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 MΩ-m	682 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

Table 4: Specific heat

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

Table 5: Thermal conductivity

Temperature		Thermal Conductivity	
°F	°C	BTU-in/ft^2-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

Table 6: Young's Modulus of elasticity

Temperature		Young's Modulus	
°F	°C	10^3 ksi	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).

Figure 1 shows a Blow Out Preventer (BOP) made out of alloy 945X intended for use in a well where high strength and corrosion are required.

Table 7: Mechanical properties of annealed plus aged 22-inch (560 mm) rod. YS, UTS, El and RA stand for yield strength, tensile strength, elongation, and reduction-of-area respectively. Impact toughness was determined at -75°F at mid-radius in the transverse orientation.

Test loc	YS, ksi (MPa)	UTS, ksi (MPa)	% El	% RA	Impact, Strength ft-lbs (Joules)	120 - Hardness range, Rc	Grain Size, ASTM #
Near Surface	157.5 (1086)	187.2 (1291)	23.3	41.2			3.5
Mid-Radius	164.6 (1135)	187.4 (1291)	21.1	37.4	47 (64)	38 – 41.2	2.5
Center	164.1 (1132)	190.0 (1310)	19.6	37.1			2

Figure 2 shows a 22-inch (560 mm) rod weighing over 11000 lbs (5000 Kg) and a macro-etched quarter of it showing a rather homogenous material.

Figure 3 shows a Packer made out of alloy 945X intended for use in aggressive environment for an oil and gas well.

Table 8: Raw data on de-rating factor

Heat/lot	Size, inches	Test temp	Yield strength, ksi	Tensile strength, ksi	% El	% RA
#1 XX3755 RY-16	9.5	RT	164.0	195.0	21.5	26.3
		300°F	148.2	174.5	17.3	29.3
		350°F	150.5	174.2	17.7	30.1
		400°F	144.8	170.1	19.3	35.7
		450°F	144.4	175.5	25.0	78.9
		500°F	144.7	166.6	19.5	34.2
#2 EX0035 PY-13	3.5	RT	148.7	183.0	34.0	53.0
		300°F	134.8	175.1	27.5	50.2
		350°F	129.3	159.9	31.4	55.5
		400°F	134.3	167.7	28.3	55.4
		450°F	131.1	159.7	28.9	59.2
		500°F	134.5	167.7	29.9	56.1
#3 XX3755 RY-15	7.5	RT	160.8	187.3	23.7	31.2
		250°F	147.6	182.2	21.0	36.0
		350°F	147.9	172.8	20.8	31.6
		450°F	143.1	169.5	22.7	34.9
#4 XX3755 RY-14	8	RT	157.7	185.7	23.6	45.1
		300°F	144.8	168.8	27.0	49.0
		350°F	144.8	168.8	26.2	49.1
		400°F	143.5	166.9	25.0	49.0
		450°F	151.4	180.6	24.0	47.8

Table 9: De-rating factor up to 500°F (260°C) for rod product

Rod dia., inches (mm)	Heat	RT, ksi	300°F (149°C)	350°F (177°C)	400°F (204°C)	450°F (232°C)	500°F (260°C)
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)		
Avg			0.91	0.91	0.90	0.88	0.90

Table 10: De-rating factor for tubing of 3.5-inch (89 mm) outer diameter and 0.449-inch (11.4 mm) wall. The values are for longitudinal tensile yield strength.

Heat number	RT, ksi	350°F (177°C), ksi	450°F (232°C), ksi	550°F (288°C), ksi
XX5167RY	171.4	158.6 (0.93)	152.0 (0.89)	150.6 (0.88)
XX5115Y	166.6	155.9 (0.94)	151.1 (0.91)	150.9 (0.91)
XX5158RY	161.5	159.9 (0.99)	149.0 (0.92)	144.5 (0.90)
XX5117RY	165.2	158.4 (0.96)	154.7 (0.94)	151.2 (0.92)
XX5168RY	164.3	152.6 (0.93)	149.8 (0.91)	147.9 (0.90)
XX5154RY	160.8	151.5 (0.94)	148.7 (0.93)	148.1 (0.92)
Average	-	0.95	0.92	0.91

Table 11: Tensile and compressive longitudinal yield strength of alloy 945X® tubing of 3.5-inch (89 mm) outer diameter and 0.449-inch (11.4 mm) wall from room temperature to 550°F (288°C). YS, UTS, El and RA stand for yield strength, tensile strength, elongation, and reduction-of-area respectively.

S. No	Heat # / piece #	Temperature	Compressive YS, ksi	Tensile YS, ksi	Compressive / tensile
1	5167-2H	RT	177.5	171.4	1.04
		350°F (177°C)	171.7	158.6	1.08
		450°F (232°C)	168.4	152.0	1.11
		550°F (288°C)	164.6	150.6	1.10
2	5115-3T	RT	176.9	166.6	1.06
		350°F (177°C)	166.5	155.9	1.08
		450°F (232°C)	163.5	151.1	1.08
		550°F (288°C)	161.9	150.9	1.07
3	5158-2T	RT	173.4	161.5	1.08
		350°F (177°C)	164.9	159.9	1.03
		450°F (232°C)	160.1	149.0	1.08
		550°F (288°C)	159.1	144.5	1.10
4	5117-2H	RT	178.6	165.2	1.10
		350°F (177°C)	174.1	158.4	1.08
		450°F (232°C)	164.3	154.7	1.10
		550°F (288°C)	161.1	151.2	1.06
5	5168-2T	RT	175.6	164.3	1.07
		350°F (177°C)	165.4	152.6	1.08
		450°F (232°C)	163.2	149.8	1.09
		550°F (288°C)	161.7	147.9	1.09
6	5154-2H	RT	172.3	160.8	1.07
		350°F (177°C)	163.4	151.5	1.08
		450°F (232°C)	161.0	148.7	1.08
		550°F (288°C)	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.

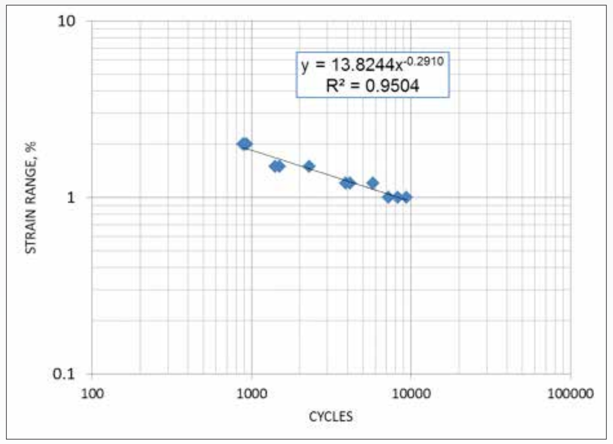
Table 12: Yield strength of alloy 945X® at various temperatures. Listed values represent averages of 3 tests.

S. No	Test Temperature	Yield strength, ksi (MPa)	De-rating Factor
1	Room Temp	151.3 (1043)	-
2	200°F (93°C)	145.0 (1000)	0.96
3	300°F (149°C)	145.0 (1000)	0.96
4	400°F (204°C)	138.8 (952)	0.92
5	450°F (232°C)	138.8 (952)	0.92

Table 13 shows fracture toughness, KJIC in C-R orientation. Tests were done using compact tension samples in lab air.

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

Figure 4: Strain controlled low cycle fatigue (LCF) tested at 450°F (232°C) as per ASTM E606-4. Tests were done using sinusoidal waveform at a frequency of 10 CPM. R-ratio for all was -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
XX4057RY-13	5.1" (130)	164.1 (1131)	197.9 (1358)	25.0	48.8	71.7 (97)	44
XX4571RY-12	8" (203)	167.1 (1152)	200.0 (1379)	23.3	43.3	41.2 (56)	46
XX4571RY-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
XX4057RY-13 (1)	145.8 (1005)	No failure, 90 days
XX4057RY-13 (2)	145.8 (1005)	No failure, 90 days
XX4057RY-13 (3)	145.8 (1005)	No failure, 90 days
XX4571RY-12 (1)	150.0 (1034)	No failure, 90 days
XX4571RY-12 (2)	150.0 (1034)	No failure, 90 days
XX4571RY-12 (3)	150.0 (1034)	No failure, 90 days
XX4571RY-13 (1)	149.4 (1030)	No failure, 90 days
XX4571RY-13 (2)	149.4 (1030)	No failure, 90 days
XX4571RY-3 (3)	149.4 (1030)	No failure, 90 days

Figure 5: Photograph of a set of C-rings after 90 days exposure in 180,000 mg/L Cl , 500 psi (3.5 MPa) H_2S and 500 psi (3.5 MPa) CO_2 at 401°F (205°C)

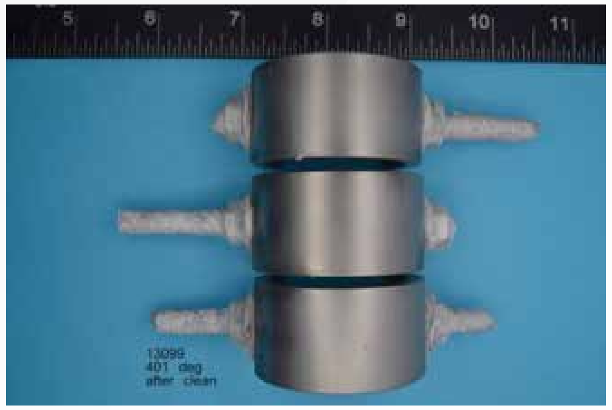


Table 16: C-ring test results in NACE level VI-450°F (232°C). The environmental conditions were as follows: 3.5 MPa (500 psia) H_2S, 3.5 MPa (500 psia) CO_2, 20 wt% (139,000 mg/L Cl) NaCl, at 232°C (450°F). The applied stress was 100% of the actual yield stress at temperature.

Sample	Applied Stress, ksi (MPa) at 232°C (450°F)	Results
XX4057RY-13 (1)	145.9 (1006)	No failure, 90 days
XX4057RY-13 (2)	145.9 (1006)	No failure, 90 days
XX4057RY-13 (3)	145.9 (1006)	No failure, 90 days
XX4571RY-12 (1)	151.9 (1047)	No failure, 90 days
XX4571RY-12 (2)	151.9 (1047)	No failure, 90 days
XX4571RY-12 (3)	151.9 (1047)	No failure, 90 days
XX4571RY-13 (1)	148.9 (1027)	No failure, 90 days
XX4571RY-13 (2)	148.9 (1027)	No failure, 90 days
XX4571RY-13 (3)	148.9 (1027)	No failure, 90 days

Figure 6: Photograph of a set of C-rings after 90 days exposure in 139,000 mg/L Cl, 500 psi (3.5 MPa) H_2S and 500 psi (3.5 MPa) CO_2 at 450°F (232°C)

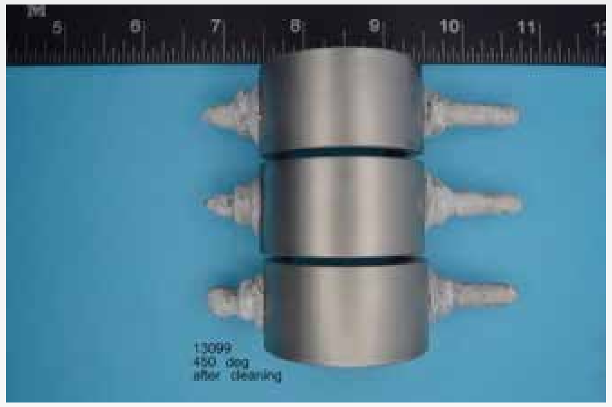


Table 17: Testing for GHSC and SSC were done in accordance with TM0177-2004, method A - Tensile test, in NACE solution A$^{\Psi}$. One set of samples was coupled to steel via the stressing bolt and the other set was tested without steel coupling. Applied stress was 90% of actual yield strength.

Sample	Applied Stress	Steel Coupled		Results
XX4057RY-13 (1)	147.7	Yes	No	No failure, 30 days
XX4057RY-13 (2)	147.7	Yes	No	No failure, 30 days
XX4057RY-13 (3)	147.7	Yes	No	No failure, 30 days
XX4571RY-12 (1)	150.4	Yes	No	No failure, 30 days
XX4571RY-12 (2)	150.4	Yes	No	No failure, 30 days
XX4571RY-12 (3)	150.4	Yes	No	No failure, 30 days
XX4571RY-13 (1)	149.8	Yes	No	No failure, 30 days
XX4571RY-13 (2)	149.8	Yes	No	No failure, 30 days
XX4571RY-13 (3)	149.8	Yes	No	No failure, 30 days

Ψ The composition of NACE solution A is 5% NaCl plus 0.5% glacial acetic acid 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

Table 18 lists mechanical properties of 3 commercial heats used for testing in S environment. Triplicate samples from these 3 heats were tested at 300°F (149°C) and 350°F (177°C) for 90 days at 100% actual yield strength (AYS) at temperature at 1100 psi (7.7 MPa) H_2S, 600 psi (4.2MPa) CO_2; 125,000 mg/L Cl. In both sets of tests, 5-gm/L elemental sulfur was magnetically stirred by impeller inside the autoclave at 120 rpm. This stirring was continued throughout the test. Elemental sulfur was directly added to the autoclave by pouring into bottom of the autoclave. Tests were conducted in accordance with Group 1 as defined in NACE conference paper 95047 and EFC 17, Appendix S1. The dimensions of the C-ring 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. Tables 19 and 20 show test results at 300°F (149°C) and 350°F (177°C) respectively. Figure 7 shows 350°F (177°C) tested C-rings in as-exposed and cleaned conditions. Further, Figure 7 also shows optical photographs of sectioned C-ring, revealing that C-rings are devoid of any micro-cracks. Table 21 shows test results for GHSC and SSC conducted as per TM0177-2004, method A - Tensile test, in NACE solution A$^{\Psi}$. One set of samples was coupled to steel via the stressing bolt, and other set was tested without steel coupling. Applied stress was 90% of actual yield strength.

Table 18: Mechanical properties of the heats used SCC in sulfur, SSC and GHSC. YS, UTS, El and RA stand for yield strength, tensile strength, elongation, and reduction-of-area respectively.

Heat No.	Rod dia., inches (mm)	YS ksi (MPa)	UTS, ksi (MPa)	El (%)	RA (%)	Average impact lf-lbs (Joules)	Hard-ness, Rc
XX4154RY-12	6.5" (165)	146.6 (1011)	179.3 (1236)	26.9	51.6	70.9 (96)	41
XX3888RY-11	6.5" (165)	147.5 (1017)	181.6 (1252)	26.0	44.6	61.2 (83)	41
XX4040RY-11	10" (254)	152.4 (1051)	180.6 (1252)	26.6	50.6	79.0 (107)	42

Table 19: C-ring test results at 300°F (149°C) for 90 days at 100% actual yield strength (AYS) at temperature at 1100 psi (7.7 MPa) H_2S, 600 psi (4.2MPa) CO_2; 125,000 mg/L Cl. S content and stirring is mentioned in the foregoing paragraph.

Sample	Applied stress 300°F (149°C)	Results
XX4154RY-12 (1)	138.5	No failure, 90 days
XX4154RY-12 (2)	138.5	No failure, 90 days
XX4154RY-12 (3)	138.5	No failure, 90 days
XX3888RY-11 (1)	141.4	No failure, 90 days
XX3888RY-11 (2)	141.4	No failure, 90 days
XX3888RY-11 (3)	141.4	No failure, 90 days
XX4040RY-11 (1)	143.9	No failure, 90 days
XX4040RY-11 (2)	143.9	No failure, 90 days
XX4040RY-11 (3)	143.9	No failure, 90 days

Table 20: C-ring test results at 350°F(177°C) for 90 days at 100% actual yield strength (AYS) at temperature at 1100 psi (7.7 MPa) H_2S, 600 psi (4.2MPa) CO_2; 125,000 mg/L Cl. S content and stirring is mentioned in the foregoing paragraph.

Sample	Applied stress 350°F (177°C)	Results
XX4154RY-12 (1)	133.4	No failure, 90 days
XX4154RY-12 (2)	133.4	No failure, 90 days
XX4154RY-12 (3)	133.4	No failure, 90 days
XX3888RY-11 (1)	134.2	No failure, 90 days
XX3888RY-11 (2)	134.2	No failure, 90 days
XX3888RY-11 (3)	134.2	No failure, 90 days
XX4040RY-11 (1)	138.7	No failure, 90 days
XX4040RY-11 (2)	138.7	No failure, 90 days
XX4040RY-11 (3)	138.7	No failure, 90 days

Figure 7: Photographs of C-rings tested in S containing environment at 350°F [177°C] for 90 days at 100% actual yield strength [AYS] at temperature at 1100 psi [7.7 MPa] H_2S, 600 psi [4.2MPa] CO_2; 125,000 mg/L Cl. As-exposed, cleaned after exposure and optical photograph of sectioned C-ring are shown.

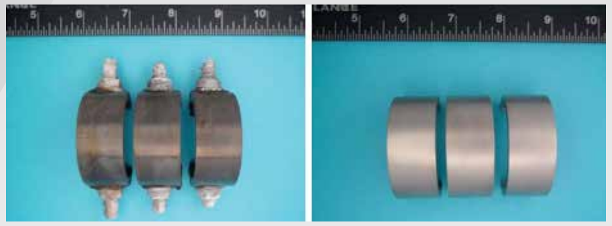


Table 21: Testing for GHSC and SSC were done in accordance with TM0177-2004, method A - Tensile test, in NACE solution A^Ψ. One set of samples was coupled to steel via the stressing bolt and other set were tested without steel coupling. Applied stress was 90% of actual yield strength.

Sample	Applied Stress	Steel Coupled		Results
XX4154RY-12 [1]	146.6	Yes	No	No failure, 30 days
XX4154RY-12 [2]	146.6	Yes	No	No failure, 30 days
XX4154RY-12 [3]	146.6	Yes	No	No failure, 30 days
XX3888RY-11 [1]	147.5	Yes	No	No failure, 30 days
XX3888RY-11 [2]	147.5	Yes	No	No failure, 30 days
XX3888RY-11 [3]	147.5	Yes	No	No failure, 30 days
XX4040RY-11 [1]	152.4	Yes	No	No failure, 30 days
XX4040RY-11 [2]	152.4	Yes	No	No failure, 30 days
XX4040RY-11 [3]	152.4	Yes	No	No failure, 30 days

Ψ The composition of NACE solution A is 5% NaCl plus 0.5% glacial acetic acid 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.

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] rod	146.5 [1010]	177.4 [1223]	29.4	52.5	66.6 [90]	41.1	3
10 [254] rod	160.0 [1103]	184.8 [1274]	23.9	47.4	57.7 [78]	41.3	3
4.2 [107] OD 0.9 [23] wall	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
Air	17.8	-	25.6	-	51.6	-	-
Air	15.9	-	22.9	-	51.3	-	-
Air [Avg]	16.9	-	24.3	-	51.5	-	-
Env	12.8	0.76	18.4	0.76	36.7	0.71	No
Env	14.7	0.87	21.2	0.87	36.4	0.71	No
Env	12.9	0.77	18.6	0.77	36.6	0.71	No
Avg	-	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
Air	16.8	-	24.2	-	44.6	-	-
Air	15.0	-	21.6	-	47.9	-	-
Air [Avg]	15.9	-	22.9	-	46.3	-	-
Env	14.6	0.92	21.0	0.92	33.0	0.71	No
Env	12.6	0.79	18.4	0.80	36.2	0.78	No
Env	13.1	0.75	17.3	0.76	36.4	0.79	No
Avg	-	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
Air	15.7	-	17.9	-	53.0	-	-
Air	12.3	-	13.6	-	51.8	-	-
Air	13.1	-	14.5	-	51.9	-	-
Air [Avg]	13.7	-	15.3	-		-	-
Env	13.4	0.98	14.3	0.93	41.8	0.80	No
Env	15.7	1.15	17.7	1.15	43.8	0.84	No
Env	14.7	1.07	16.0	1.04	41.8	0.80	No
Avg	-	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.

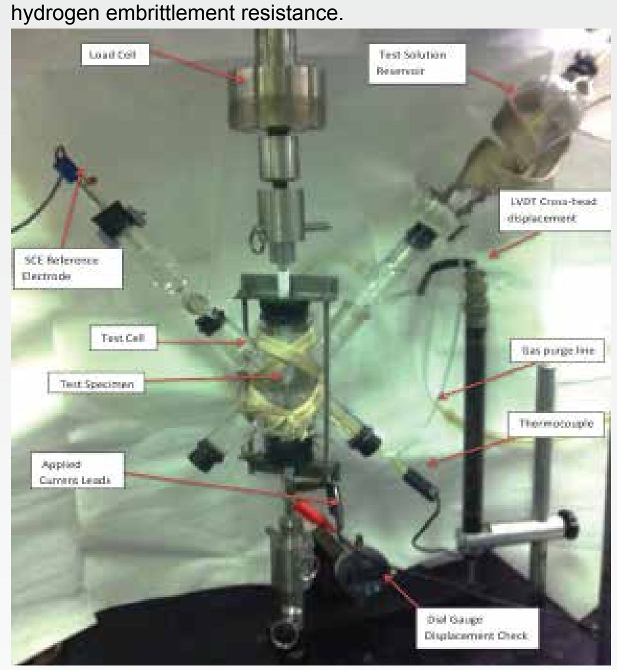


Figure 9 shows plastic strains of alloy 945X® and 718 in glycerol and in the listed environment.

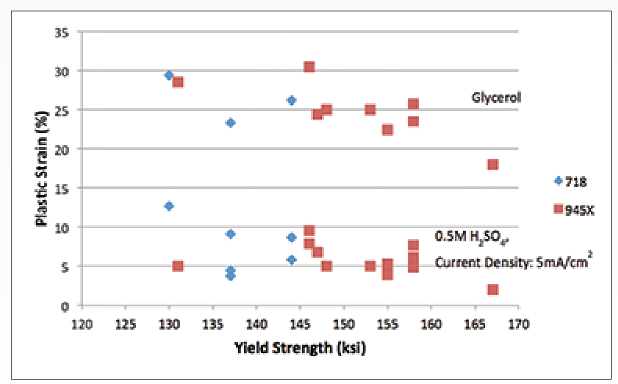
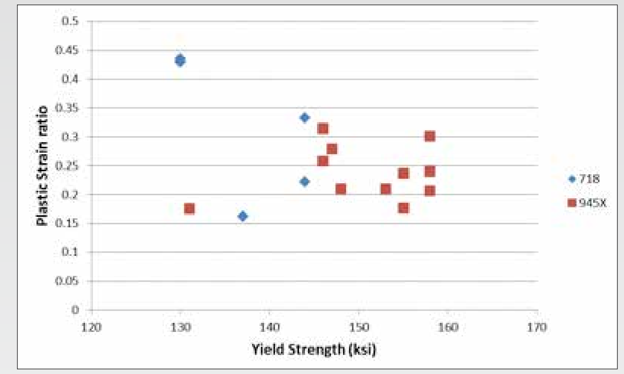


Figure 10 shows plastic strain ratios of alloy 945X® and 718 in glycerol and in the listed hydrogen embrittlement environment. The latter is divided by the former to get these values.



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 #
945X® 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

Figure 11: Weight loss of alloys 945X®, 718 and 725 at various HCl concentrations 100°F (38°C)

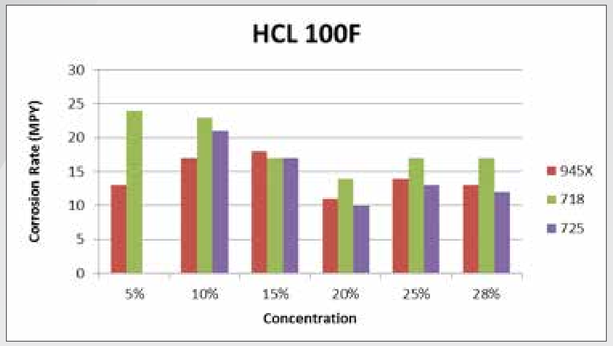


Figure 12: Weight loss of alloys 945X®, 718 and 725 at various HCl concentrations at 190°F (88°C)

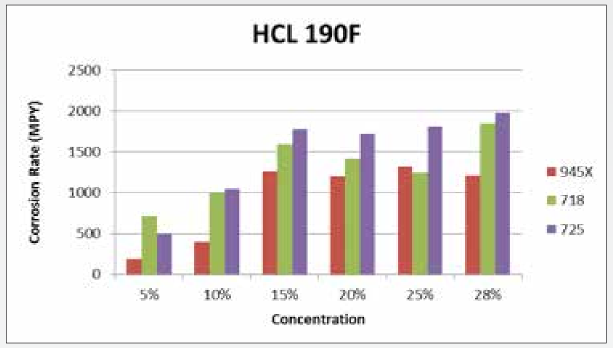
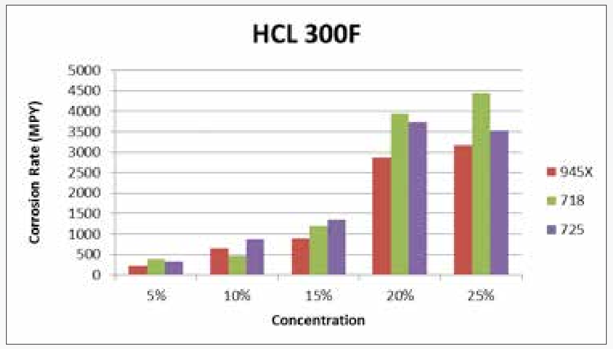


Figure 13: Weight loss of alloys 945X®, 718 and 725 at various HCl concentrations 300°F (149°C)



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®

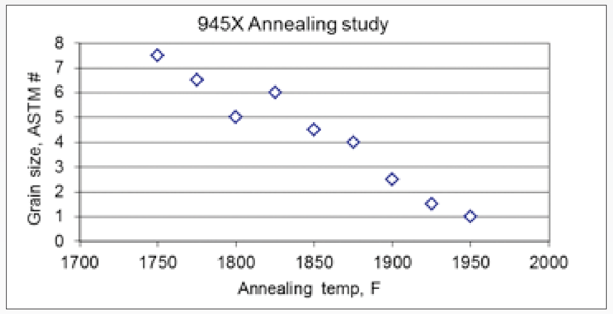
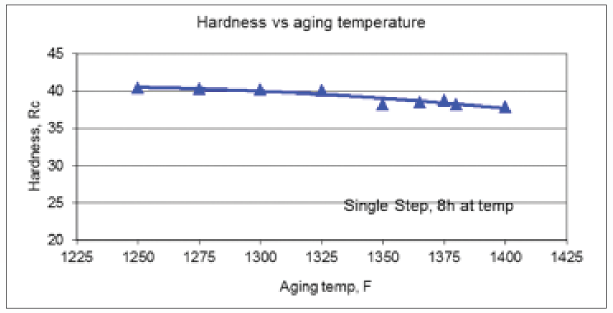


Figure 15: Hardness of alloy 945X® on single step age hardening in the temperature range of 1250 to 1400F.



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.

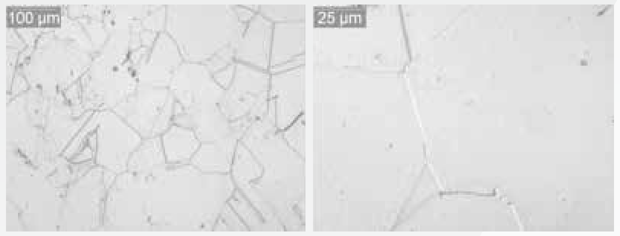
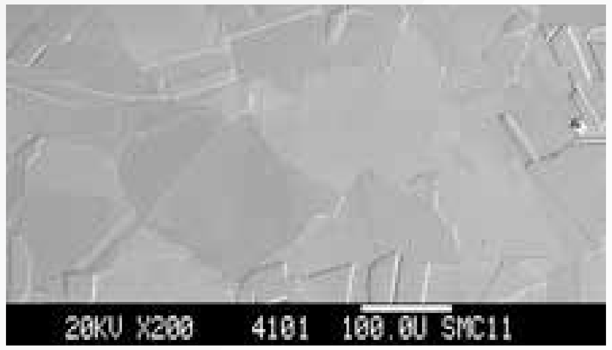


Figure 17: Scanning electron micrographs of 10-inch (254 mm) diameter alloy 945X® rod at center in longitudinal orientation.



JOINING

INCOLOY® alloy 945X® has been shown to demonstrate excellent weldability. Sound welds were successfully deposited in both solution annealed and solution annealed and precipitation hardened material. Refer to Special Metals Welding Handbook for details on welding parameters.

The GTAW process can be used to produce satisfactory welds in alloy 945X® with matching filler metal and INCO-WELD 725NDUR filler metal. Material was annealed prior to welding and annealed and aged after welding. Matching composition welds in material that solution annealed and solution annealed and aged prior to welding were satisfactory. The GMAW-P process produced sound welds using matching composition filler metal and INCO-WELD 725NDUR filler metal. While the welds were sound and strong, the ductility of matching composition welds deposited by GMAW-P was less than desired.

Tables 27 and 28 show mechanical properties of as-welded INCOLOY® alloy 945X® using GTA and GMA-P processes respectively. The alloy was welded with INCOLOY® 945X® Filler Metal. As would be expected, welds tested without post weld heat treatment exhibited lower strength. Mechanical Properties INCOLOY® alloy 945X® GTA Welded with INCOLOY® 945X® Filler Metal with post weld heat treatments are shown in Table 29. Material develops full strength on post weld anneal and age.

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
Cross Weld	85.9	125.3	21.8	37.4	Weld
Cross Weld	85.3	124	18.4	40.7	Weld
All Weld Metal	78.7	119.3	38.1	39.2	N/A
Pre-weld condition – Annealed + Aged Post-Weld – As Welded					

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
Cross Weld	78.2	120.0	17.3	40.3	Weld
Cross Weld	78.2	118.8	17.3	30.2	Weld
All Weld Metal	72.9	115.3	36.9	31.1	N/A
Pre-weld condition – Annealed + Aged Post-Weld – As Welded					

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)
Cross Weld	144.0	181.8	18.7	32.3	40.2
Cross Weld	146.2	182.0	20.3	41.4	36.7
All Weld Metal	137.2	178.1	27.7	36.3	38.6
All Weld Metal	138.4	176.8	26.1	30.6	39.4
All Weld Metal	130.6	169.1	24.4	35.6	34.2
All Weld Metal	138.0	167.0	17.5	27.3	37.1
Pre-weld condition – Annealed + Aged Post-Weld – Annealed + Aged					

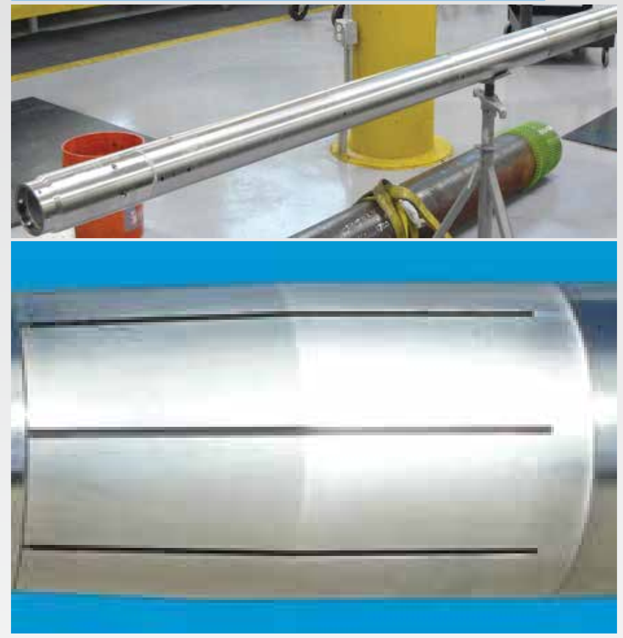
AVAILABLE PRODUCT FORMS

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

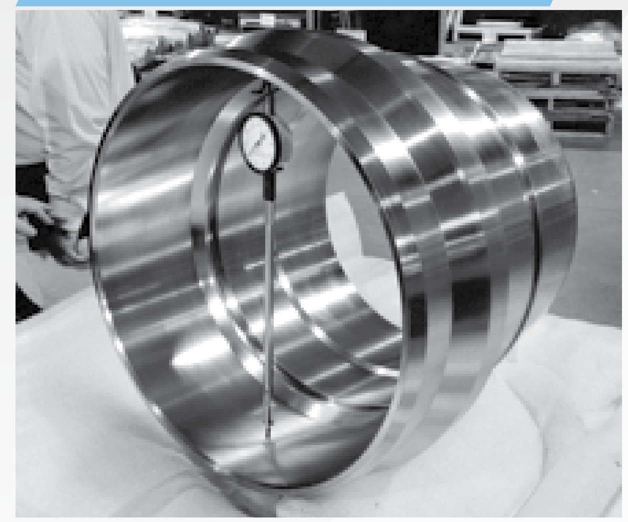


SAFETY VALVE FLAPPER SEAT

FORGING FOR A TUBING HANGER

FLAPPER VALVE FOR A PACKER

PISTON ACTUATOR



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