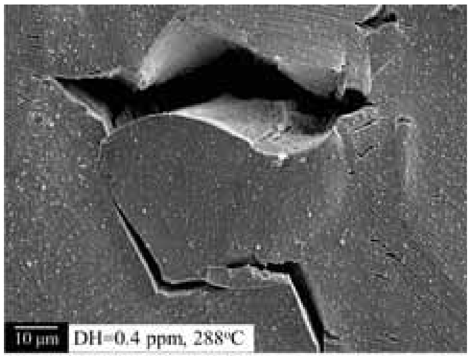


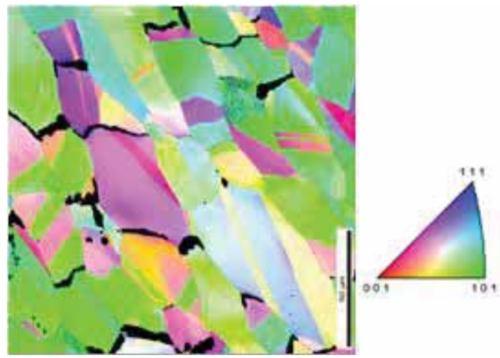
Condition	150°C.DH=0.4	220°C.DH=0.4	25°C.DH=1.4	220°C.DH=1.4
Side Surface				
Fracture Surface				
IG+TG[%]	0	0	0	22

5. SCC susceptibility dependence on DH / Temperature – Fracture mode

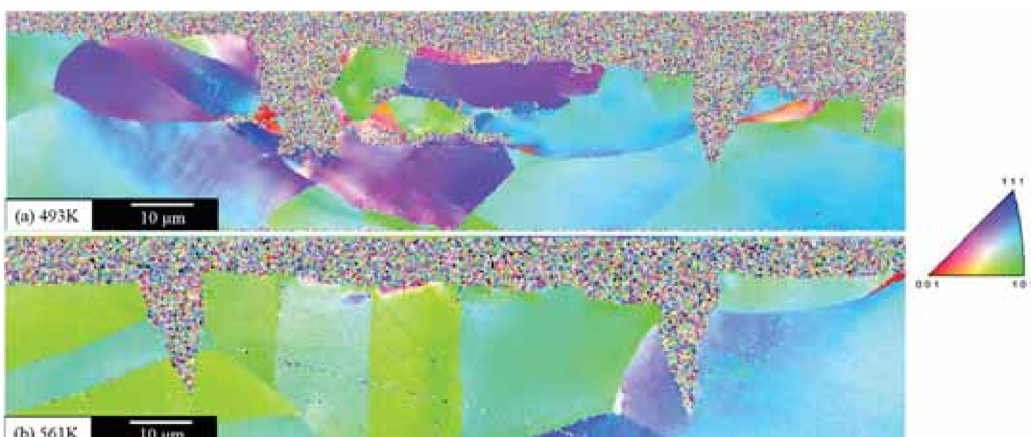
5. SA-316L in HW (RT-288°C) with various DH content

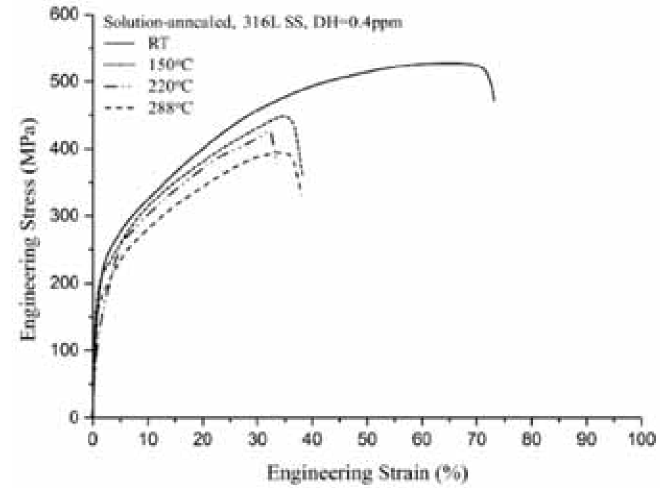
- 288°C,DH 0.4ppm, IG initiation

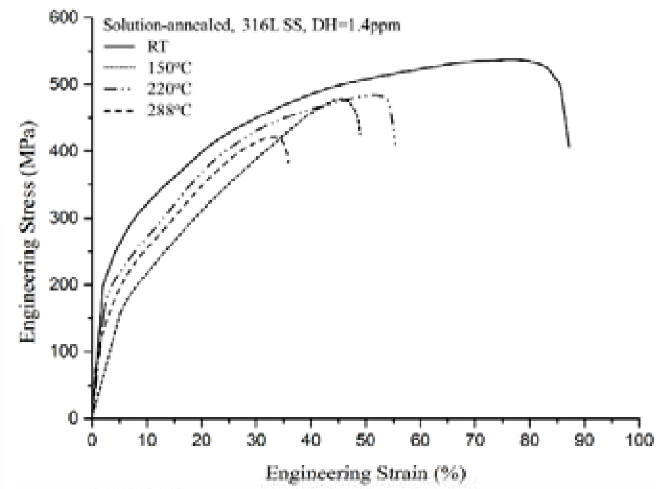


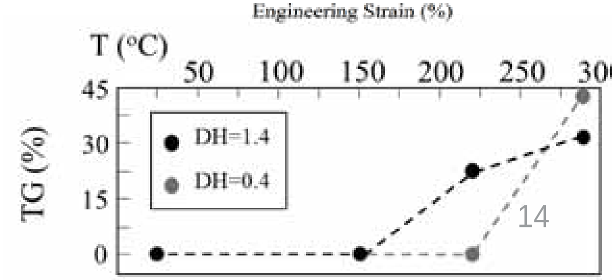


- 288°C,DH 1.4ppm, IG initiation – TG propagation
- 220°C,DH 1.4ppm, pure TG



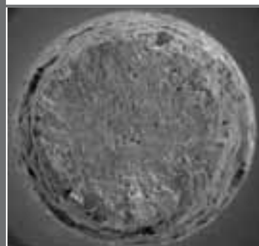
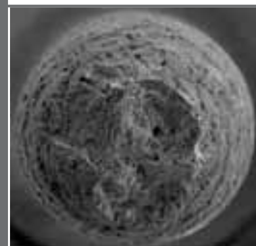
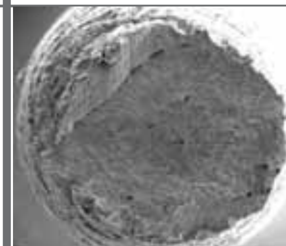


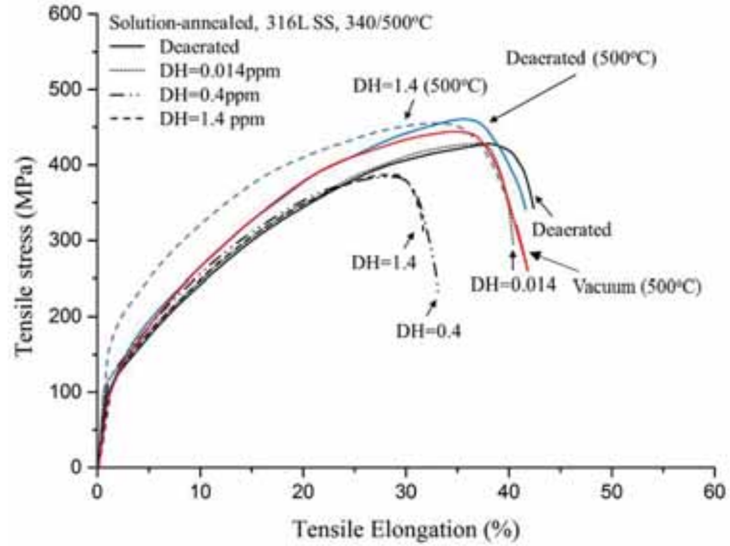


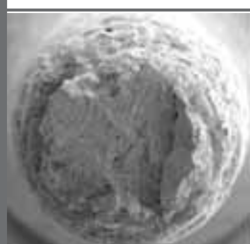
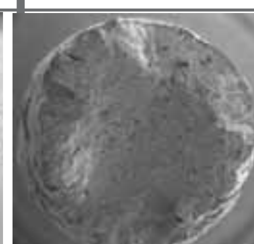
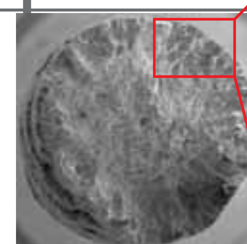
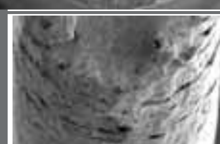


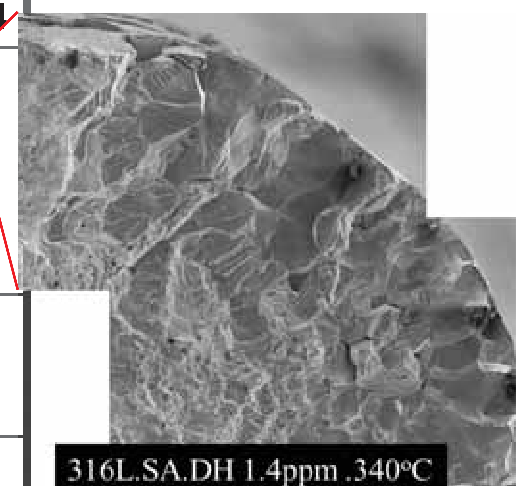
5. SCC susceptibility dependence on DH / Temperature

5. SA-316L in PW (288-340°C) /SCW (500°C), DH condition

Condition	500°C.De.	500°C.DH0.4	500°C.DH1.4
Side Surface			
Fracture Surface			
IG+TG[%]	0	0	0



Condition	288°C.De	340°C.De	288°C.DH1.4	340°C.DH1.4
Side Surface				
Fracture Surface				
IG+TG[%]	0	25	23	36

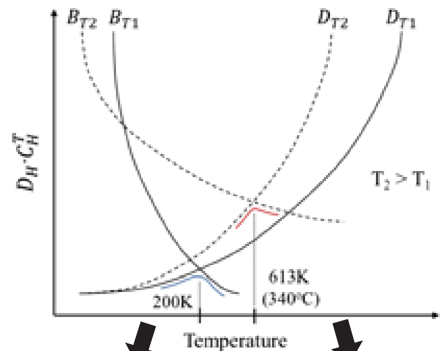


HE behavior in Fe-Cr-Ni alloys

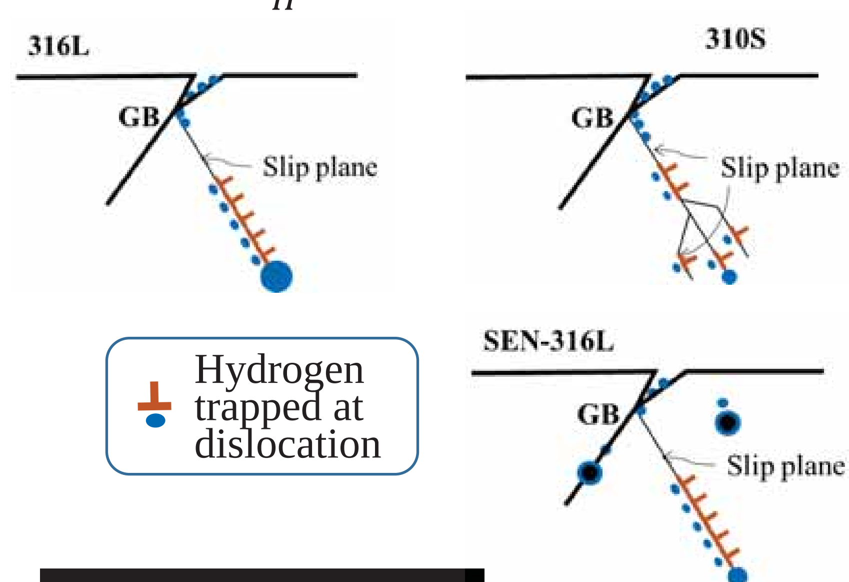
5. Hydrogen Embrittlement:

- Two major factors: H_2 diffusivity and H_2-trapping ability of dislocations

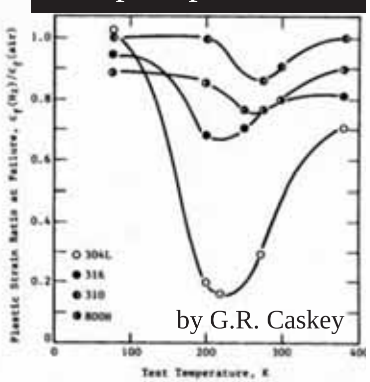
- H_2 Diffusivity $\quad D_H = D_0 exp\left(-\frac{Q}{RT}\right)$
- H_2 trapping amount $\quad C_H^T = C_L \exp\left(\frac{E_b}{RT}\right)$
- HE index $\quad D_H \cdot C_H^T(C,T) = D_0 C_L exp\left(-\frac{Q - E_b}{RT}\right)$



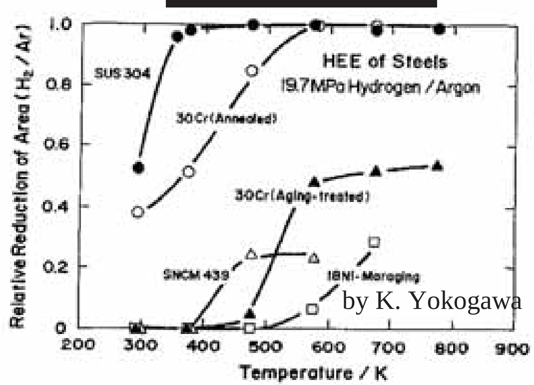
To decrease $C_H^{Dislocation}$:



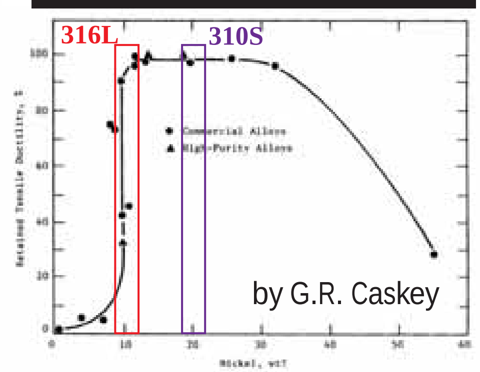
Temp. dependence



Fe-based Alloy



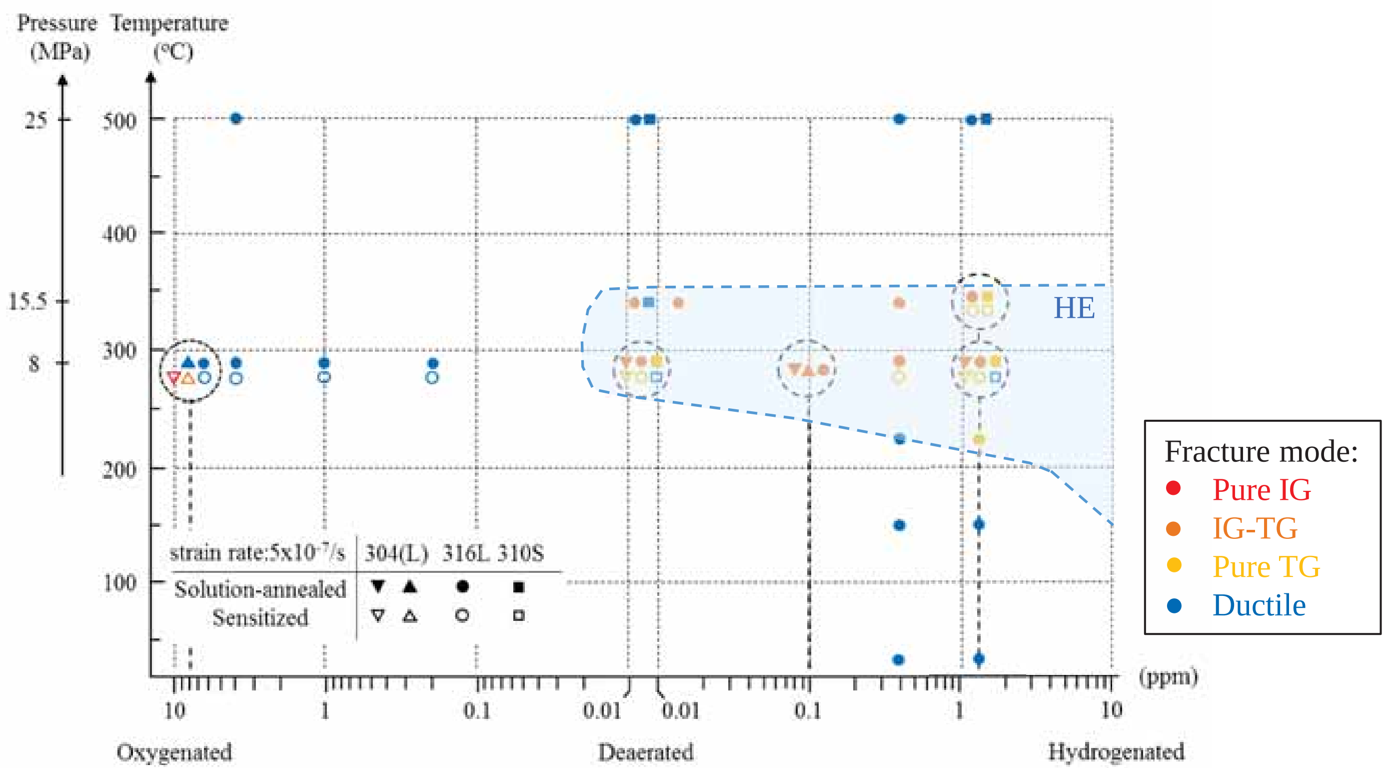
Ni content dependence



Summary

Summary

- Different water chemistries, heat-treated steels determines different SCC mechanisms
- Hydrogen effect depend on both hydrogen concentration and temperature
- No SCC found at 500°C (too high to form H_2 atmosphere)
- Presence of carbide, and increment of Ni could decrease SCC susceptibility



Future Prospective

Publications:

- D. Morrall, Y.-J. Huang, K. Yabuuchi, A. Kimura, T. Ishizaki, Y. Maruno, “Corrosion Behavior of Mechanically Alloyed SUS304L with Zirconium Addition in High-Temperature Water”, Int. J. Metall. Met. Phys. 3:026
- Y.-J. Huang, T. Yamaguchi, H. Murai, H. Sugino, T. Nakajima, M. Nono, K. Kawakita, A. Kimura, “SCC susceptibility of solution-annealed 316L SS in hydrogenated hot water below 288 ° C”, Corros. Sci. 145 (2018) 1-9
- Y.-J. Huang, A. Kimura, “Stress corrosion cracking behavior of 316L and 310S stainless steels in fusion relevant environments”, Mater. Trans. 59 (2018) 1267-1274
- Y.-J. Huang, K. Kawakita, A. Kimura, “Stress corrosion cracking susceptibility of 310S stainless steel in hydrogenated hot water”, NME 15 (2018) 103-109
- E. Hasenhuetl, R. Kasada, Z. Zhang, K. Yabuuchi, Y.-J. Huang, A. Kimura, “Evaluation of Ion-Irradiation Hardening of Tungsten Single Crystals by Nanoindentation Technique Considering Material Pile-Up Effect,” Mater. Trans. 58 (2017) 749-756

Acknowledgements

Supporters from NTHU:

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Thank you for your attention