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Task 1: Evaluation of the Causes & Mechanisms of IASCC in BWRs - IASCC Susceptibility of Austenitic SSs & Alloy 690

Investigators: Yiren Chen, Omesh Chopra, Bill Shack, Bill Soppet, and Nancy Dietz Rago[1]

Experimental Effort: Loren Knoblich and Ed Listwan

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Nuclear Engineering Division

Argonne National Laboratory, Argonne, IL 60439

[1]Chemical Engineering Division

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Objectives and Approach

Objectives:

- Evaluate the influence of GBE treatment;
- Evaluate the influence of alloy composition;
- Evaluate the effect of irradiation dose.

Approach:

SSRT tests in high-DO water at 289ºC, complemented with Fractography on:

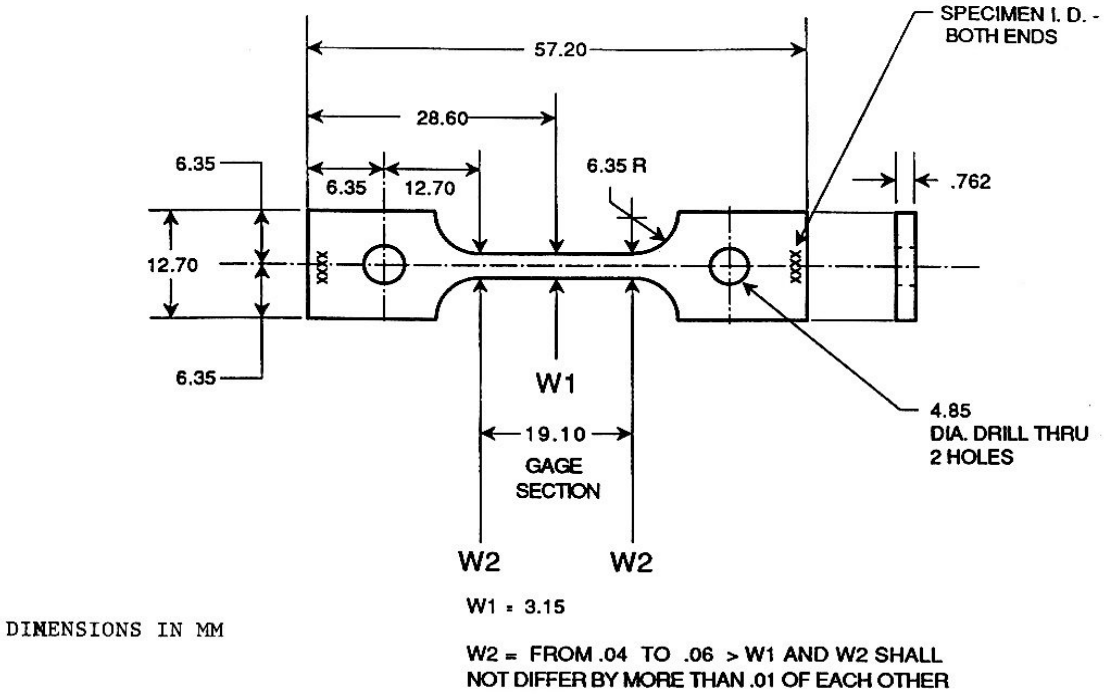
- specimens with different proportions of special boundaries
- specimens with various chemical compositions
- specimens irradiated to a range of doses.

Alloys

Heat ID	Description	Composition (wt.%)								
		Ni	Si	P	S	Mn	C	N	Cr	Others
333	Type 304 SS from ABB[a]	8.45	0.68	0.027	0.019	1.38	0.04	0.068	18.54	Mo 0.37
GBE304	GBE Type 304 SS	8.19	0.41	0.029	0.006	1.73	0.054	0.052	18.28	Mo 0.23, Co 0.10, Cu 0.31
304L	Type 304L SS.	8.33	0.45	0.028	0.007	1.74	0.023	0.090	18.35	Mo 0.37, Co 0.13, Cu 0.35
GBE304L	GBE Type 304L SS	8.33	0.45	0.028	0.007	1.74	0.020	0.090	18.35	Mo 0.37, Cu 0.35
327	High-purity Type 304L SS with low O	9.54	0.01	0.001	0.002	1.12	0.006	<0.001	19.71	Mo 0.02, O 0.008
945	High-purity Type 304L SS with high O	9.03	0.03	<0.005	0.005	1.11	0.005	0.003	19.21	Mo <0.005, O 0.047
GBE316	GBE Type 316 SS	11.16	0.35	0.029	0.025	1.59	0.041	0.050	16.34	Mo 2.07, Cu 0.37, Co 0.09
623	Type 316LN SS	12.20	0.7	0.007	0.002	0.97	0.019	0.103	17.23	Mo 2.38, Cu 0.21
625	Type 316LN SS, Ti-doped	12.30	0.72	0.007	0.002	0.92	0.012	0.064	17.25	Mo 2.39, Ti 0.027, Cu 0.21
690	Alloy 690	61.49	0.05	-	0.001	0.15	0.030	-	29.24	Fe 9.02, Co 0.007, Cu 0.01
GBE690	GBE Alloy 690	59.40	0.42	0.026	0.003	0.42	0.010	-	29.10	Fe 10.26, Al 0.22, Ti 0.29

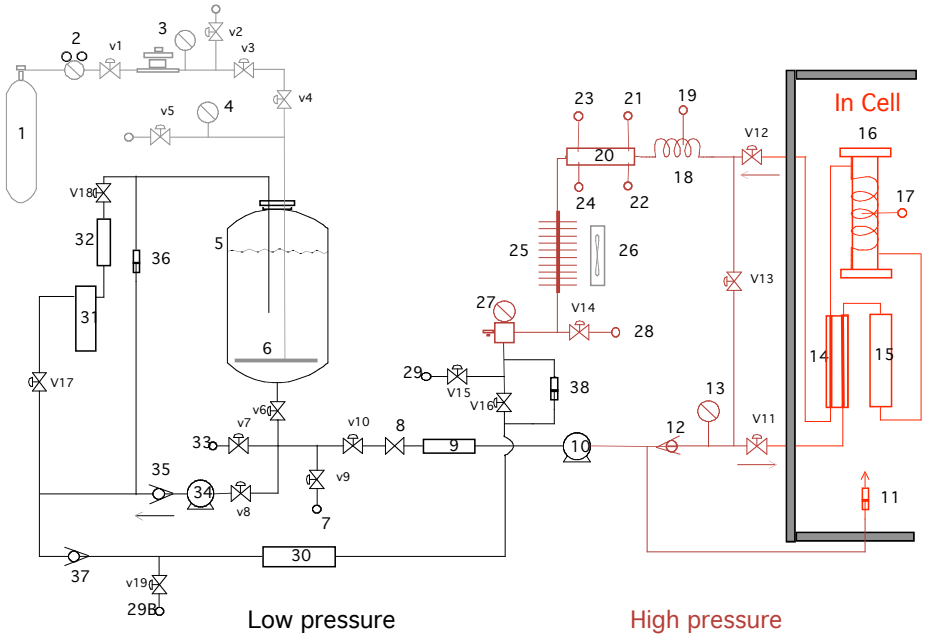
SSRT specimens and Irradiation condition

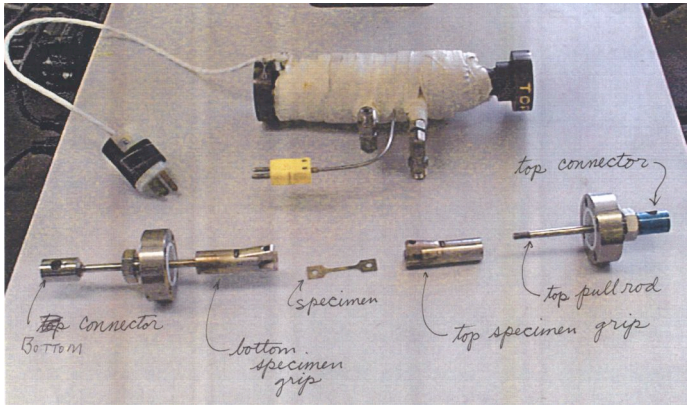
- Flat dog-bone specimen



- Dry irradiation in He-sealed capsules in Halden boiling heavy water reactor
  - Dose: 0.45, 1.34 and 3 dpa (phase-I); 1.96 and 2.44 dpa (phase-II)
  - Irradiation temperature (phase-II): ~290-305°C
  - Radioactivity: ~ 200 R/hr on contact, 0.3 Ci.

SSRT test condition



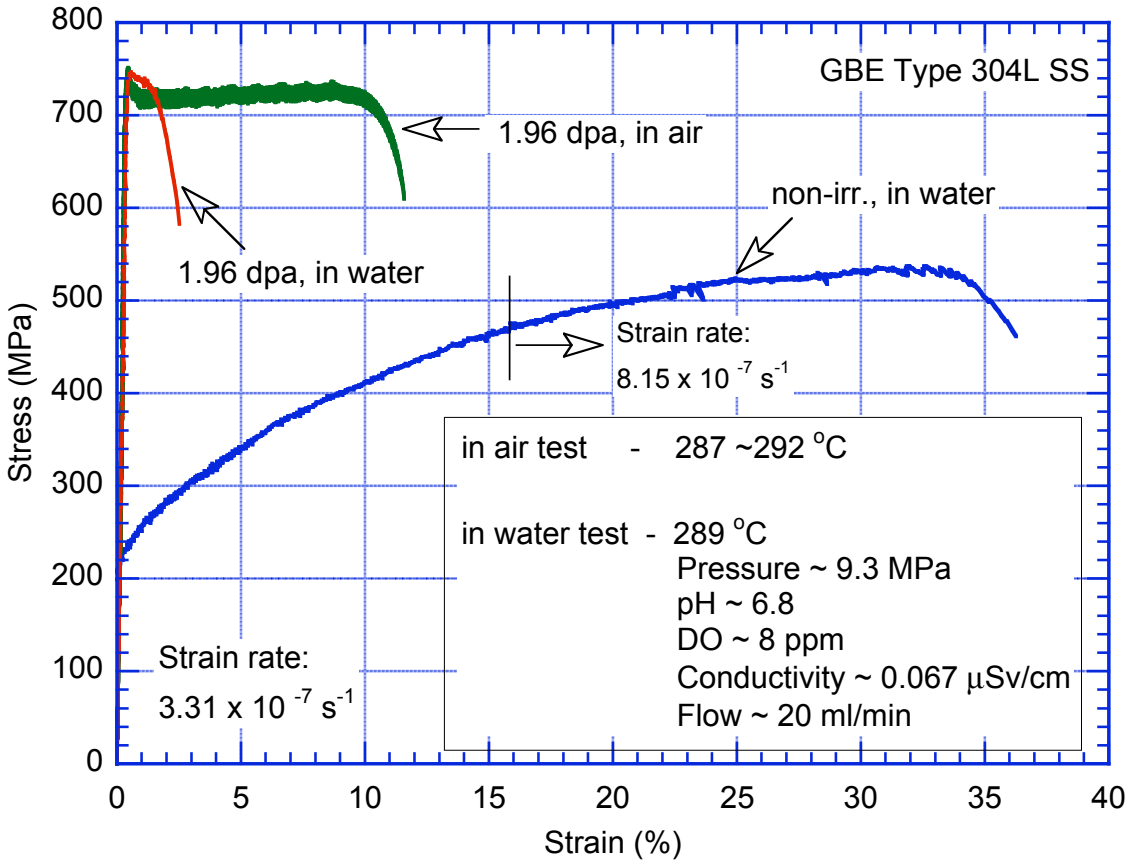


Temperature - 289°C
Pressure - 9.31 MPa (1350 psig)
pH - 6.4 ~ 7.2
Flow rate – 15~30 ml /min
Strain rate ~ 3.31×10^{-7} s^{-1}

DO - 8 ppm
Conductivity - 0.06~0.1 μS/cm
ECP – 150~200 mV (ss)
270~310 mV (Pt)

Stabilize test condition by soaking the specimen in high-DO water >24 hr

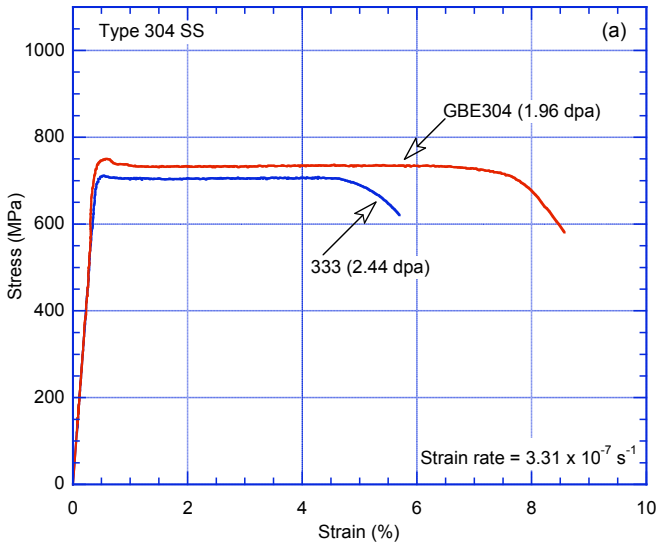
Influence of irradiation and high-DO water on SSRT curve

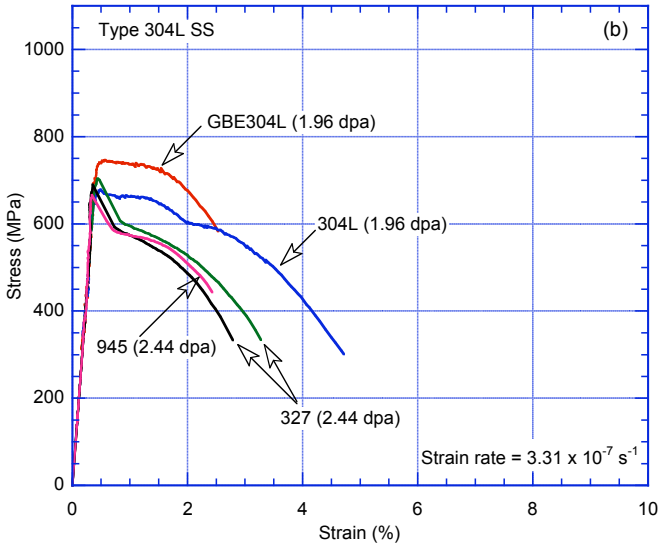


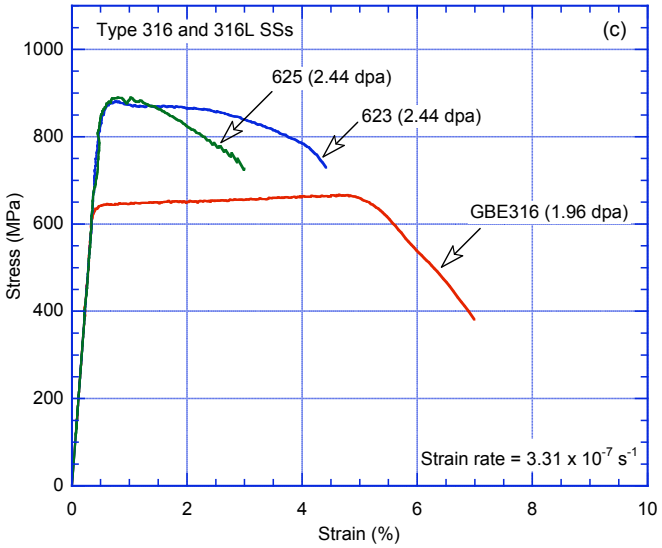
Strain rate:
~ 3.31×10^{-7} s^{-1}

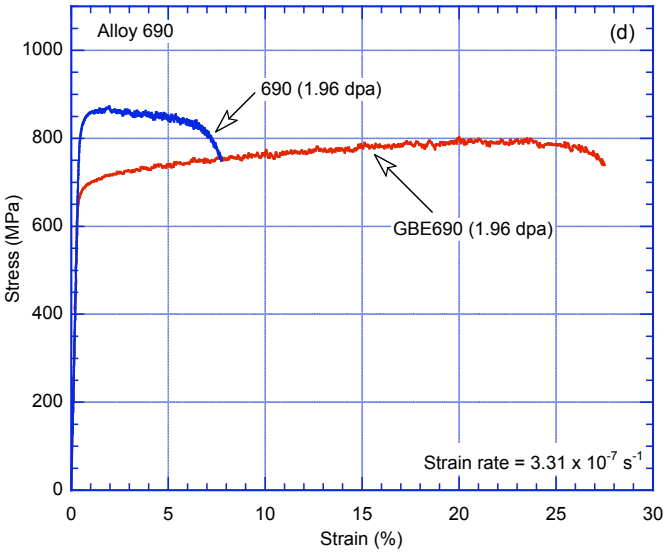
- The yield strength for irradiated material is similar in air and in water.
- The reduction in ductility is attributed to both neutron irradiation and high-DO water environment.

SSRT tests in high-DO water environment

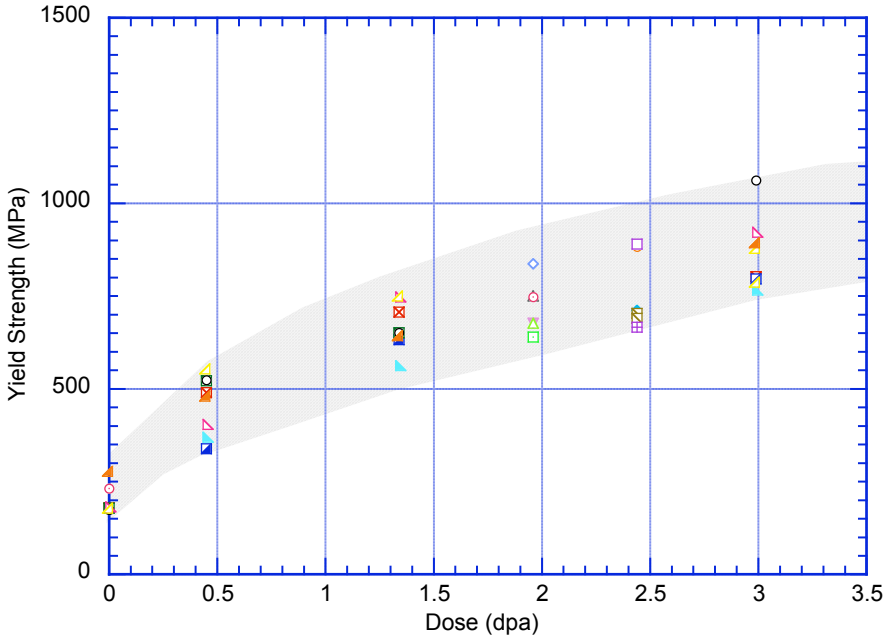




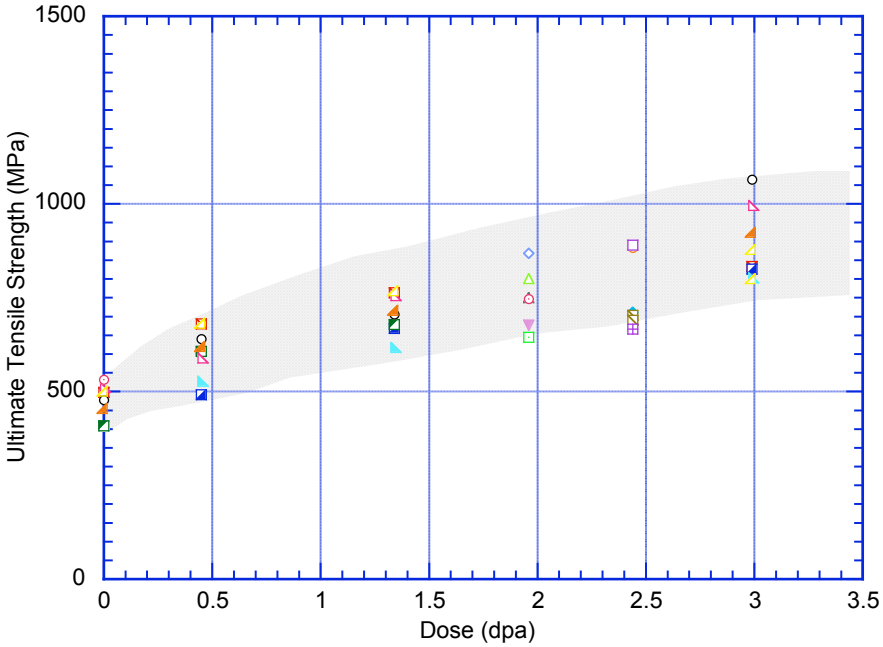




Dose dependence of yield strength and ultimate tensile strength

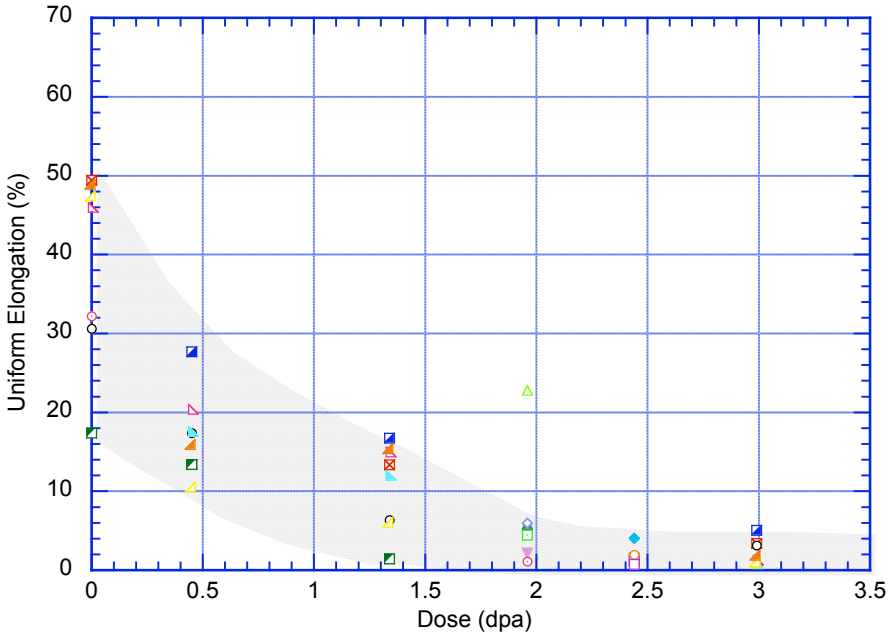


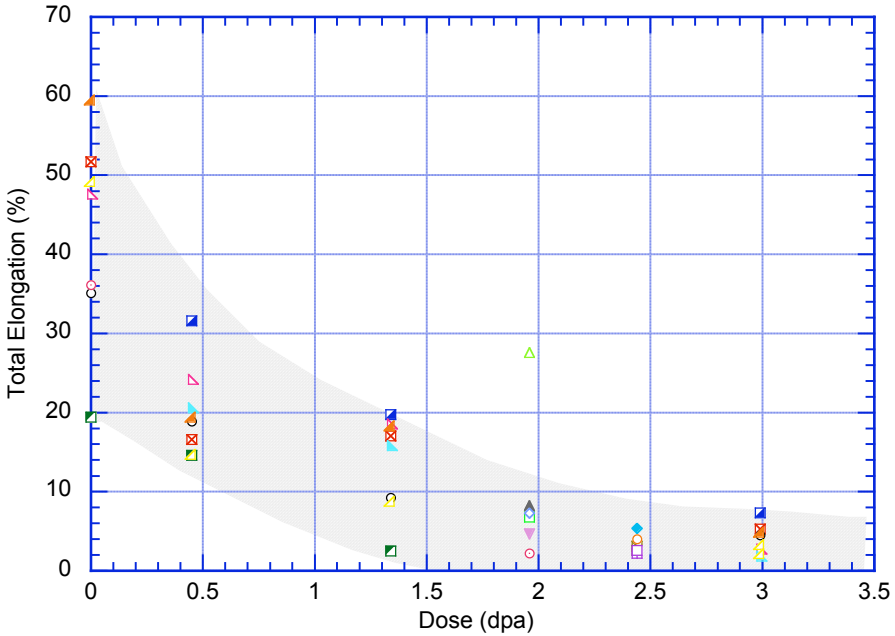
Rate of increase of yield strength decreases significantly at 3 dpa.



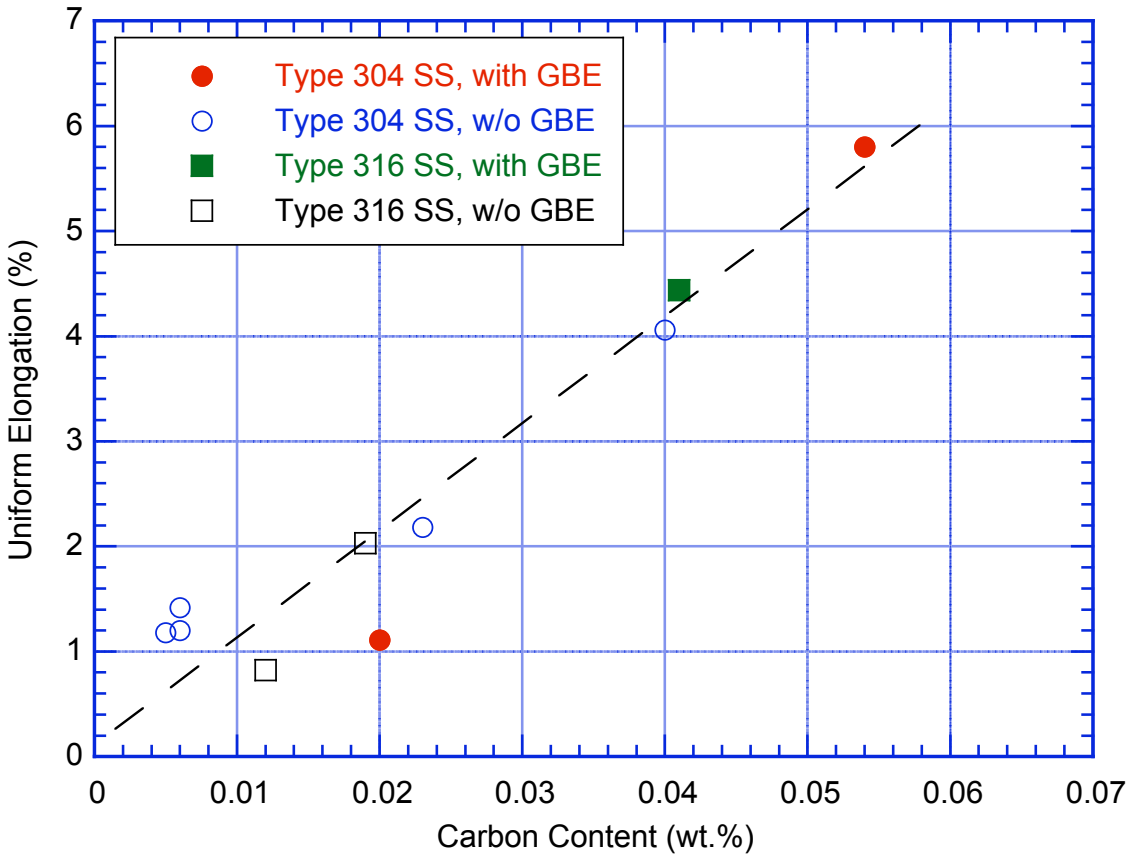
Dose dependence of uniform elongation and total elongation

Loss of elongation reaches minimum at less than 2 dpa in high-DO water.





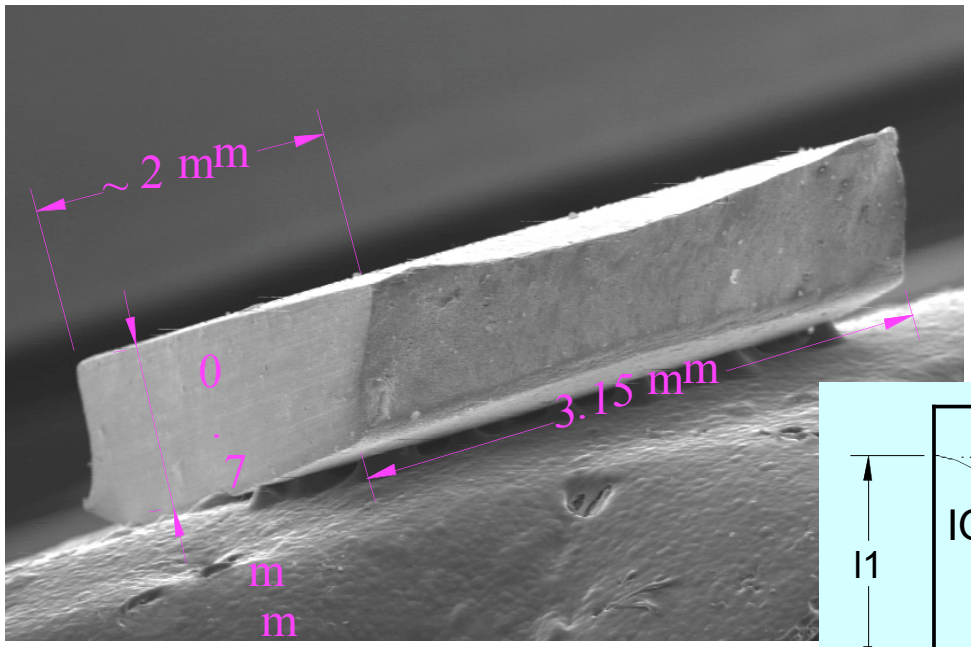
Correlation between C content and UE of SSRT tests



No other correlation found between other elements & SSRT elongation

Fractographic analyses

- Cut fracture tip to reduce radioactivity: <100 mR/hr @ 30 cm; <7mCi.
- Clean off loose contamination: < 200 dpm
- Hitachi S-3000N SEM, secondary electron image at 30-kV acceleration voltage with a 25-mm work distance.



- Characterize fracture surface
  - IG or TG area fractions
  - Number of IG or TG cracks

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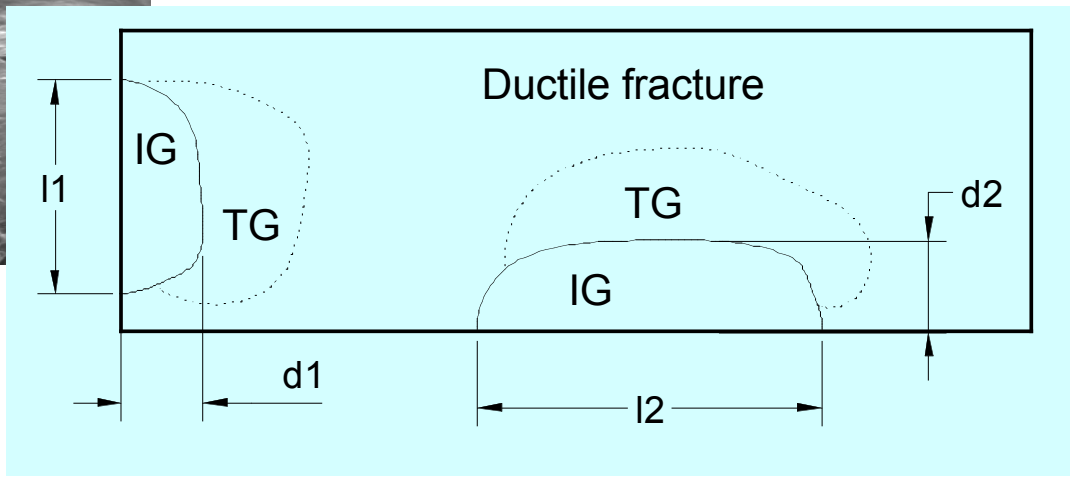
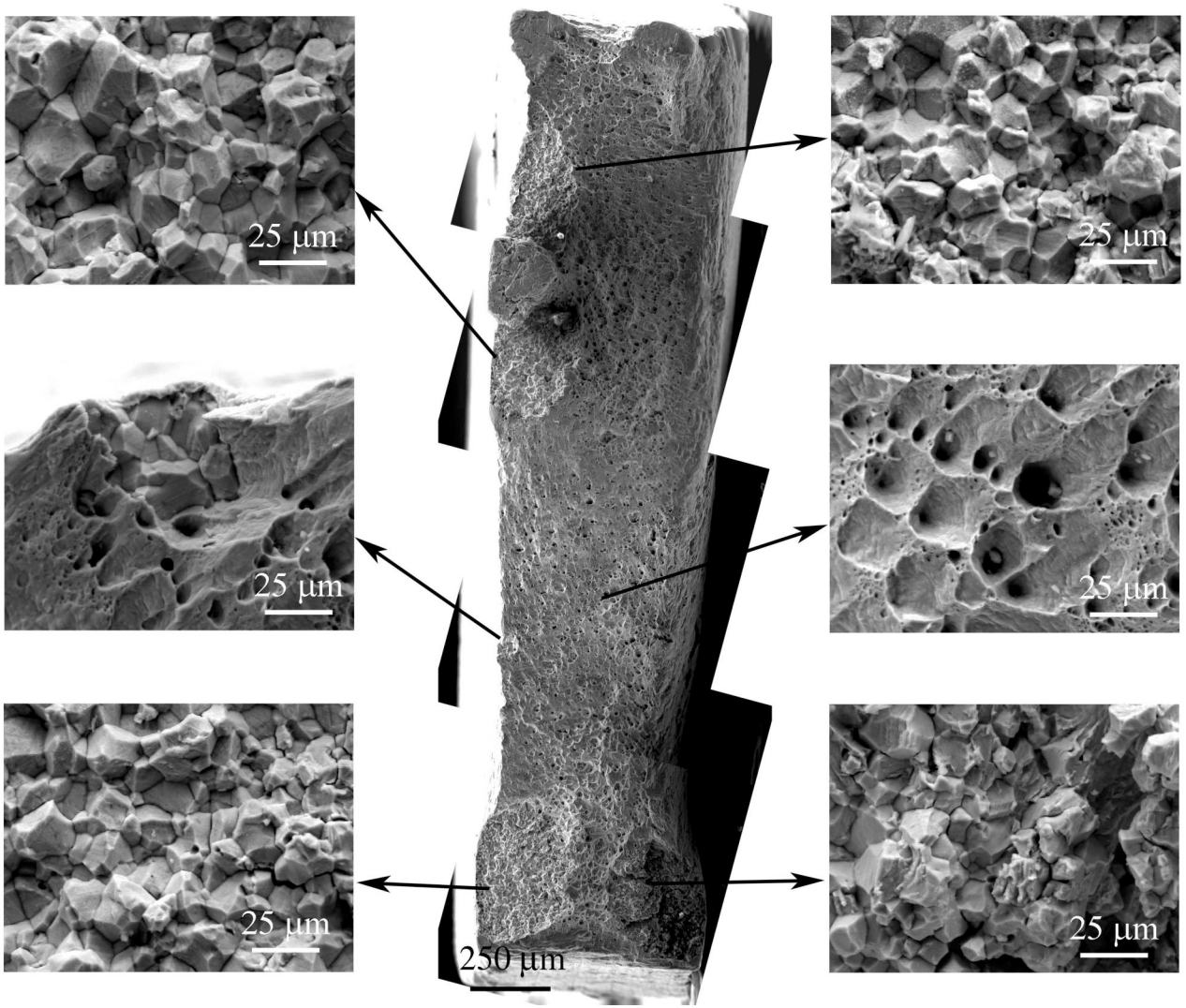


Type 304L SS with high O content (Heat 945)



Dose = 2.44 dpa

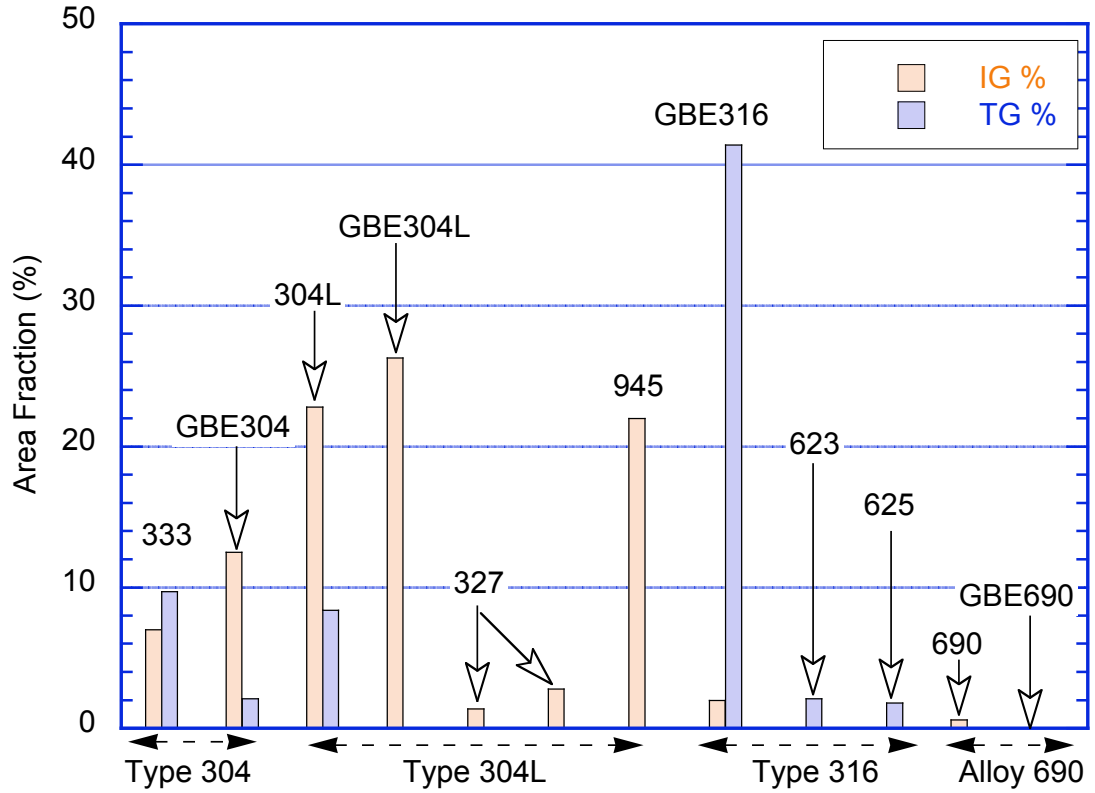
YS = 666 MPa

UTS = 666 MPa

UE = 1.22%

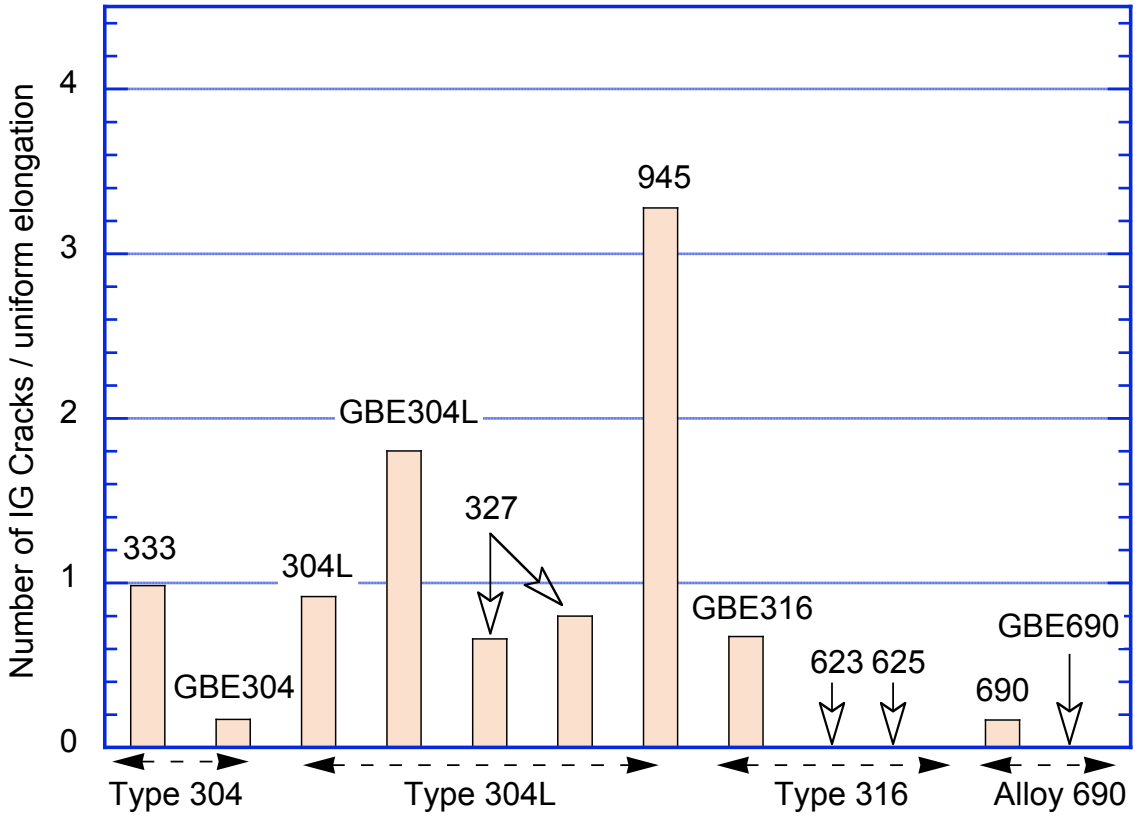
TE = 2.20%

Susceptibility to cracking – IG and TG area fractions



- Type 304 and 304L SSs are more vulnerable to IG cracking in high-DO water;
- Large TG cracking was observed in GBE Type 316;
- High-O content stimulates IG cracking in HP Type 304L SS;
- Low-C Type 304 SSs show more IG cracking.

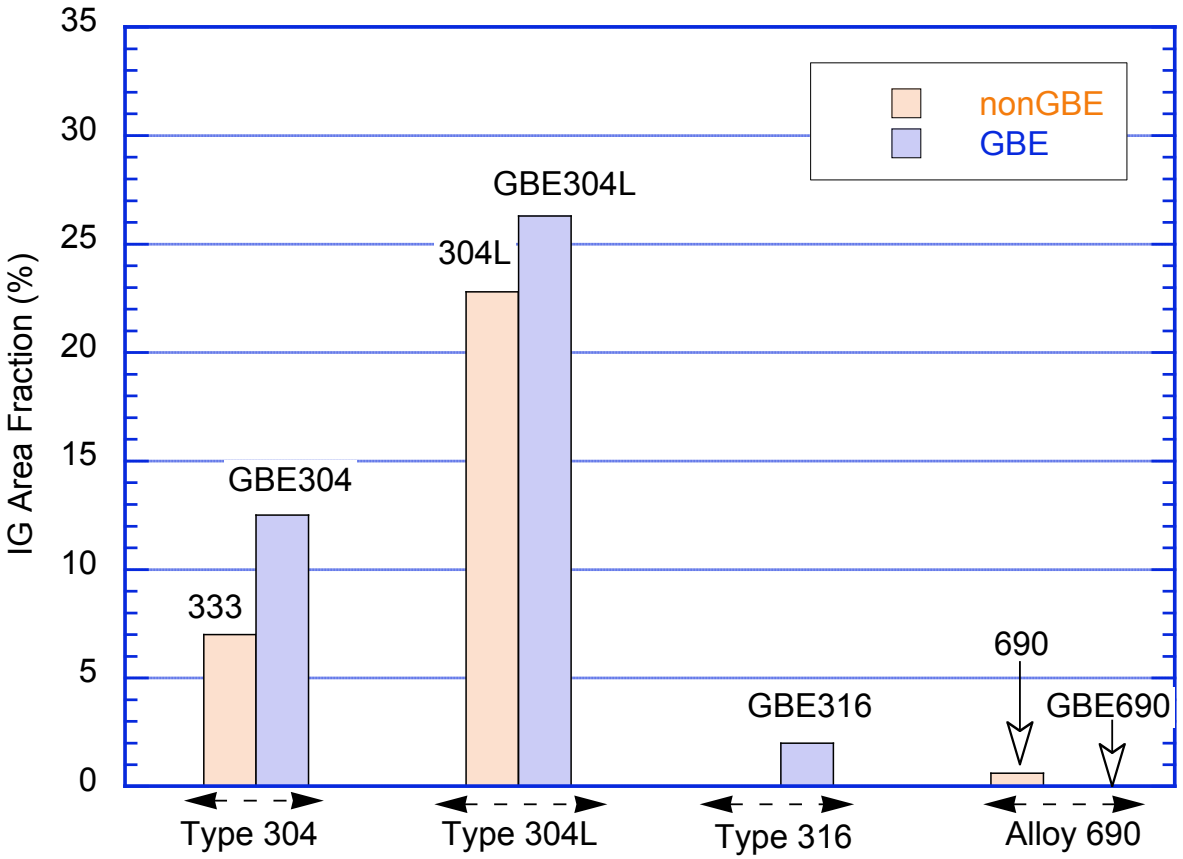
Likelihood of IG crack initiation



-The highest IG initiation is found in Type 304L SS with high-O content.

- No IG initiation in high-purity Type 316 SSs, and GBE 690.

Effect of GBE Treatment*



* GBE CSL (Σ≤29) fractions:
  - 67% Type 304 SS;
  - 66% Type 304L SS;
  - 66% Type 316 SS;
  - 71% Alloy 690.

- GBE treatment does not appear to improve IG cracking in Type 304 and 304L SSs
- The effectiveness of GBE treatment is inconclusive for Type 316 SS (no base tested)
- GBE treatment appears to suppress IG cracking in Alloy 690 at ≈2 dpa

Work sponsored by the
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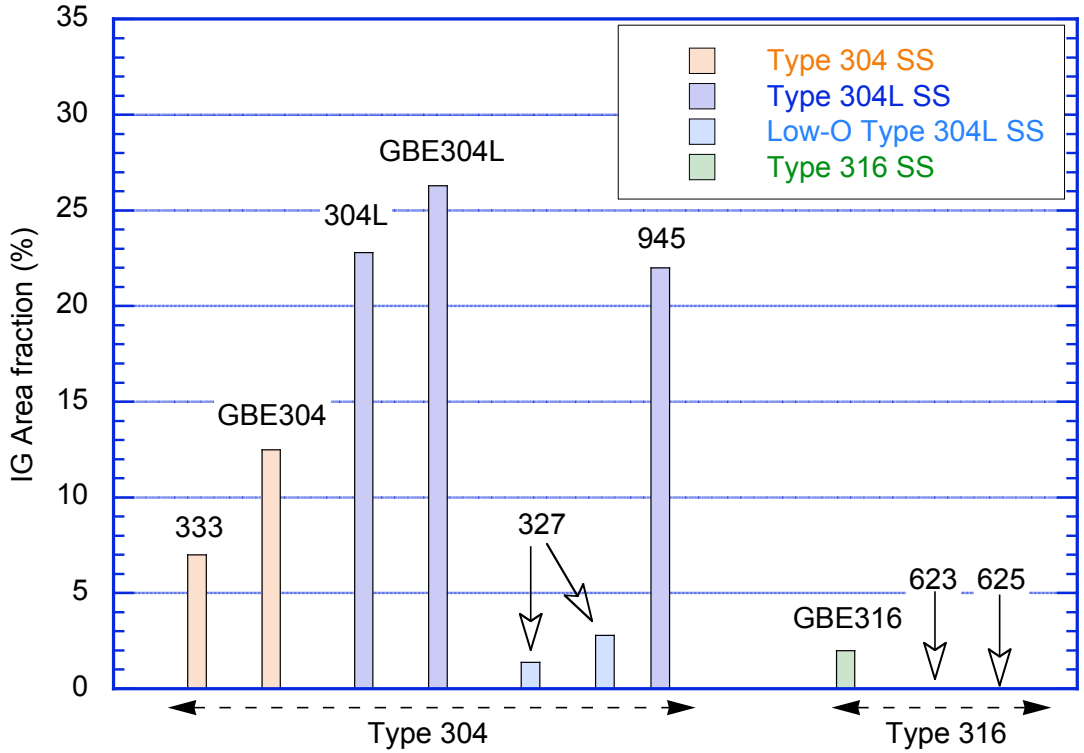
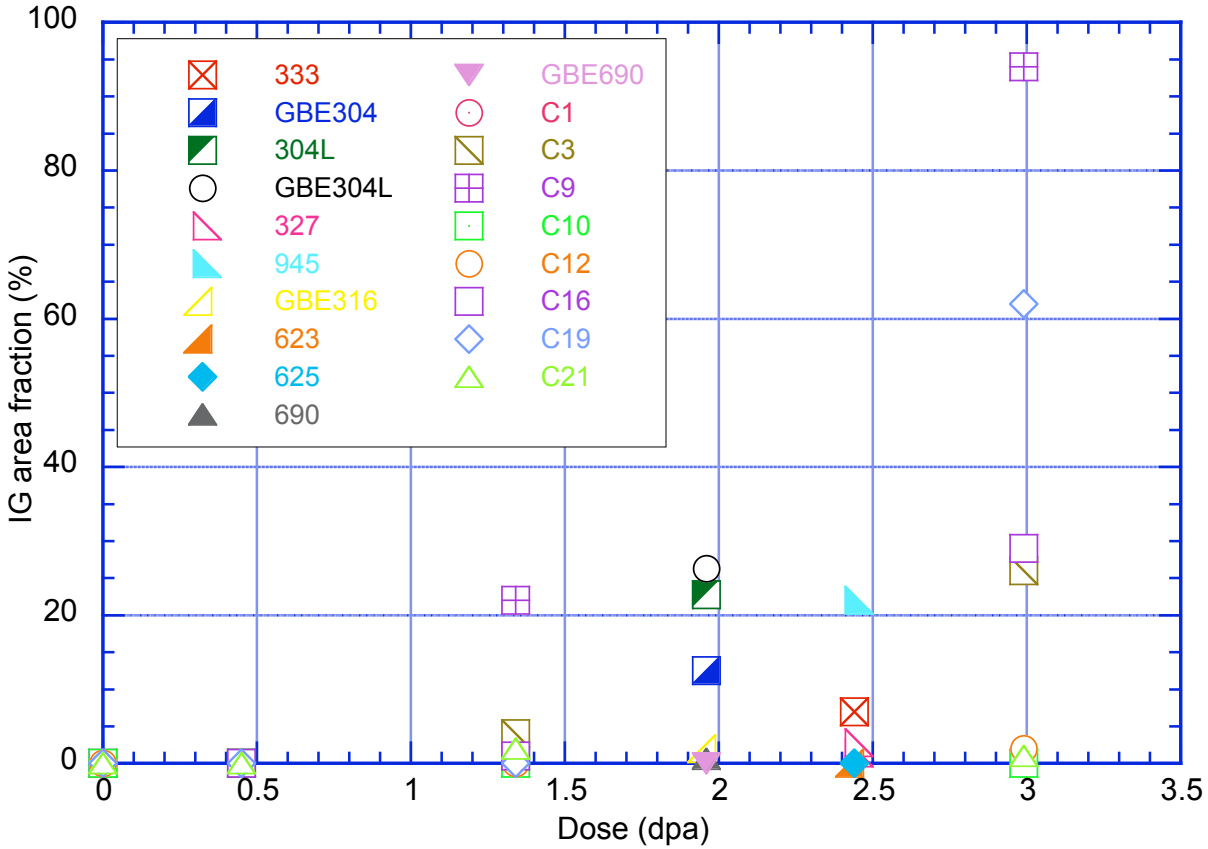
Effect of Alloying Elements



- Type 304 SSs cracked more than Type 316 SSs (Mo addition is helpful to reduce cracking)
- Type 304L SS cracked more than Type 304 SS (blue vs. orange)
- Low-O Type 304 SS cracked less (light blue vs. dark blue)

Appear to be significant differences within alloy types; such heat-to-heat variability may be dependent on differences in microstructure & minor impurity levels

Effect of Irradiation-Dose Threshold



Halden-I data is included.

IG cracking does not occur below 0.45 dpa (3 x 10^{20} n/cm^2) for the commercial heats of austenitic SSs in the Halden irradiations.

Conclusions

- GBE process used in this study shows no beneficial effect for Types 304 or 304L SS. However, the GBE treatment results in a smaller reduction in UE for Alloy 690 at 2 dpa, & reduces its IASCC susceptibility in high-DO water.
- Type 316 SSs are generally more resistant to IG cracking than Type 304 SSs. The presence of Mo or the higher Ni concentrations in Type 316 SSs may be responsible.
- The O content of the material is critical for IASCC susceptibility; high O content contributes to IASCC susceptibility by enhancing IG crack initiation.
- The UE obtained from SSRT tests in high-DO water increases linearly with C content below 0.06 wt.%. Also, the low-C SSs are more susceptible to IGSCC (results consistent with data from Halden-I irradiations).