The Combined Effect of Bicarbonate and Chloride Ions on the Stress Corrosion Cracking Susceptibility of Alloy 22

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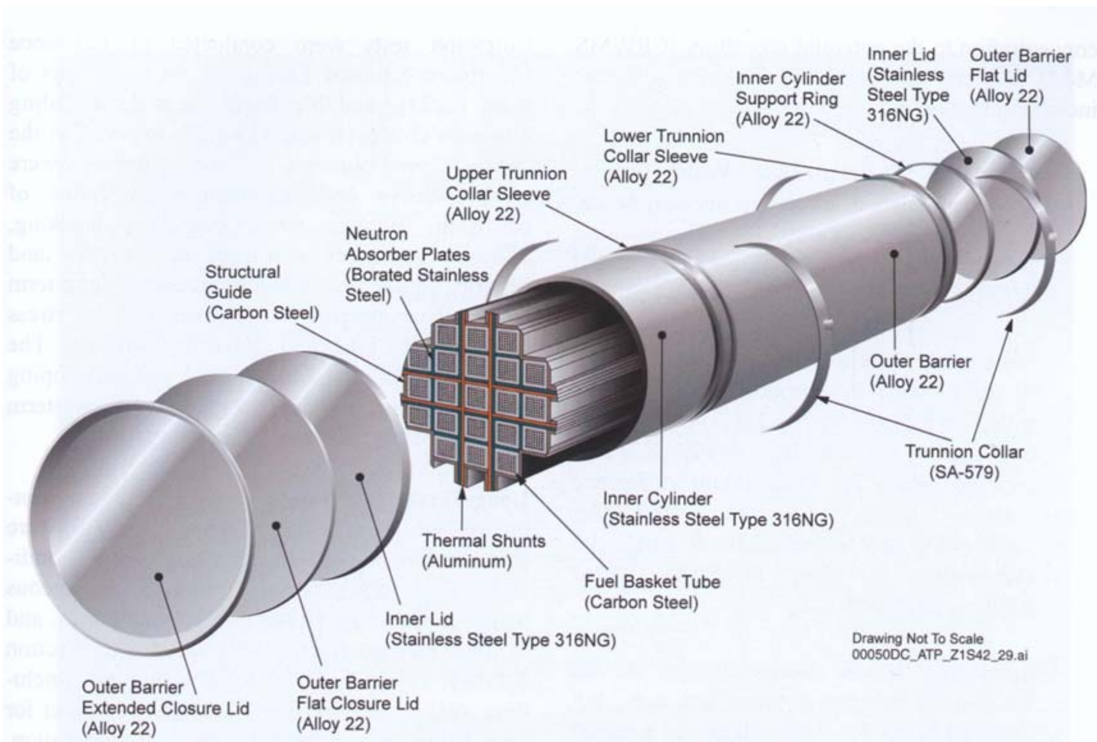
Outline

- Introduction
- Stress Corrosion Cracking (SCC) of Alloy 22 in Solutions Containing Bicarbonate & Chloride Ions
- Effect of Electrochemical Potential
- Effect of Solution Temperature
- Summary & Conclusions

Potential Waste Package Design for High-Level Nuclear Waste Disposal



(DOE, 2001)

- Alloy 22 (Ni-22Cr-13Mo-4Fe-3W in weight %) Outer Barrier for Corrosion Resistance
- Stainless Steel (Type 316NG) Inner Cylinder for Structural Support
- Long Lifetime of Waste Package as Key Attribute for Performance of Potential Yucca Mountain Repository

Simulated Concentrated Water (SCW) for Alloy 22 Testing

Ion	K^+	Na^+	Mg^{2+}	Ca^{2+}	F^-	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-
mg/L	3,400	40,900	<1	<1	1,400	6,700	6,400	16,700	70,000
mM	87	1,780	<0.041	<0.025	74	189	103	174	1,148

Reference: G.M. Gordon, "Corrosion Considerations Related to Permanent Disposal of High-Level Radioactive Waste", ***Corrosion***, 58(10), p. 811, 2002.

- Estill, et al. (*Corrosion 2002*) Reported SCC in Slow Strain Rate Tests (SSRTs) in SCW at 73 °C [163 °F] and 400 mV_{SSC} [356 mV_{SCE}]
- Chiang, et al. (*Corrosion 2005*) Reported Bicarbonate Ions Are the Predominant Consitiuent in SCW that Promoted SCC at 95 °C [163 °F] and 400 mV_{SCE}

Objectives and Scope

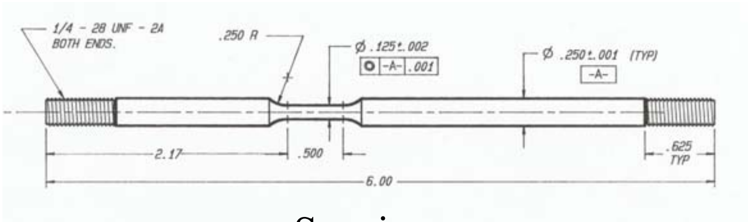
- Evaluate SCC Susceptibility of Alloy 22 in Solutions Containing a Combination of Chloride and Bicarbonate Ions Using SSRTs
- Determine the Effect of Electrochemical Potential on SCC Susceptibility
- Determine the Effect of Temperature on SCC Susceptibility
- Correlate SSRT Results with Potentiodynamic and Potentiostatic Anodic Polarization Tests

Chemical Composition & Tensile Properties of Alloy 22

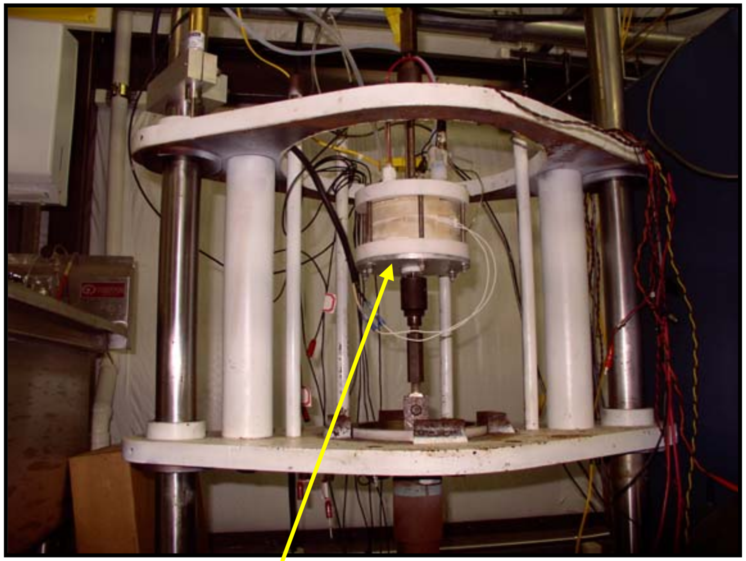
Material	Composition (wt%)											
	Ni	**Cr**	**Mo**	**W**	**Fe**	**Co**	**Si**	**Mn**	**V**	**P**	**S**	**C**
Alloy 22 Heat 2277-3-3266	Bal	21.40	13.30	2.81	3.75	1.19	0.03	0.23	0.14	0.008	0.004	0.005

Material	Tensile Strength MPa [ksi]	Yield Strength MPa [ksi]	Elongation (%)	Reduction in Area (%)	Modulus MPa [ksi]
Alloy 22 Heat 2277-3-3266	787 [114.2]	347 [50.3]	71	79	1.95×10^5 [2.83×10^4]

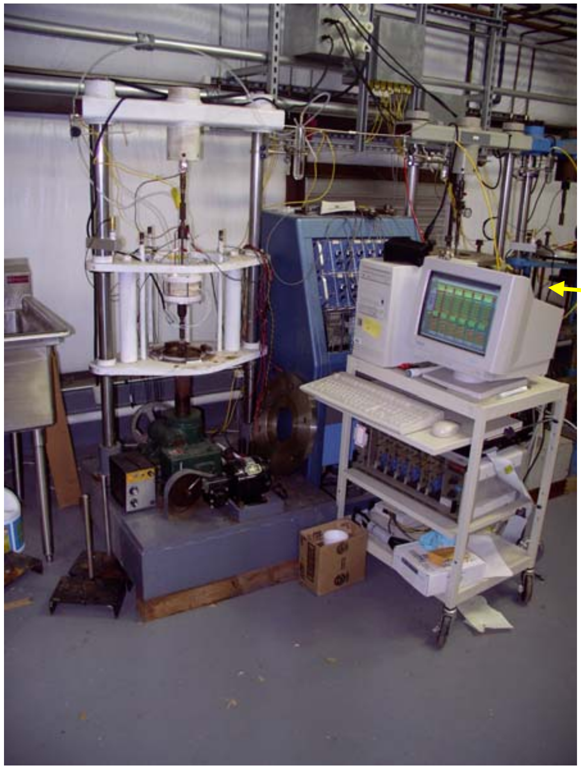
SSRT Experimental Setup



Specimen



Test Cell



Data Acquisition System

SCC Testing Conditions

- SSRT
  - SCW and electrolyte containing [Cl^-] & [HCO_3^-] ions
  - Electrochemical potentials 100 to 400 mV_{SCE}
  - Test temperatures 22 to 95 ^oC [72 ^oF to 203 ^oF]
  - Strain rate 3.2×10^{-6}/s
  - Air test at 22 ^oC [72 ^oF] as control
- Potentiodynamic & Potentiostatic Anodic Polarization Tests
  - Environment: Electrolyte containing [Cl^-] & [HCO_3^-] ions at 95 ^oC [203 ^oF]

SSRT Conditions & Results for Alloy 22

(Strain Rate: 3.2×10^{-6}/s)

Environment	T(°C) [°F]	$E_{Applied}$ (mV_{SCE})	t_f/t_f^{air}	P_{max}/P_{max}^{air}	SCC
Air	22 [72]	N/A	—	—	N
SCW	95 [203]	400	0.77	0.79	Y
SCW	95 [203]	200	1.0	1.0	N
7.2 m Cl^-	95 [203]	400	1.02	1.09	N
1.1 m HCO_3^- + 4.2 m Cl^-	95 [203]	400	0.51	0.70	Y
1.1 m HCO_3^- + 7.2 m Cl^-	95 [203]	400	0.41	0.64	Y
	95 [203]	300	0.62	0.78	Y
	95 [203]	200	0.91	0.91	Y
	95 [203]	100	1.03	0.92	N
1.1 m HCO_3^- + 2.2 m Cl^-	95 [203]	400	0.65	0.77	Y
	75 [167]	400	0.73	0.92	Y
	55 [131]	400	0.91	0.98	Y§
	22 [72]	400	0.92	1.05	N

§ Minor transgranular cracking, mostly on side surfaces

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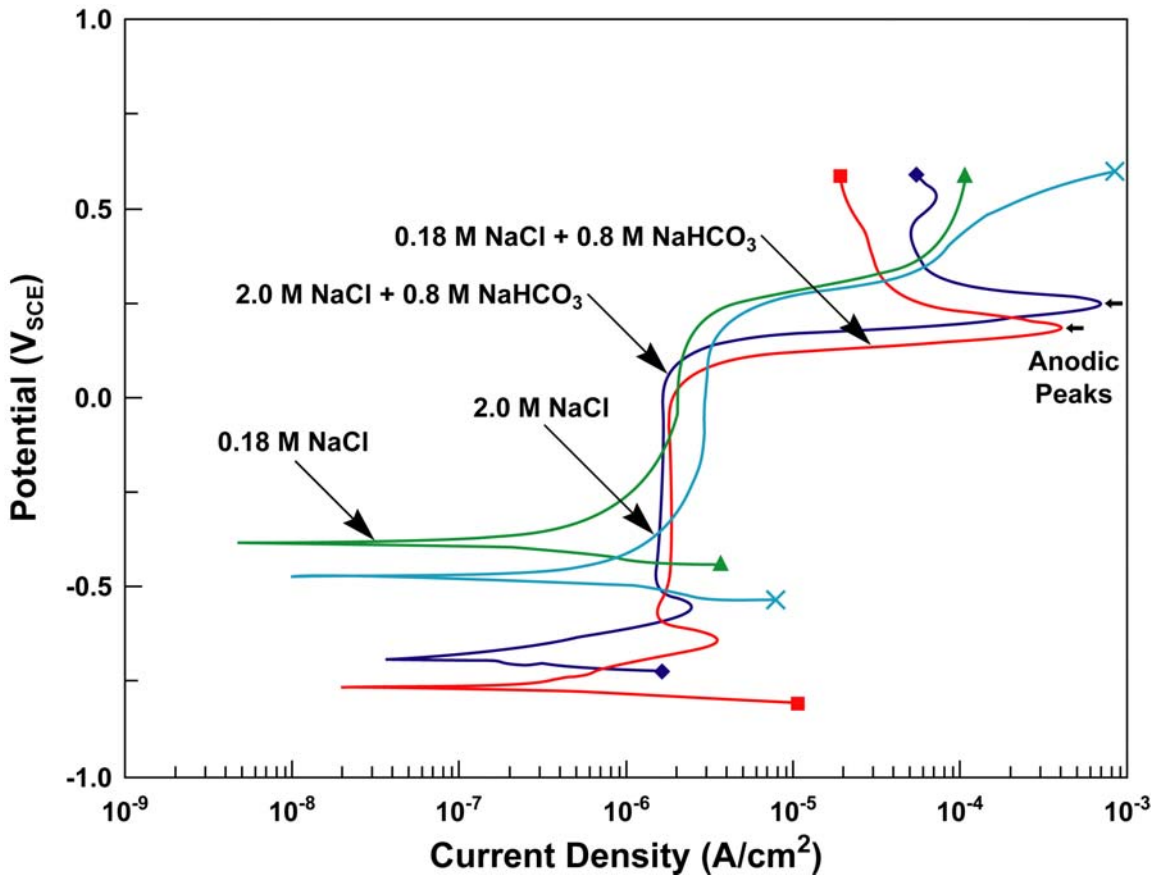
Anodic Polarization Behavior

Mill-Annealed Alloy 22 at 95°C [203 °F]
Deaerated $NaHCO_3$ + NaCl Solution



- Anodic Peaks Were Observed in $NaHCO_3$ + NaCl Solutions
- No Anodic Peak in NaCl-Only Solutions

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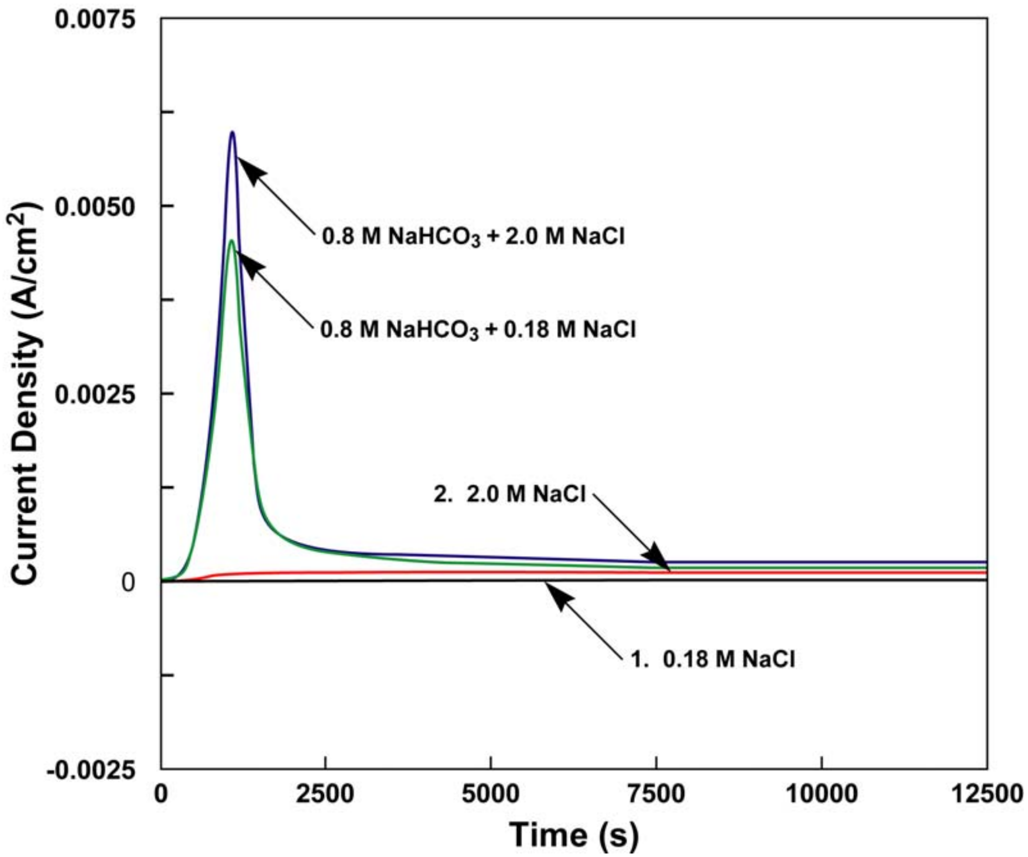
Anodic Current Density Versus Time Behavior

Mill-Annealed Alloy 22 at 95°C [203 °F] and 400 mV_{SCE}
Deaerated $NaHCO_3$ + NaCl Solution



- No Peak Exists in NaCl-Only Solutions
- Pronounced Current Peaks Observed in $NaHCO_3$ + NaCl Solutions

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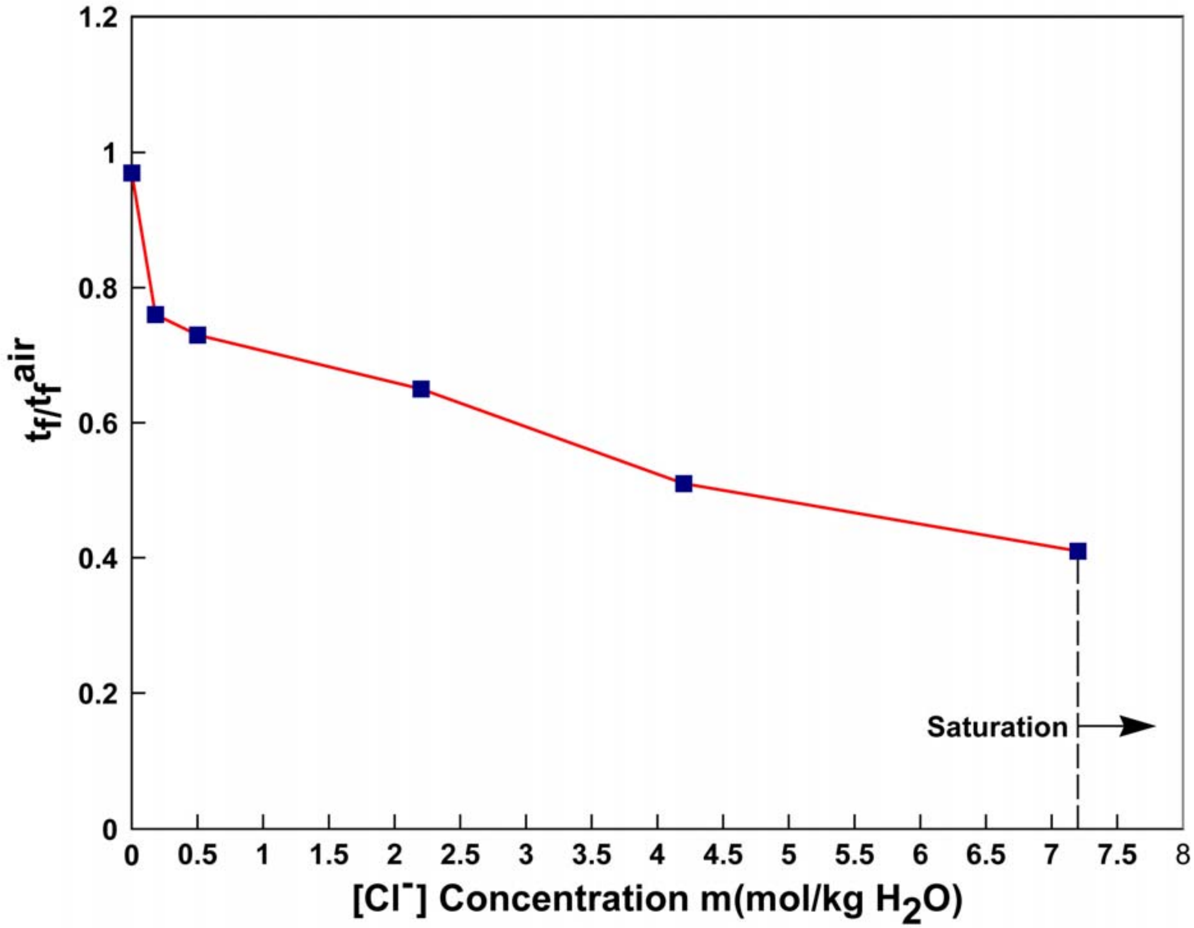
Effect of [Cl^-] and [HCO_3^-] on Time-to- Failure of Alloy 22 in SSRTs

Mill-Annealed Alloy 22 at 400 mV_{SCE} and 95°C [203 °F], SSRTs at 3.2×10^{-6}/s



- At a Constant Bicarbonate Level (1.1 m), Susceptibility of Alloy 22 to SCC Increases with Increasing Chloride Ion Concentrations

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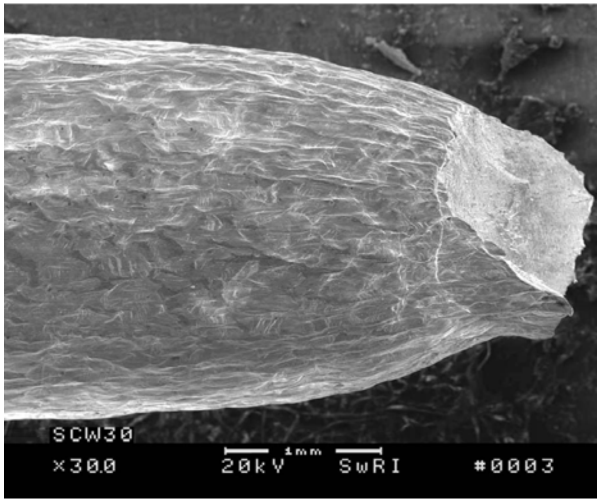
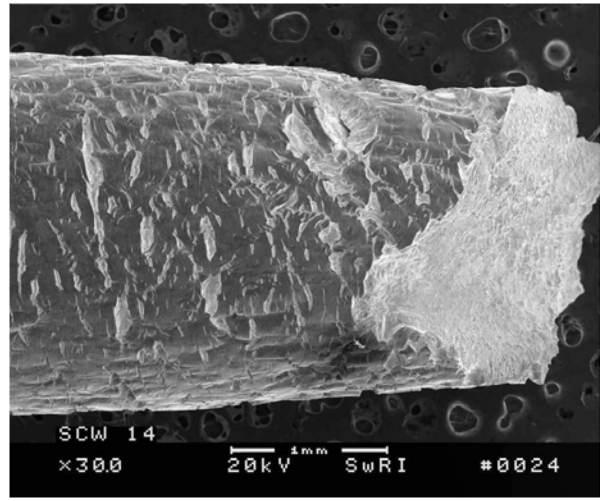
Synergistic Effect of [Cl^-] and [HCO_3^-] in Causing SCC of Alloy 22 at 400 mV_{SCE}

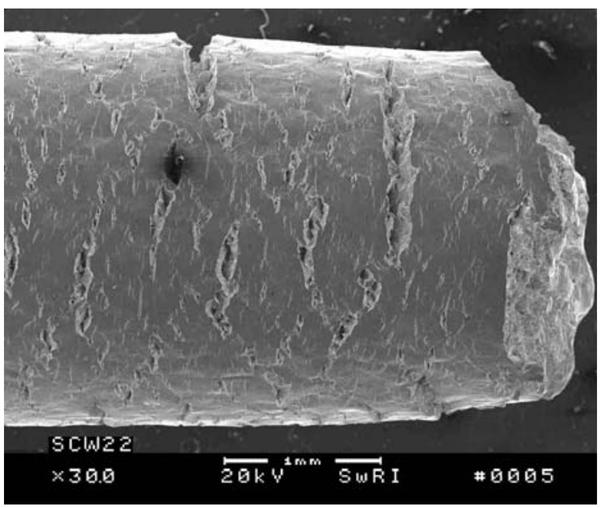
7.2 m Cl^- only

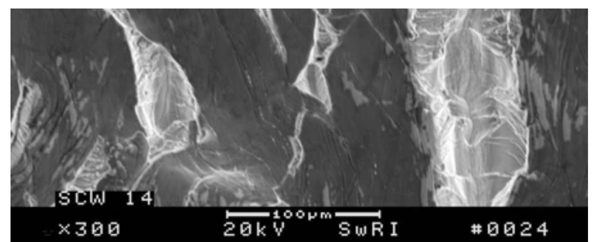




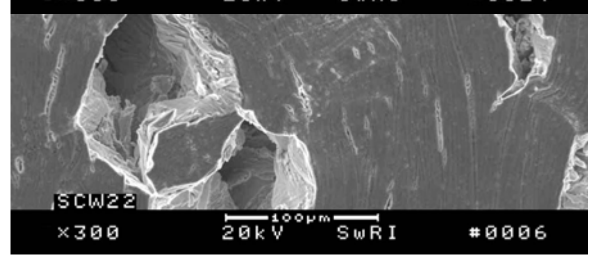
1.1 m HCO_3^- only

1.1 m HCO_3^- + 4.2 m Cl^-





1.1 m HCO_3^- only



1.1 m HCO_3^- + 4.2 m Cl^-

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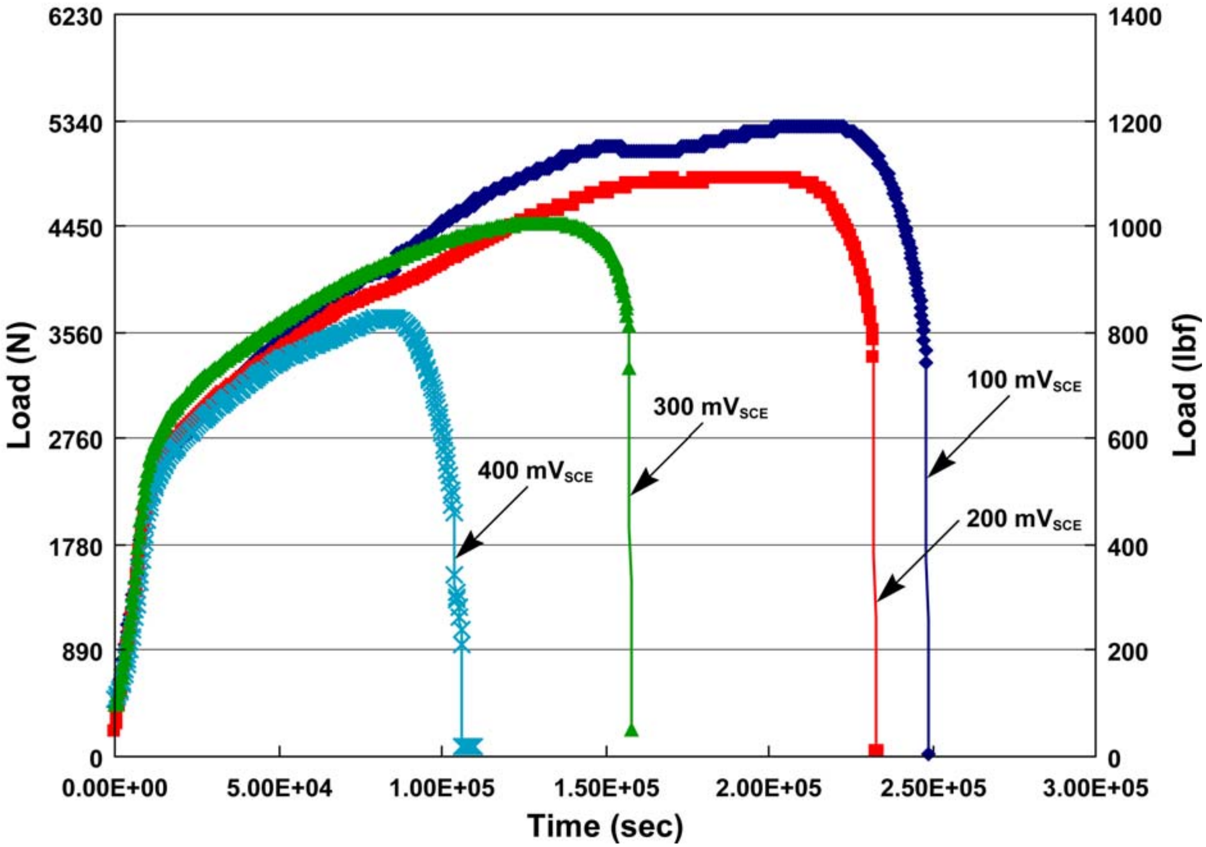
Effect of Electrochemical Potential

Mill-Annealed Alloy 22 at 95°C [203 °F], SSRTs at 3.2×10^{-6}/s
1.1 m HCO_3^- and 7.2 m Cl^- Solution



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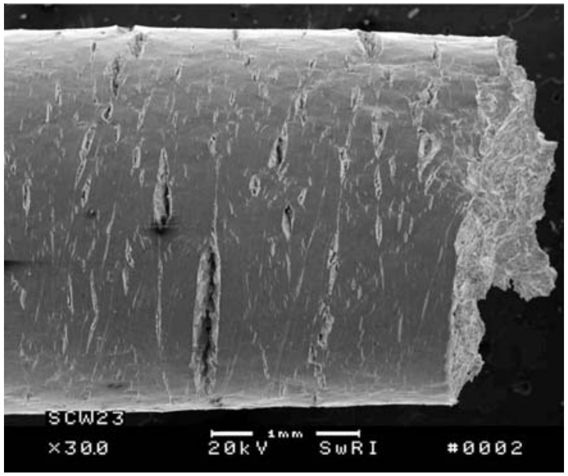
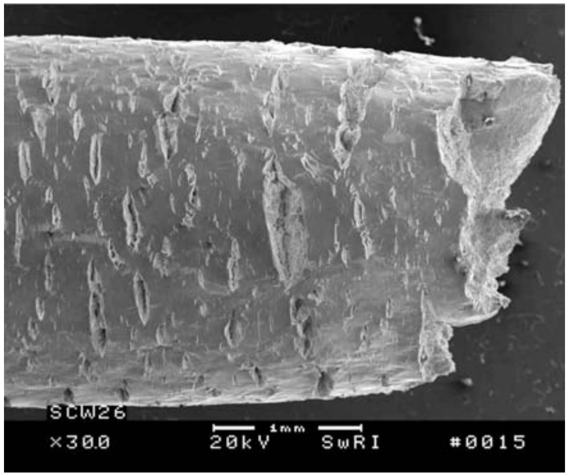
- Susceptibility of Alloy 22 to SCC Decreased with Decreasing Electrochemical Potential

Fracture End of Alloy 22 in 1.1 m HCO_3^- and 7.2 m Cl^- Solution at Various Electrochemical Potentials

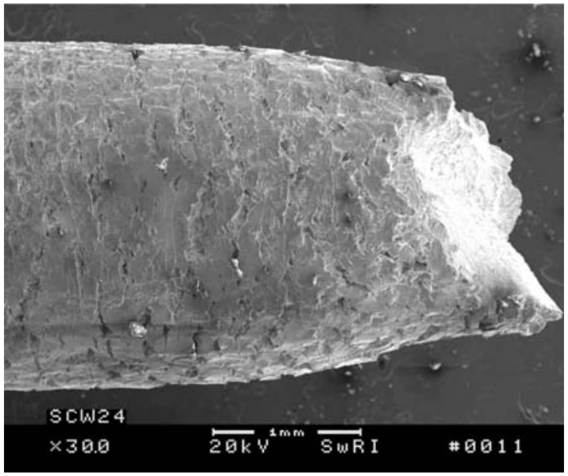
400 mV_{SCE}

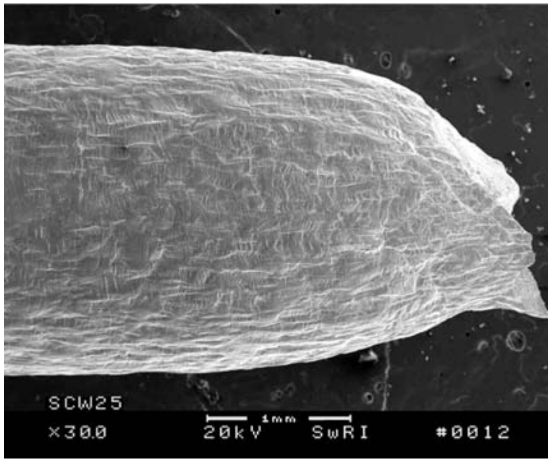




300 mV_{SCE}

200 mV_{SCE}

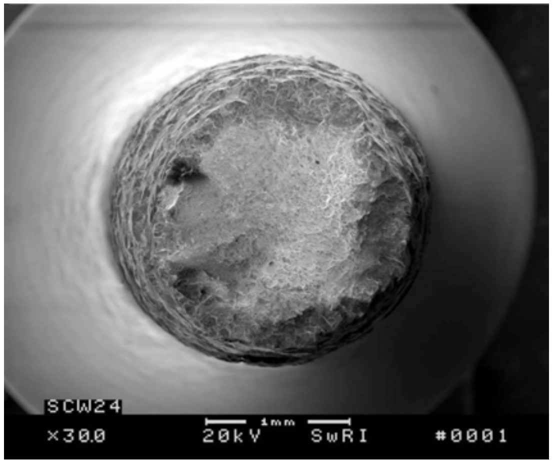


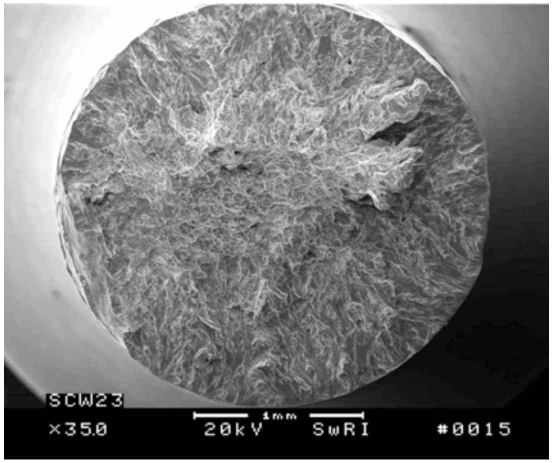


100 mV_{SCE}

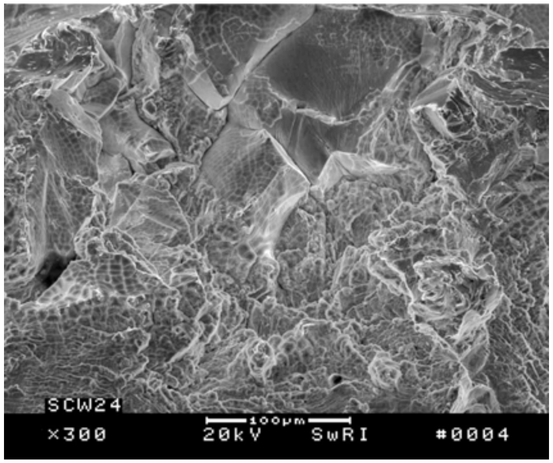
Fracture Surface of Alloy 22 Strained in 1.1 m HCO_3^- and 7.2 m Cl^- Solution

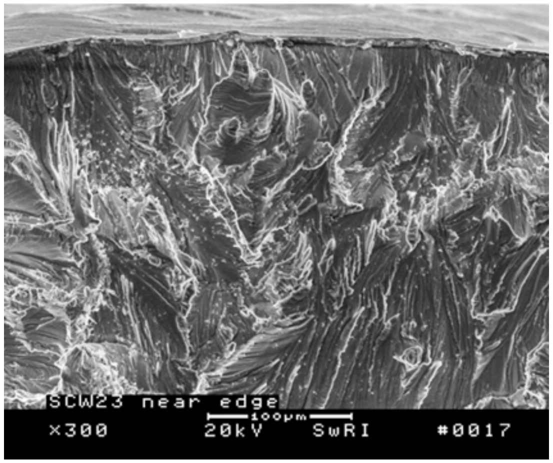
200 mV_{SCE}





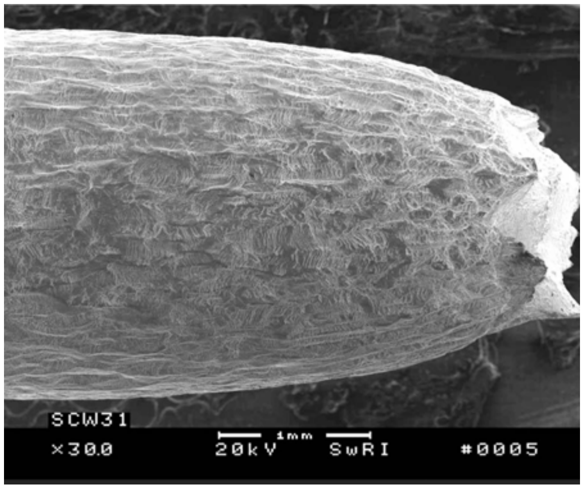
400 mV_{SCE}

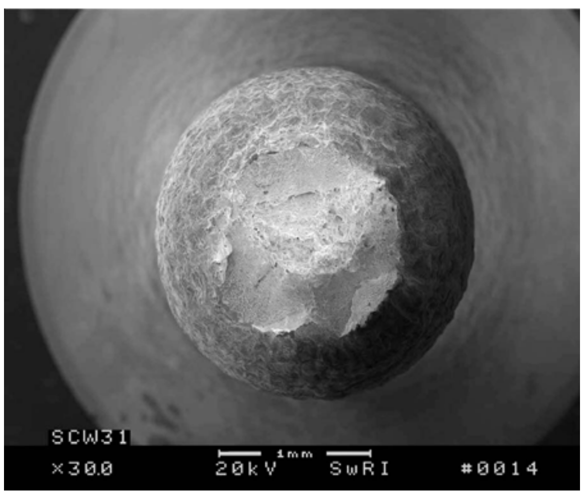




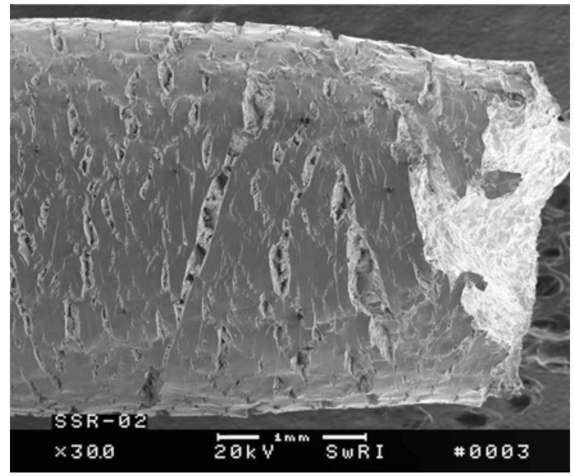
Fracture Surface of Alloy 22 Strained in Simulated Concentrated Water

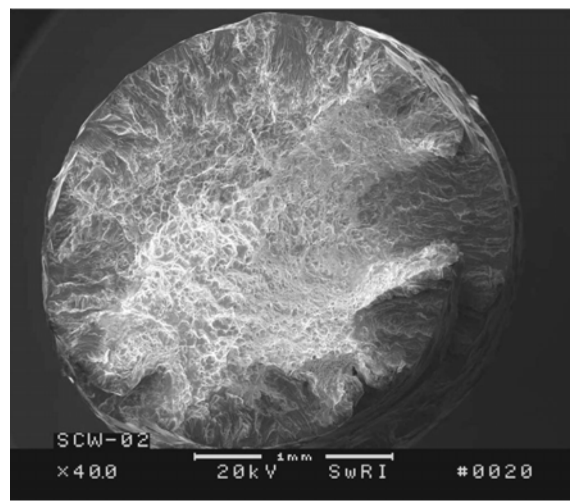
200 mV_{SCE}





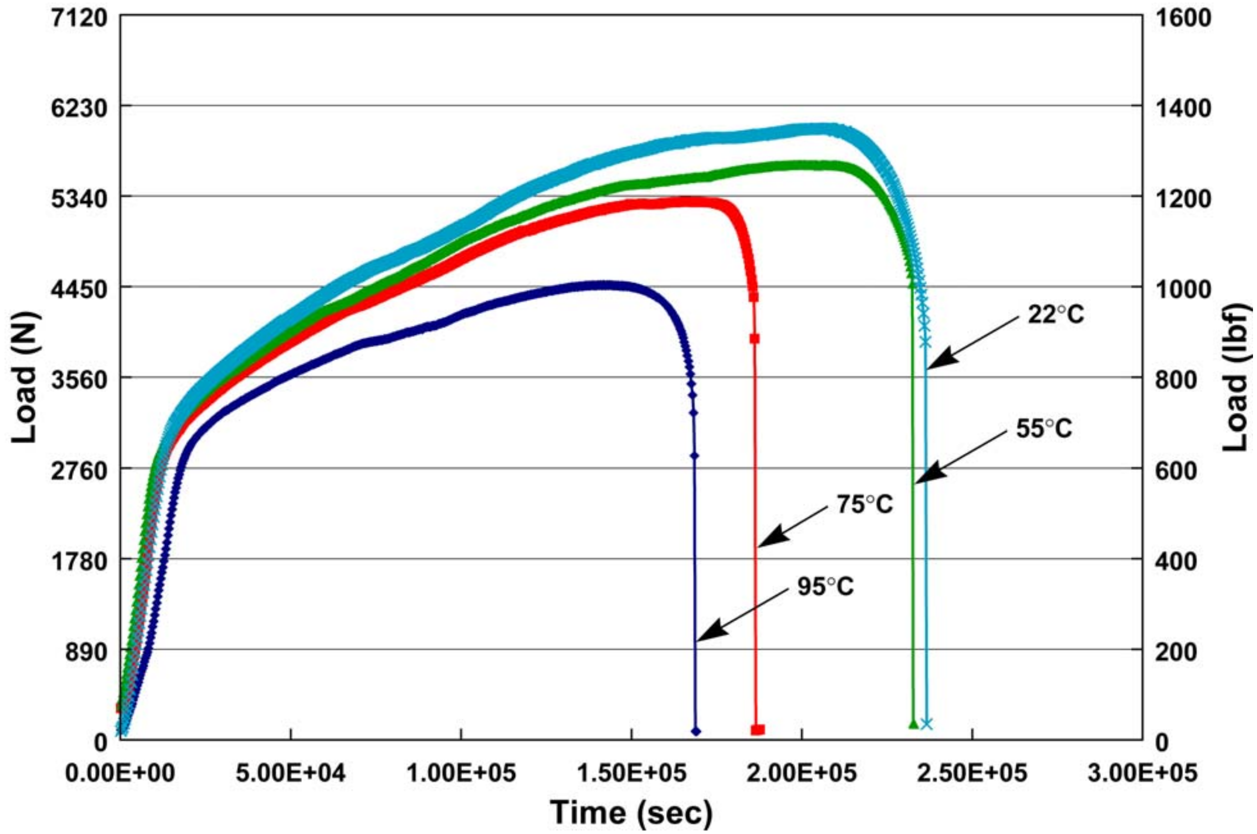
400 mV_{SCE}





Effect of Solution Temperature

Mill-Annealed Alloy 22 at 400 mV_{SCE}, SSRT at 3.2×10^{-6}/s
1.1 m HCO_3^- and 2.2 m Cl^- Solution



- Susceptibility of Alloy 22 to SCC Decreased with Decreasing Temperature

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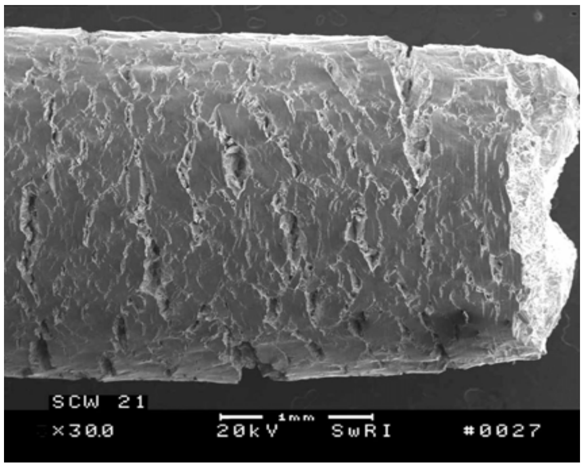
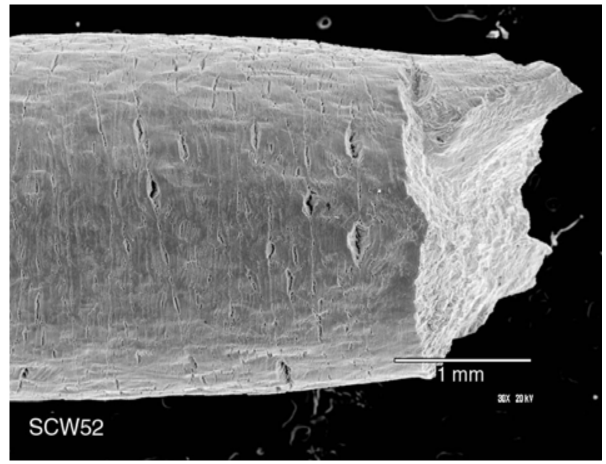
Fracture End of Alloy 22 in 1.1 m HCO_3^- Solution Containing 2.2 m Cl^- at Various Temperatures

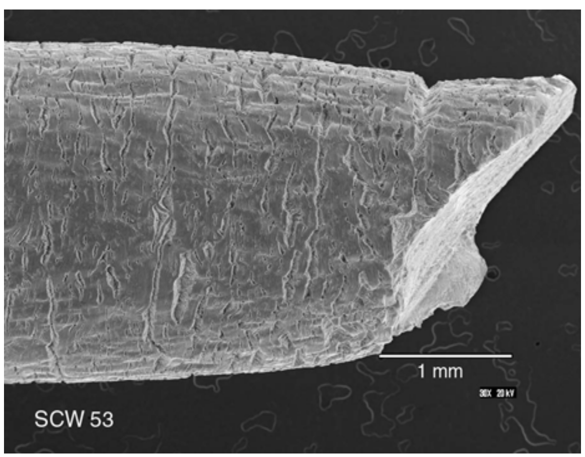
95°C
[203°F]

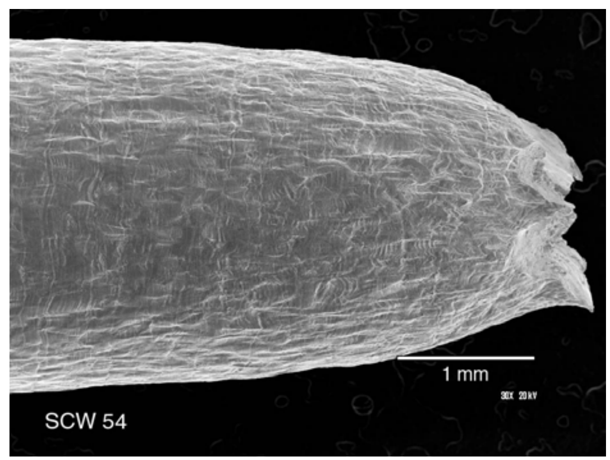




75°C
[167°F]

55°C
[131°F]





22°C
[72°F]

Summary and Conclusions

- Transgranular SCC of Alloy 22 Was Observed in SCW and Its Variations at 95°C [203°F] and a High Anodic Potential of 400 mV_{SCE} Using SSRTs
- Two Major Anionic Constituents of SCW, HCO_3^- and Cl^- Ions Act Synergistically to Promote SCC in SCW
- For SCW and Its Variations Containing HCO_3^-, and Cl^- Ions, the SCC Susceptibility of Alloy 22 Is Strongly Dependent Upon Applied Electrochemical Potentials
  - For SCW, the transition from no cracking to transgranular SCC occurs between 200 and 400 mV_{SCE}
  - For a 1.1 m HCO_3^- and 7.2 m Cl^- solution, the transition occurs between 100 and 200 mV_{SCE}
- At an Applied Potential of 400 mV_{SCE}, the Susceptibility of Alloy 22 to SCC in HCO_3^- and Cl^- Solutions Decreases as Temperature Decreases, and No SCC Was Observed at Room Temperature

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