TECHNICAL BULLETIN

INCOLOY® ALLOY 945X®: HIGH STRENGTH AND CORROSION RESISTANCE FOR YOUR MOST CHALLENGING APPLICATIONS

SPECIAL METALS
A PCC COMPANY

INCOLOY®ALLOY 945X®

INCOLOY® alloy 945X® (UNS N09946) is an age hardenable nickel-iron-chromium alloy with additions of molybdenum, copper, niobium, titanium, and aluminum. The alloy chemical composition, listed in Table 1, is designed to provide a combination of high strength and excellent corrosion resistance. The nickel content is sufficient to provide protection against chloride-ion stress corrosion cracking. The nickel, in conjunction with the molybdenum and copper, also gives outstanding general corrosion resistance to reducing chemicals. The molybdenum aids resistance to pitting and crevice corrosion. The alloy's high chromium content provides resistance to oxidizing environments. The niobium, titanium and aluminum are added to provide high volume fraction of sub-micron size uniformly distributed $Ni_3(NbTiAl)$-type gamma prime and $Ni_3(TiNbAl)$-type gamma double prime precipitates. Their precipitates are responsible for high strength of the alloy by virtue of a dispersion strengthening mechanism. A special precipitation hardening (age hardening) heat treatment is developed to provide required strength.

INCOLOY® alloy 945X® is suitable for various applications requiring a combination of high strength and corrosion resistance. Because of the alloy's resistance to sulfide stress corrosion cracking and stress corrosion cracking in H_2S containing environments, the alloy has been used in oil and natural gas components for down-hole and surface gas-well including SSSV, MWE/LWD tools, liner hangers, packers, components for BOPs and more. One of the primary uses of alloy 945X® is OCTG and coupling stock. Further, the alloy is suitable to use in landing nipples, tool joints, gas lift, fasteners, pump shafting and high strength piping systems.

Based on extensive corrosion testing, INCOLOY® alloy 945X® has been incorporated in NACE MR0175 / ISO-15156-3 for up to NACE level VII at max hardness level of 42Rc.

Table 1: Limiting chemical composition (UNS N09946) of INCOLOY® alloy 945X® , wt%.

Nickel	50.0– 55.0
Chromium	19.5-22.5
Iron	Balance
Molybdenum	3.0 – 4.0
Niobium	3.5– 4.5
Copper	1.5 – 3.0
Titanium	0.5 – 2.5
Aluminum	0.01 – 0.7
Manganese	1.0 max
Silicon	0.5 max
Sulfur	0.03 max
Phosphorous	0.03 max
Carbon	0.005 to 0.030

PHYSICAL PROPERTIES

Some physical properties of INCOLOY® alloy 945X® can be seen in Table 2. The valves shown in this table are based on room temperatures except for the melting range value. Tables 3 and 4 provide co-efficient of expansion and specific heat data over a range of temperatures. Thermal conductivity and modulus of elasticity over range of temperatures can be seen in Tables 5 and 6.

Table 2: Physical Properties of INCOLOY® alloy 945X®

Density,	lbs/in^3 g/cm^3	0.298 8.265
Melting Range,	°F °C	2323 - 2424 1273 - 1329
Electrical Resistivity,	ohm.cmil/ft	682 MΩ-m 1.10
Permeability at 200 oersteds (15.9 kA/m)		= 1.002
Young's Modulus,	10^6psi GPa	29.4 202.7

Table 3: Coefficient of thermal expansion. The values show mean coefficient of liner expansion between 77°F (25°C) and the listed temperature.

Temperature		Coefficient of Thermal Expansion	
°F	°C	in/in/°F x 10^{-6}	cm/cm/°C x 10^{-6}
200	93	7 46	13 43
300	149	7 62	13 72
400	204	7 69	13 84
500	260	7 82	14 08
600	316	7 90	14 22
700	371	8 00	14 40
800	427	8 09	14 56
900	482	8 18	14 72
1000	538	8 28	14 90
1100	593	8 44	15 19
1200	649	8 60	15 48
1300	704	8 80	15 84
1400	760	9 04	16 27
1500	816	9 29	16 72
1600	871	9 48	17 06

4:

Temperature		Specific Heat	
°F	°C	Btu/lb-°F	J /Kg-°C
70	21	0 104	436
200	93	0 108	452
300	149	0 110	461
400	204	0 113	473
500	260	0 115	482
600	316	0 117	490
700	371	0 119	498
800	427	0 121	507
900	482	0 123	515
1000	538	0 128	536
1100	593	0 139	582
1200	649	0 139	582
1300	704	0 154	645
1400	760	0 176	737
1500	816	0 179	750
1600	871	0 183	766
1700	927	0 146	611
1800	982	0 146	611
1900	1038	0 146	611
2000	1093	0 152	637
2100	1149	0 154	645

5:

Temperature		Thermal Conductivity	
°F	°C	BTU-in/ft²-h- °F	W/m-°C
70	21	74	10 6
200	93	81	11 7
400	204	94	13 5
600	316	105	15 1
800	427	116	16 7
1000	538	128	18 5
1200	649	147	21 2
1400	760	151	21 8
1600	871	158	22 6
1800	982	162	23 4
2000	1093	176	25 4

6:

Temperature		Young's Modulus	
°F	°C	10^3ksi	GPa
70	24	29 43	203
200	93	29 15	201
300	149	28 67	198
400	204	28 53	197
500	260	27 72	191
600	316	27 32	188
700	371	26 85	185
800	427	26 33	182
900	482	25 98	179
1000	538	25 42	175
1100	593	24 92	172
1200	649	24 40	168
1300	704	23 84	164
1400	760	23 27	161

MECHANICAL PROPERTIES

Alloy 945X® is supplied in the form of rod, tube and wire. Annealing and age hardening parameters are given below.

Annealing
1850°F-1950°F (1010°C-1066°C) for ½ hour to 4 hours, water quench.

Age Hardening
1300°F-1350°F (704°C-732°C) / 6-8 hours, furnace cool 50°F-100°F (26-56 °C) / h to 1125°F -1175°F (607°C – 635°C), hold at this temperature for 6-8 hours, air cool.

Alloy 945X® can easily be made to ultra large rod of diameters up to 22 inch (560 mm). Table 7 shows properties of a 22-inch (560 mm) diameter rod at center, mid-radius and near-edge. Figure 2 shows this 22-inch (560 mm) rod weighing over 11,000 lbs (5000 Kg) and a macro-etched quarter of it showing a rather homogenous material. The de-rating factor, drop in yield strength at high temperature, is an important parameter as materials in O&G wells are used at elevated temperatures. Table 8 and 9 shows de-rating factors of alloy 945X® rods product. Different diameter heats were picked up from mill production and tested at different temperatures. Table 10 shows de-rating factor for tubing and Table 11 shows tensile versus compressive yield strength of tubing from room temperature to 550ºF (288ºC).

1 945

7: 22- 560

- - -75°

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Test loc	YS, ksi (MPa)	UTS, ksi (MPa)	% El	% RA	Impact, Strength ft-lbs (Joules)	120 - Hardness range, Rc	Grain Size, ASTM #
	157 5 1086	187 2 1291	23 3	41 2		38 – 41 2	3 5
-	164 6 1135	187 4 1291	21 1	37 4	47 64		2 5
	164 1 1132	190 0 1310	19 6	37 1			2

2 22- 560 11000 5000

-

3 945

8: -

Heat/lot	Size, inches	Test temp	Yield strength, ksi	Tensile strength, ksi	% El	% RA
1 3755 - 16	9 5		164 0	195 0	21 5	26 3
		300	148 2	174 5	17 3	29 3
		350	150 5	174 2	17 7	30 1
		400	144 8	170 1	19 3	35 7
		450	144 4	175 5	25 0	78 9
		500	144 7	166 6	19 5	34 2
2 0035 - 13	3 5		148 7	183 0	34 0	53 0
		300	134 8	175 1	27 5	50 2
		350	129 3	159 9	31 4	55 5
		400	134 3	167 7	28 3	55 4
		450	131 1	159 7	28 9	59 2
		500	134 5	167 7	29 9	56 1
3 3755 - 15	7 5		160 8	187 3	23 7	31 2
		250	147 6	182 2	21 0	36 0
		350	147 9	172 8	20 8	31 6
		450	143 1	169 5	22 7	34 9
4 3755 - 14	8		157 7	185 7	23 6	45 1
		300	144 8	168 8	27 0	49 0
		350	144 8	168 8	26 2	49 1
		400	143 5	166 9	25 0	49 0
		450	151 4	180 6	24 0	47 8

9: - 500 260

Rod dia., inches (mm)	Heat	RT, ksi	300ºF (149ºC)	350ºF (177ºC)	400ºF (204ºC)	450ºF (232ºC)	500ºF (260ºC)
9 5	1	164 0	148 2 0 90	150 5 0 92	144 8 0 88	144 4 0 88	144 7 0 88
3 5	2	148 7	134 8 0 91	129 3 0 87	134 3 0 90	131 1 0 88	134 5 0 91
7 5	3	160 8		147 9 0 92		143 1 0 89	
8	4	157 7	144 8 0 92	144 8 0 92	143 5 0 91		
			0 91	0 91	0 90	0 88	0 90

10: - 3 5- 89
0 449- 11 4

Heat number	RT, ksi	350ºF (177ºC), ksi	450ºF (232ºC), ksi	550ºF (288ºC), ksi
5167	171 4	158 6 0 93	152 0 0 89	150 6 0 88
5115	166 6	155 9 0 94	151 1 0 91	150 9 0 91
5158	161 5	159 9 0 99	149 0 0 92	144 5 0 90
5117	165 2	158 4 0 96	154 7 0 94	151 2 0 92
5168	164 3	152 6 0 93	149 8 0 91	147 9 0 90
5154	160 8	151 5 0 94	148 7 0 93	148 1 0 92
	-	0 95	0 92	0 91

11: 945
3 5- 89 0 449- 11 4
550 288
- -

S. No	Heat # / piece #	Temperature	Compressive YS, ksi	Tensile YS, ksi	Compressive / tensile
1	5167-2		177 5	171 4	1 04
		350 177	171 7	158 6	1 08
		450 232	168 4	152 0	1 11
		550 288	164 6	150 6	1 10
2	5115-3		176 9	166 6	1 06
		350 177	166 5	155 9	1 08
		450 232	163 5	151 1	1 08
		550 288	161 9	150 9	1 07
3	5158-2		173 4	161 5	1 08
		350 177	164 9	159 9	1 03
		450 232	160 1	149 0	1 08
		550 288	159 1	144 5	1 10
4	5117-2		178 6	165 2	1 10
		350 177	174 1	158 4	1 08
		450 232	164 3	154 7	1 10
		550 288	161 1	151 2	1 06
5	5168-2		175 6	164 3	1 07
		350 177	165 4	152 6	1 08
		450 232	163 2	149 8	1 09
		550 288	161 7	147 9	1 09
6	5154-2		172 3	160 8	1 07
		350 177	163 4	151 5	1 08
		450 232	161 0	148 7	1 08
		550 288	160 5	148 1	1 08

Fracture Mechanics Properties

Table 12 shows yield strength of alloy 945X® at various temperatures. This heat was used to evaluate fracture mechanics properties. De-rating factor at a temperature is determined by dividing yield strength at temperature by yield strength at room temperature. Table 13 shows fracture toughness, KJIC in C-R orientation. Tests were done using compact tension samples in lab air at various temperatures. Strain controlled low cycle fatigue (LCF) test were done at 450°F (232°C) as per ASTM E606-4. A sinusoidal waveform at a frequency of 10 CPM was used. R-ratio for all was -1.

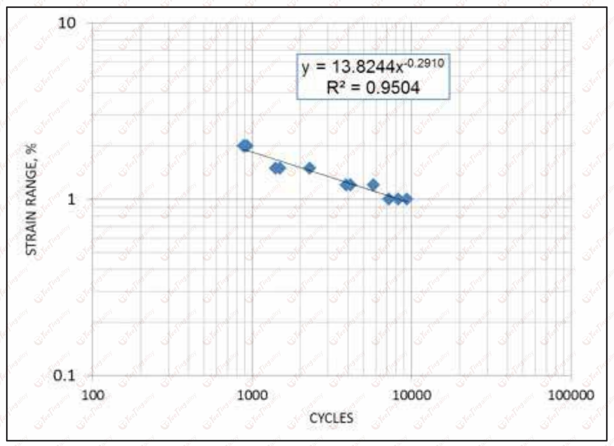
Table 12: Yield strength of alloy 945X® at various temperatures. Listed values represent averages of 3 tests.

S. No	Test Temperature	Yield strength, ksi (MPa)	De-rating Factor
1		151 3 1043	-
2	200° 93°	145 0 1000	0 96
3	300° 149°	145 0 1000	0 96
4	400° 204°	138 8 952	0 92
5	450° 232°	138 8 952	0 92

13 -

S. No	Test Temperature	Fracture Toughness values, ksi √in	Average Fracture Toughness values, ksi √in
1		221 / 209	215
2	200° 93°	228 / 237 / 238	234
3	300° 149°	224 / 233 / 240	232
4	400° 204°	222 / 227 / 235	228
5	450° 232°	201 / 207 / 210	206

4: 450° 232°
606-4
10 - -1



CORROSION RESISTANCE

Concentrations of Nickel, Chromium, Molybdenum, and Copper are optimized to provide excellent corrosion resistance in oil and gas environments for Galvanically - Induced Hydrogen Stress Cracking (GHSC), Sulfide Stress Cracking (SSC), and Stress Corrosion Cracking (SCC). Corrosion resistance of INCOLOY alloy 945X® under these types of corrosion mechanisms is illustrated by the tests below.

NACE Qualification testing

Extensive testing was conducted to obtain NACE MR0175/ ISO 15156-3:2009 approval for UNS N99046, alloy 945X.

Table 14 lists mechanical properties of 3 commercial heats used for testing in NACE MR0175 / ISO 15156 - 3 for levels VII and level VI-450ºF (232ºC). Test results of triplicate samples from these 3 heats are given in tables 15 and 16 respectively. Tests were conducted in accordance with NACE TM0177-2004, method C - C-Ring tests. The dimensions of the samples were: 2 inch (51 mm) OD, 0.15-inch (3.8 mm) wall thickness, 0.95-inch (24.1 mm) width. The results are based on 20X visual observations. Photographs showing C-rings exposed to level VII and level VI-450ºF are shown in Figure 4 and 5 respectively. Test results for GHSC and SSC
are given in Table 17. Samples were nominally of gauge diameter 0.25 inch (6.34 mm) and gauge length 1 inch (25.4 mm). The results are based on 30X visual observations.

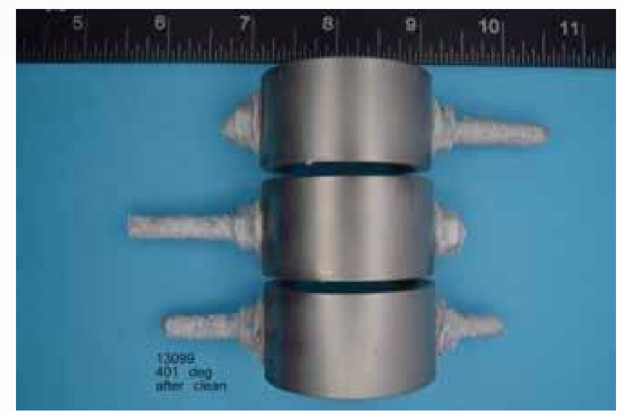
Table 14 lists mechanical properties of the heats used for SCC, SSC and GHSC. YS, UTS, El and RA stand for yield strength, tensile strength, elongation, and reduction-of-area respectively.

Heat No.	Rod dia., in. (mm)	YS ksi (MPa)	UTS, ksi (MPa)	El (%)	RA (%)	Average impact lf-lbs (Joules)	Hard-ness, Rc
4057 -13	5 1 130	164 1 1131	197 9 1358	25 0	48 8	71 7 97	44
4571 -12	8 203	167 1 1152	200 0 1379	23 3	43 3	41 2 56	46
4571 -13	10 254	166 4 1147	200 0 1379	22 4	38 5	34 8 47	44

Table 15: C-ring test results in NACE level VII. The environmental conditions are as follows: 3.5 MPa (500 psia) H_2S, 3.5 MPa (500 psia) CO_2, 25 wt% (180,000 mg/L Cl) NaCl, at 205°C (401°F). The applied stress was 100% of the actual yield stress at temperature.

Sample	Applied Stress at 205°C (401°F), ksi (MPa)	Results
4057 -13 1	145 8 1005	90
4057 -13 2	145 8 1005	90
4057 -13 3	145 8 1005	90
4571 -12 1	150 0 1034	90
4571 -12 2	150 0 1034	90
4571 -12 3	150 0 1034	90
4571 -13 1	149 4 1030	90
4571 -13 2	149 4 1030	90
4571 -3 3	149 4 1030	90

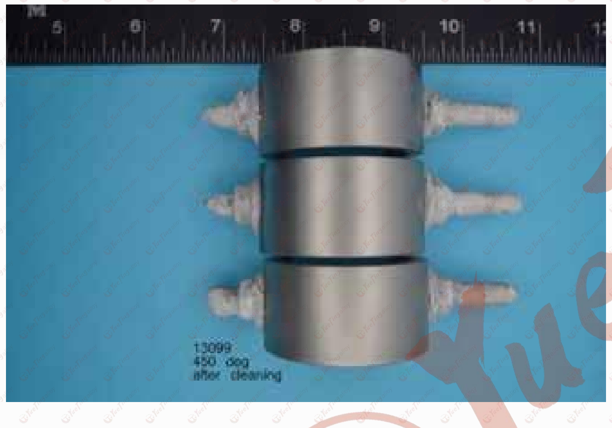
5: - 90 180 000
/ 500 3 5 2 500 3 5 2 401° 205°



16: - -450° 232°
:3 5 500
2 3 5 500 2 20 % 139 000 /
232° 450° 100%

Sample	Applied Stress, ksi (MPa) at 232°C (450°F)	Results
4057 -13 1	145 9 1006	90
4057 -13 2	145 9 1006	90
4057 -13 3	145 9 1006	90
4571 -12 1	151 9 1047	90
4571 -12 2	151 9 1047	90
4571 -12 3	151 9 1047	90
4571 -13 1	148 9 1027	90
4571 -13 2	148 9 1027	90
4571 -13 3	148 9 1027	90

6: - 90 139 000
/ 500 3 5 2 500 3 5 2 450° 232°



17:
0177-2004 - Ψ
90%

Sample	Applied Stress	Steel Coupled		Results
4057 -13 1	147 7			30
4057 -13 2	147 7			30
4057 -13 3	147 7			30
4571 -12 1	150 4			30
4571 -12 2	150 4			30
4571 -12 3	150 4			30
4571 -13 1	149 8			30
4571 -13 2	149 8			30
4571 -13 3	149 8			30

Ψ The composition of NACE solution A is 5% NaCl plus 0.5% glacial aceticacid in distilled or ionized water. As per the NACE standard, tests were carried out at room temperature (24°C, 75°F) at H2S pressure of 100 kPa. Start and finish pH of the solution was 2.7 and 3.6 respectively.

Testing in Sour Sulfur Containing Environment

18 3
3
300° 149° 350° 177° 90
100% 1100 7 7
2 600 4 2 2 125 000 / 5-
/
120
1
95047 17
1 - :2
51 0 15- 3 8 0 95- 24 1
20 19
20 300° 149° 350° 177°
7 350° 177° - -
7
- - -
21
0177-2004 -
Ψ
90%

18:
- -

Heat No.	Rod dia., inches (mm)	YS ksi (MPa)	UTS, ksi (MPa)	El (%	RA (%)	Average impact lf-lbs (Joules)	Hard-ness, Rc
4154 -12	6 5 165	146 6 1011	179 3 1236	26 9	51 6	70 9 96	41
3888 -11	6 5 165	147 5 1017	181 6 1252	26 0	44 6	61 2 83	41
4040 -11	10 254	152 4 1051	180 6 1252	26 6	50 6	79 0 107	42

19: - 300° 149° 90 100%
1100 7 7
2 600 4 2 125 000 /

Sample	Applied stress 300°F (149°C)	Results
4154 -12 1	138 5	90
4154 -12 2	138 5	90
4154 -12 3	138 5	90
3888 -11 1	141 4	90
3888 -11 2	141 4	90
3888 -11 3	141 4	90
4040 -11 1	143 9	90
4040 -11 2	143 9	90
4040 -11 3	143 9	90

20: - 350° 177° 90 100%
1100 7 7 2 600 4 2 2
125 000 /

Sample	Applied stress 350°F (177°C	Results
4154 -12 1	133 4	90
4154 -12 2	133 4	90
4154 -12 3	133 4	90
3888 -11 1	134 2	90
3888 -11 2	134 2	90
3888 -11 3	134 2	90
4040 -11 1	138 7	90
4040 -11 2	138 7	90
4040 -11 3	138 7	90

7: - 350°
177° 90 100%
1100 77 2 600 42 2 125 000 /
- -

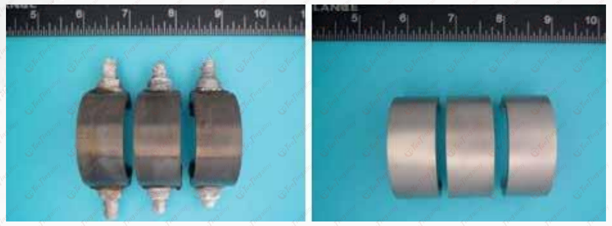


Table 21: Testing for GHSC and SSC were done in accordance with TM0177-2004, method A - Tensile test, in NACE solution AΨ. One set of samples was coupled to steel via the stressing bolt and other set were tested without steel coupling. Applied stress was 90% of actual yield strength.

Sample	Applied Stress	Steel Coupled		Results
4154 -12 1	146 6			30
4154 -12 2	146 6			30
4154 -12 3	146 6			30
3888 -11 1	147 5			30
3888 -11 2	147 5			30
3888 -11 3	147 5			30
4040 -11 1	152 4			30
4040 -11 2	152 4			30
4040 -11 3	152 4			30

Ψ 5% 0 5%
24° 75° 2 100
27 36

Slow Strain Rate Testing (SSRT)

SSRT of alloy 945X® rod and tubular products were done in level VII as per TM0198-2004. Mechanical properties of the rod and tubular tested are given in Table 22. Results are listed in Tables 23 to 26. It should be mentioned that SSRT is used for Ni-base precipitation strengthened alloys to evaluate relative performance, no pass / fail criteria is established for these materials.

Table 22: Mechanical properties of the materials on which slow strain rate tests were done as per NACE TM0198-2004. The YS, UTS, El and RA denote yield strength, tensile stress, elongation and reduction-of-area respectively. Impact toughness was tested in transverse orientation at -75°F (-59°C).

Rod/Tube Size, inches (mm)	YS, ksi (MPa)	UTS, ksi (MPa)	% El	% RA	Impact, ft-lbs (Joules)	Max Hard-ness, Rc	Grain Size, ASTM #
3 5 90	146 5 1010	177 4 1223	29 4	52 5	66 6 90	41 1	3
10 254	160 0 1103	184 8 1274	23 9	47 4	57 7 78	41 3	3
4 2 107 0 9 23	168 7 1163	193 6 1335	22 6	48 5	51 5 70 0	44 3	5 5

Table 23: Slow strain rate (SSRT) testing of 3.50-inch (90 mm) rod of alloy 945X® in NACE MR0175 / ISO 15156-3 level VII in accordance with TM0177-2004, method A. The environment was 3500 kPa (500 psia) H_2S, 3500 kPa (500 psia) CO_2, 25 wt% (180,000 mg/L Cl) NaCl, at 205°C (400°F) at strain rate of 4 x 10^{-6} in/in/sec. Samples were nominally of diameter 0.15 inch (3.8 mm) and gauge length 1 inch (25.4 mm). TTF, El, RA, Env and Avg denote time-to-failure, elongation, tensile stress, reduction-of-area, environment and average respectively.

Test	TTF (h)	TTF Ratio	% El	% El Ratio	% RA	% RA Ratio	Secondary Cracking
	17 8	-	25 6	-	51 6	-	-
	15 9	-	22 9	-	51 3	-	-
	16 9	-	24 3	-	51 5	-	-
	12 8	0 76	18 4	0 76	36 7	0 71	
	14 7	0 87	21 2	0 87	36 4	0 71	
	12 9	0 77	18 6	0 77	36 6	0 71	
	-	0 80	-	0 80	-	0 71	-

Table 24: Slow strain rate (SSRT) testing of 10-inch (254 mm) rod of alloy 945X® in NACE MR0175 / ISO 15156-3 level VII in accordance with TM0177-2004, method A. The environment was 3500 kPa (500 psia) H_2S, 3500 kPa (500 psia) CO_2, 25 wt% (180,000 mg/L Cl) NaCl, at 205°C (400°F) at strain rate of 4 x 10^{-6} in/in/sec. Samples were nominally of diameter 0.15 inch (3.8 mm) and gauge length 1 inch (25.4 mm). TTF, El, RA, Env and Avg denote time-to-failure, elongation, tensile stress, reduction-of-area, environment and average respectively.

Test	TTF (h)	TTF Ratio	% El	% EL Ratio	% RA	% RA Ratio	Secondary Cracking
	16 8	-	24 2	-	44 6	-	-
	15 0	-	21 6	-	47 9	-	-
	15 9	-	22 9	-	46 3	-	-
	14 6	0 92	21 0	0 92	33 0	0 71	
	12 6	0 79	18 4	0 80	36 2	0 78	
	13 1	0 75	17 3	0 76	36 4	0 79	
	-	0 82	-	0 83	-	0 76	-

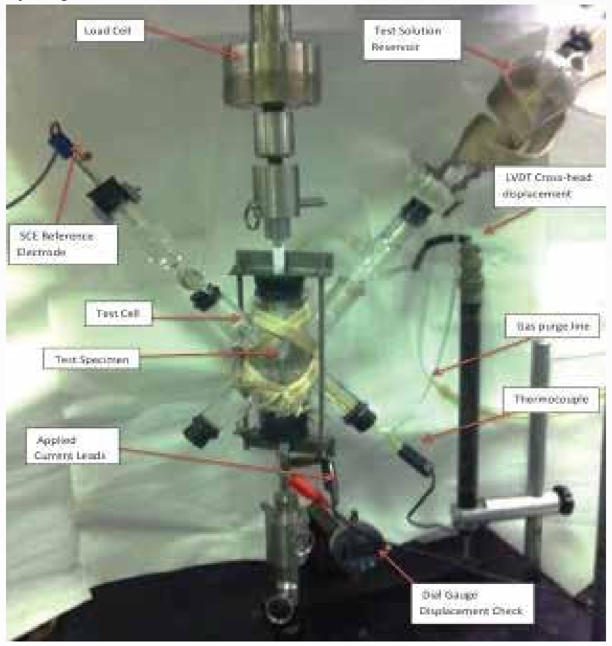
Table 25: Slow strain rate (SSRT) testing of 168.7 ksi yield strength mechanical tube of alloy 945X® of OD 4.20" (107 mm) and wall thickness 0.90" (23 mm) in NACE MR0175 / ISO 15156-3 level VII in accordance with TM0177-2004, method A. The rest of the mechanical properties are listed in Table 10. The environment was 3500 kPa (500 psia) H_2S, 3500 kPa (500 psia) CO_2, 25 wt% (180,000 mg/L Cl) NaCl, at 205°C (400°F) at strain rate of 4 x 10^{-6} in/in/sec. Samples were nominally of diameter 0.15 inch (3.8 mm) and gauge length 1 inch (25.4 mm). TTF, El, RA, Env and Avg denote time-to-failure, elongation, reduction-of-area, environment and average respectively.

Test	TTF (h)	TTF Ratio	% El	% EL Ratio	% RA	% RA Ratio	Secondary Cracking
	15 7	-	17 9	-	53 0	-	-
	12 3	-	13 6	-	51 8	-	-
	13 1	-	14 5	-	51 9	-	-
	13 7	-	15 3	-		-	-
	13 4	0 98	14 3	0 93	41 8	0 80	
	15 7	1 15	17 7	1 15	43 8	0 84	
	14 7	1 07	16 0	1 04	41 8	0 80	
	-	1 07	-	1 04	-	0 81	-

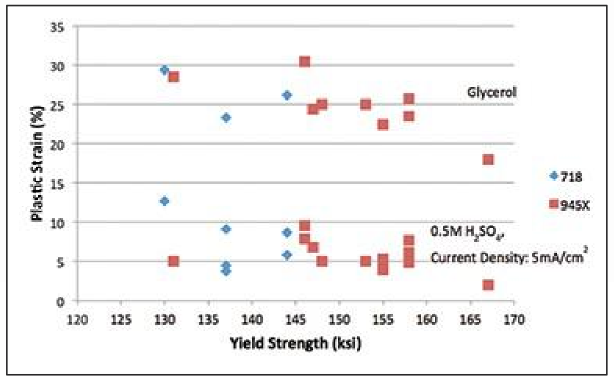
Hydrogen Embrittlement

Materials in O&G wells are prone to hydrogen embrittlement. To evaluate hydrogen embrittlement resistance, tests were done using a specially designed apparatus shown in Figure 8. SSRT sub-size samples were used as per NACE TM0198. In a dearated solution of 0.5M H_2SO_4 at 40°C (104°F), a current density of 5mA/cm^2 was applied at strain rate 10^{-6} s^{-1}. Figure 9 shows plastic strains of alloy 945X® and 718 in glycerol and in the listed environment and Figure 10 shows plastic strain ratio of alloy 945X® and 718. These ratios are obtained by dividing plastic strain in environment by plastic strain in glycerol. It shows that both alloys have comparable hydrogen embrittlement resistance. Further, higher yield strength tends to lower hydrogen embrittlement resistance.

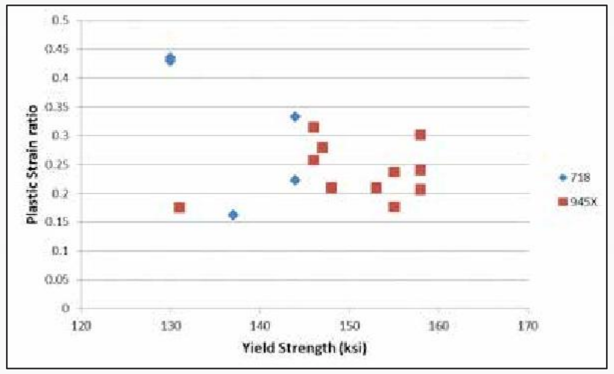
Figure 8: A specially designed apparatus used to evaluate hydrogen embrittlement resistance.



9 945 718



10 945 718



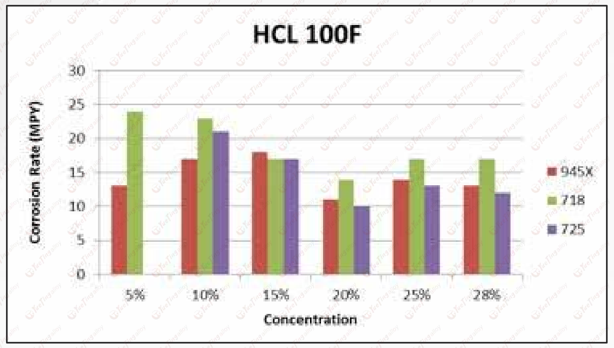
Corrosion in Aqueous Acidic Media

Materials used in petrochemical industries are tested in various acidic media to evaluate their corrosion resistance. Commercial alloys 945X®, 718 and 725 were tested at different temperatures for various concentrations of hydrochloric acid, acetic acid and formic acid for 5 days, and weight loss was monitored. Mechanical properties of tested heats are given in Table 26. Weight loss for hydrochloric acid concentrations of 5%, 10%, 15%, 20% and 25% at 100°F (38°C), 190°F (88°C) and 300°F (149°C) are shown in Figures 11 to 13 respectively. Acetic acid concentrations of 5% and 9% at temperatures 100°F (38°C), 190°F (88°C) and 300°F (149°C) did not show any weight loss for all these alloys. Similarly, formic acid concentrations of 2% and 4% did not show any detectable weight loss at temperatures 190°F (88°C) and 300°F (149°C).

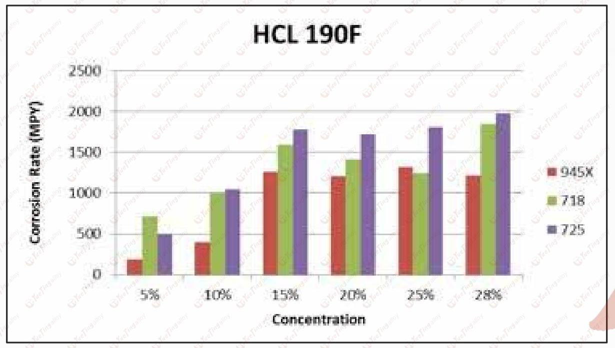
Table 26: Mechanical properties of the materials on which acidic media corrosion tests were done. The YS, UTS, El and RA denote yield strength, tensile stress, elongation and reduction-of-area respectively. Impact toughness was tested in transverse orientation at -75°F (-59°C).

Alloy/rod dia, inch (mm)	YS, ksi (MPa)	UTS, ksi (MPa)	% El	% RA	Impact, ft-lbs (Joules)	Max Hard-ness, Rc	Grain Size, ASTM #
945 6 152	159 3 1098	183 6 1266	23 0	41 9	46 6 63 2	42	2 5
718 7 178	129 2 891	174 7 1205	28 8	44 2	61 3 83 1	37 9	4
725 1 25 32	141 0 972	186 8 1288	28 0	41 6	53 8 73 0	39 8	3

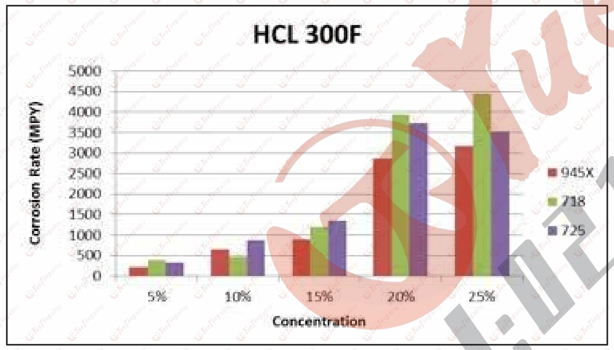
11: 945 718 725
100° 38°



12: 945 718 725
190° 88°



13: 945 718 725
300° 149°



Resistance to Localized Corrosion

Acid - halide conditions such as those commonly encountered in oil and gas service tend to induce localized corrosion of nickel alloy and stainless steel components. Pitting and crevice corrosion are especially damaging as they can cause perforation in a very short period of time. So, while equipment may appear to be undamaged as there is no loss of material by general corrosion, leaks can occur due to this very aggressive form of attack. NiCrMo and FeNiCrMo materials have been shown to demonstrate resistance
to localized attack. By virtue of its contents of chromium and molybdenum, alloy 945X® offers good resistance. The resistance of an alloy to localized attack can be estimated by its pitting resistance equivalency number (PREN). This number is calculated based upon the composition of the material. Alloys with higher PREN values are normally found to more resistant than alloys with lower values. The resistance of alloys to localized corrosion can be measured by the ASTM G48 test procedure. These corrosion tests expose alloys in an acidified ferric chloride solution and establish values for critical pitting temperature (CPT) and critical crevice temperature (CCT). Values for PREN* and CPT for alloy 945X® are 31 and 45°C respectively.

* PREN = %Cr + 3.3 (%Mo + 0.5W) + 16N

MACHINABILITY AND HOT/COLD WORKABILITY

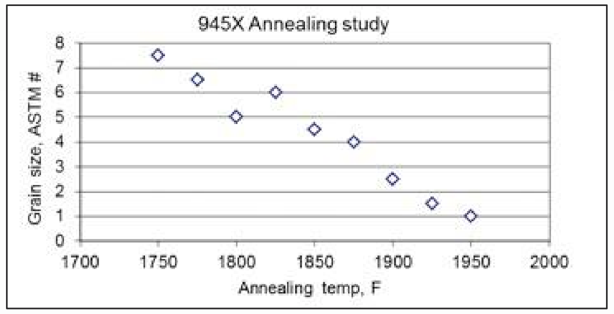
INCOLOY® alloy 945X® is an age hardenable alloy with good machinability in solution annealed or aged conditions. Rigid tools with positive rake angles and techniques that minimize work hardening of the material are required. Best results are obtained by rough machining before age hardening and finishing after heat treatment. Machinability of alloy 945X® is comparable to alloy 718.

Alloy 945X® can be hot/cold worked similar to other conventional Ni-base super alloys. Hot working range of INCOLOY® alloy 945X® is 1700°F to 2100°F (930°C to 1150°C). Hot working characteristics of alloy 945X® are very similar to alloy 718.

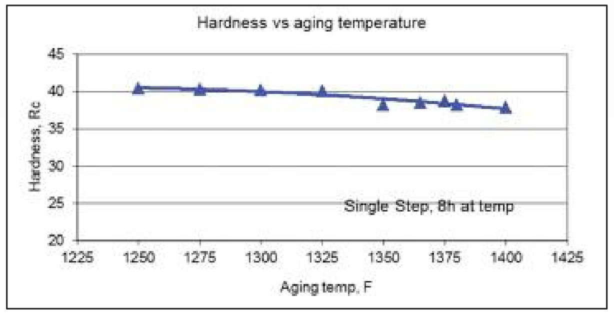
ANNEALING AND AGE HARDENING

Alloy 945X® can be annealed in the temperature range of 1750°F (954°C) to 1950°F (1066°C). For best microstructure and properties the alloy should be annealed in the range
of 1850°F (1010°C) to 1950°F (1066°C). Figure 14 shows grain size versus annealing temperature of a hot rolled material. Hardness of alloys 945X® on age hardening in the temperature range of 1250°F (678°C) to 1400°F (760°C) is shown in Figure 15. Recommended age hardening of alloy 945X® is 1300°F-1350°F (704°C-732°C) / 6-8 hours, furnace cool 50°F-100°F (26-56°C)/h to 1125°F-1175°F (607°C-635°C), hold at this temperature for 6-8 hours, air cool.

Figure 14: Grain size versus annealing temperature of alloy 945X®



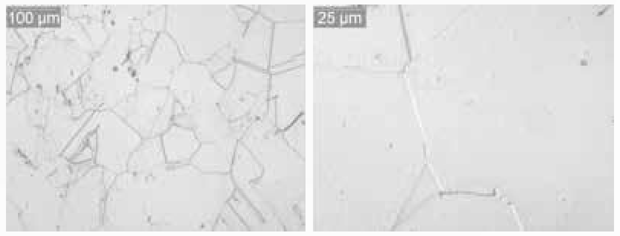
15: 945
1250 1400



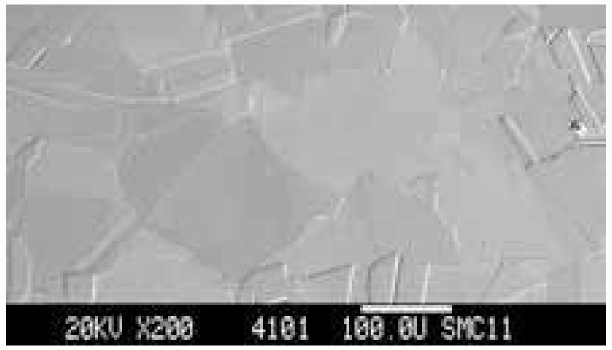
METALLOGRAPHY

Conventional grinding and polishing techniques for Ni-based alloys are adequate for INCOLOLY® alloy 945X®. To reveal the microstructure, the recommended procedure is to swab etch using Seven Acids etchant (Hydrochloric acid = 300ml, Nitric acid = 60ml, Phosphoric acid = 60 ml, Hydrofloric acid = 30ml, Sulfuric acid = 30ml, Anhydrous Iron Chloride = 30ml, Acetic acid = 60ml, and water = 300ml) and Kallings etchant (Methanol = 100ml, Cupric Chloride = 5gm, and Hydrochloric acid = 100 ml). Typical microstructure of annealed plus aged material is shown in Figures 16 and 17. Age hardening heat treatment of annealed material precipitates sub-micron size Ni_3 (TiNbAl)-type gamma prime and Ni_3 (NbTiAl)-type gamma double prime, which are responsible for high strength of alloy 945X®. These precipitates are too small to be seen by optical microscopy.

Figure 16: Optical photographs of 22-inch (560 mm) diameter rod of alloy 945X® at center in longitudinal orientation.



17: 10- 254
945



JOINING

945

945 - 725

-

- 725

-

27 28 -

945 -

945

945

945

29

Table 27: Mechanical Properties INCOLOY® alloy 945X® GTA Welded with INCOLOY® 945X® Filler Metal

Tensile Test Orientation	0.2% YS (ksi)	UTS (ksi)	Elongation (%)	Red of Area (%)	Failure Location
	85 9	125 3	21 8	37 4	
	85 3	124	18 4	40 7	
	78 7	119 3	38 1	39 2	/
-	–		- –		

Table 28: Mechanical Properties INCOLOY® alloy 945X® GMA-P Welded with INCOLOY 945X® Filler Metal.

Tensile Test Orientation	0.2% YS (ksi)	UTS (ksi)	Elongation (%)	Red of Area (%)	Failure Location
	78 2	120 0	17 3	40 3	
	78 2	118 8	17 3	30 2	
	72 9	115 3	36 9	31 1	/
-	–		- –		

Table 29: Mechanical Properties INCOLOY® alloy 945X® GTA Welded with INCOLOY 945X® Filler Metal

Tensile Test Orientation	0.2% YS (ksi)	UTS (ksi)	Elongation (%)	Red of Area (%)	Hardness (HRC)
	144 0	181 8	18 7	32 3	40 2
	146 2	182 0	20 3	41 4	36 7
	137 2	178 1	27 7	36 3	38 6
	138 4	176 8	26 1	30 6	39 4
	130 6	169 1	24 4	35 6	34 2
	138 0	167 0	17 5	27 3	37 1
-	–	- –			

AVAILABLE PRODUCT FORMS

INCOLOY® alloy 945X® is designated as UNS N09945. The alloy is approved for use in oil and gas applications by NACE MR0175 / ISO-15156-3 for up to NACE level VI. There is a Special Metals Corporation internal specification HA 123 Rev. 3

Alloy 945X® is available as a round fully annealed plus aged bar, forging stock, and tubing.

APPLICATIONS

PACKER

SAFETY VALVE FLAPPER SEAT

FORGING FOR A TUBING HANGER

FLAPPER VALVE FOR A PACKER

PISTON ACTUATOR

BLOW OUT PREVENTER COMPONENT

PUSHING WHAT'S POSSIBLE IN THE ENERGY INDUSTRY

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