

INCOLOY® alloy 945 (UNS N09945) is a high-strength, corrosion-resistant alloy designed for demanding applications in the oil and gas industry. The properties of this age hardenable nickel-iron-chromium alloy are enhanced by its contents of molybdenum, copper, niobium, titanium, and aluminum. The chemical composition of alloy 945 is seen in Table 1. The alloy's nickel content results in resistance to chloride-induced stress corrosion cracking. Nickel, in conjunction with the molybdenum and copper, also gives alloy 945 outstanding resistance to general corrosion in reducing media. Molybdenum also imparts resistance to localized attack (pitting and crevice corrosion). The alloy's content of chromium provides resistance in oxidizing environments. Niobium, titanium and aluminum participate in the age hardening reaction that occurs during heat treatment. Their interaction forms gamma prime and gamma double prime precipitates, which strengthen the alloy.

INCOLOY alloy 945 is suitable for downhole oil and gas applications requiring high strength and corrosion resistance in aggressive sour wells containing high levels of hydrogen sulfide and chlorides. Because of the alloy's resistance to stress cracking in environments rich in hydrogen sulfide, it is suitable for downhole and surface gas-well components including tubular products, valves, hangers, landing nipples, tool joints and packers. The alloy can also be used for fasteners, pump shafting and high strength piping systems.

INCOLOY alloy 945 is approved under NACE MR0175 / ISO 15156-3 for use in oil and gas applications up to NACE level VII and level VI-450°F severity.

INCOLOY alloy 945 products are available in several strength grades. Conventional annealed and aged alloy 945 products exhibit a minimum yield strength of 125 ksi. A high strength grade of the alloy, designated INCOLOY alloy 945X, exhibits a minimum yield strength of 140 ksi. Limiting mechanical properties are presented in Table 13. Comparative data are presented in Tables 7 and 8. The strength of alloy 945X is also higher than that of alloys 718, 725, and 925. In addition, cold worked and directed aged products are available with even higher levels of strength for applications such as shafting. Limiting mechanical properties are reported in Table 14 and comparative strength levels are found in Tables 9 and 10.

Limiting properties of alloy 945 products are defined in specifications prepared by Special Metals Corporation, the inventor and producer of the product. These include HA 119, HA 121, HA 122 and HA 123. Copies are available by contacting the Special Metals Research and Technology Department.

Table 1 – Limiting Chemical Composition of INCOLOY alloy 945, wt %

Nickel	45.0-55.0
Chromium	19.5-23.0
Iron	Balance
Molybdenum	3.0-4.0
Niobium	2.5-4.5
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 0.04



Physical Properties

Physical properties of INCOLOY alloy 945 are given in Table 2. All are room-temperature values except the melting range. 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 a range of temperatures are presented in Tables 5 and 6.

Table 2 – Physical Properties of INCOLOY alloy 945

Density, lb/in ³	0.296
g/cm ³	8.2
Melting Range, °F	2317-2510
°C	1270-1377
Electrical Resistivity, ohm•cmil/ft	663
mW•m.....	1.10
Permeability at 200 oersteds (15.9 kA/m).....	1.003
Young's Modulus, 10 ⁶ psi.....	29.1
GPa.....	200.8

Table 3 – Coefficient of thermal expansion. The values are mean coefficient of linear expansion between 77°F (25°C) and the listed temperature.

Temperature		Coefficient of thermal expansion	
°F	°C	in/in/°F•10 ⁻⁶	cm/cm/°C•10 ⁻⁶
200	93	7.88	14.19
300	149	7.91	14.24
400	204	7.98	14.36
500	260	8.04	14.47
600	316	8.16	14.69
700	371	8.30	14.94
800	427	8.40	15.12
900	482	8.48	15.26
1000	538	8.55	15.39
1100	593	8.69	15.64
1200	649	8.85	15.93
1300	704	9.07	16.32
1400	760	9.38	16.89
1500	816	9.70	17.47
1600	871	10.01	18.01

Table 4 – Specific Heat

Temperature		Specific Heat	
°C	°F	J/kg•°C	BTU/lb•°F
23	73	445	0.106
50	122	455	0.109
100	212	467	0.112
200	392	491	0.117
300	572	515	0.123
400	752	540	0.129
500	932	563	0.135
600	1112	588	0.140
700	1292	607	0.145
800	1472	639	0.153
900	1652	670	0.160
1000	1832	688	0.164
1100	2012	690	0.165
1150	2102	700	0.167

Table 5 – Thermal Conductivity

Temperature		Thermal Conductivity	
°C	°F	W/m•°C	BTU•in/ft ² •h•°F
23	73	10.9	75.9
50	122	11.5	79.8
100	212	12.5	86.9
200	392	14.4	99.6
300	572	16.4	113.7
400	752	18.4	127.3
500	932	20.3	141.0
600	1112	22.4	155.1
700	1292	23.9	165.7
800	1472	25.7	178.3
900	1652	26.2	181.8
1000	1832	28.0	194.2
1100	2012	29.5	204.4

Table 6 – Modulus of Elasticity

Temperature	Tensile Modulus	Shear Modulus	Poisson's Ratio
°F	10 ³ ksi	10 ³ ksi	
70	28.3	10.8	0.31
200	27.9	10.7	0.31
300	27.3	10.4	0.31
400	26.9	10.2	0.31
500	26.4	10.0	0.32
600	26.0	9.9	0.32
700	25.6	9.7	0.32
800	25.1	9.5	0.32
900	24.6	9.3	0.32
1000	24.2	9.1	0.33
1100	23.6	8.9	0.33
1200	23.1	8.6	0.34
1300	22.5	8.4	0.34

°C	GPa	GPa	Poisson's Ratio
23	195	74	0.31
93	192	74	0.31
149	188	70	0.31
204	185	70	0.31
260	182	69	0.32
316	179	68	0.32
371	176	67	0.32
427	173	65	0.32
482	169	64	0.32
538	167	63	0.33
593	163	61	0.33
649	159	59	0.34
704	155	58	0.34



INCOLOY alloy 945 can be used for fasteners where the operating conditions call for high strength and resistance to corrosion.

Mechanical Properties

INCOLOY alloy 945 is austenitic nickel-iron-chromium alloy made precipitation-hardenable by its contents of niobium, titanium, and aluminum. The precipitation hardening (age hardening) heat treatment induces the formation of $\text{Ni}_3(\text{TiNbAl})$ -type (gamma prime) and $\text{Ni}_3(\text{NbTiAl})$ -type (gamma double-prime) precipitates. These particles are of sub-micron size and are uniformly distributed in the matrix resulting in high strength.

Mechanical properties generated from commercially produced material are reported below. Typical properties of various sizes annealed and aged round bars of alloys 945 and 945X are reported in Tables 7 and 8. Higher strengths (such as might be desired for shafting) can be obtained in products that are cold worked and direct aged. Mechanical properties of alloy 945 and 945X products processed in this manner are reported in Tables 9 and 10. Mechanical properties of cold drawn, annealed, and aged tubing are in Table 11. Table 12 shows tensile properties of 6 inch (152 mm) diameter round bar. Limiting mechanical properties of annealed and aged alloys 945, 945X and 925 products are shown in Table 13. Limiting mechanical properties of annealed, cold drawn, and aged alloy 945 and 945X shafting bar are shown in Table 14. Yield strength values at temperatures up to 450°F are presented in Figure 1. Rotating beam fatigue strength of alloy 945 at room temperature in air is shown in Figure 2. Comparative data of alloy 925 is also shown in the plot. The figure also compares yield strength of alloy 945 with alloy 925.

The heat treatments employed for these alloy 945 products are:

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

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

Table 7 – Typical mechanical properties of annealed and aged round bar of INCOLOY alloy 945. Impact strength was determined at -75°F. Impact strength for the rod 3.5 inch and larger is determined in the transverse orientation.

Rod Size		Yield Strength		Tensile Strength		Elongation	Reduction of Area	Impact Strength		Hardness	Grain Size
in	mm	ksi	MPa	ksi	MPa	%	%	ft•lb	joules	Rc	ASTM #
1.0	25	133.4	920	173.2	1194	27.8	48.0	76	103	40	2
2.0	51	132.5	914	170.2	1174	28.2	47.6	70	95	40	3
3.5	89	135.5	934	172.0	1186	25.5	40.5	58.2	79	43	2
4.5	114	134.2	925	168.6	1163	28.6	46.7	62	84	42	2.5
6.0	152	141.0	972	176.0	1214	22.0	34.6	55.3	75	42	2.5
12.0	305	142.3	981	171.7	1184	26.3	43.6	61.2	83	40	2
14.0	356	140.3	967	169.3	1167	26.6	30.7	77	105	39	2

Table 8 – Typical mechanical properties of annealed and aged round bar of INCOLOY alloy 945X. Impact strength was determined at -75°F. Impact strength for bar 3.5 inch diameter and larger were determined in the transverse orientation.

Rod Size		Yield Strength		Tensile Strength		Elongation	Reduction of Area	Impact Strength		Hardness	Grain Size
in	mm	ksi	MPa	ksi	MPa	%	%	ft•lb	joules	Rc	ASTM #
1.0	25	143.8	992	182.8	1260	29.9	56.0	94	128	42	3.5
2.0	51	146.6	1010	184.9	1275	29.9	51.0	95	136	40.5	3.5
3.5	89	146.2	1008	177.6	1224	30.6	53.7	65	88	40.5	3.5
6.0	152	148.6	1025	179.6	1238	27.1	50.1	75	102	40	3
8.5	305	146.6	1011	179.5	1238	29.0	51.2	103	139.8	40.5	2.5

Table 9 – Typical mechanical properties of pump shaft-grade INCOLOY alloy 945 produced by cold working and aging.

Rod Size		Yield Strength		Tensile Strength		Elongation	Reduction of Area	Hardness
in	mm	ksi	MPa	ksi	MPa	%	%	Rockwell C
0.697	17.7	170.9	1178	196.6	1156	17.1	26.6	41
0.885	22.5	171.1	1180	196.5	1455	16.3	27.3	41
1.205	30.6	174.9	1206	196.5	1355	15.6	26.3	42
1.750	44.5	176.7	1218	195.2	1346	17.0	29.2	40.9

Table 10 – Typical mechanical properties of pump shaft-grade INCOLOY alloy 945X produced by cold working and aging.

Rod Size		Yield Strength		Tensile Strength		Elongation	Reduction of Area	Hardness
in	mm	ksi	MPa	ksi	MPa	%	%	Rockwell C
0.701	17.8	221.5	1527	231.2	1596	17.4	39.0	45.8
1.014	25.8	211.3	1457	219.8	1515	15.1	40.3	45.0
1.500	38.1	218.0	1503	230.2	1587	13.8	32.8	45.9

Table 11 – Typical mechanical properties of cold drawn, annealed, and aged INCOLOY alloy 945 tubing.

Outside Diameter		Wall Thickness		Yield Strength		Tensile Strength		Elongation	Reduction Of Area	Impact Strength		Hardness
in	mm	in	mm	ksi	MPa	ksi	MPa	%	%	ft•lb	joules	Rockwell C
6.184	157	0.752	19	141.1	973	174.2	1201	23.7	39.0	64	87	39

Table 12 – Tensile properties of INCOLOY alloy 945 with orientation and location for 6 inch (152 mm) diameter bar. The reported values are the average of two tests.

Orientation / Location	Yield Strength		Tensile Strength		Elongation	Reduction of Area
	ksi	MPa	ksi	MPa	%	%
Longitudinal / Mid-Radius	139.9	965	174.2	1201	22.9	35.3
Longitudinal / Center	138.6	955	170.4	1175	24.5	31.7
Longitudinal / Edge	139.0	958	173.9	1199	24.2	33.8
Transverse / Center	141.6	976	175.3	1209	22.5	30.6
Transverse / Mid-Radius	139.9	065	175.5	1210	24.3	35.1

Table 13 – Limiting mechanical properties of annealed + aged INCOLOY alloys 945, 945X and 925.

Alloy	SMC Spec	Minimum Yield Strength		Minimum Tensile Strength		Minimum Elongation	Minimum Reduction of Area	Minimum Impact	Minimum Hardness	Maximum Hardness
		ksi	MPa	ksi	MPa	%	%	ft•lb	Rc	Rc
925	HA 46 Rev. 13	110	759	140	965	18	25	35	26	38
945	HA 119 Rev. 0	125	862	150	1034	18	25	40	32	42
945X	HA 123 Rev. 0	140	965	165	1138	18	25	40	32	42

Table 14 – Limiting mechanical properties of annealed, cold drawn, and aged shaft-grade INCOLOY alloy 945 and 945X bar.

Alloy	SMC Spec	Minimum Yield Strength		Minimum Tensile Strength		Minimum Elongation	Minimum Reduction of Area	Minimum Impact	Minimum Hardness	Maximum Hardness
		ksi	MPa	ksi	MPa	%	%	ft•lb	Rc	Rc
945	HA 121 Rev. 0	165	1138	180	1281	15	20	-	38	46
945X	HA 122 Rev. 0	210	1448	220	1517	12	18	-	40	48

Figure 1. Yield strength of INCOLOY alloy 945 and 925 products at elevated temperatures.

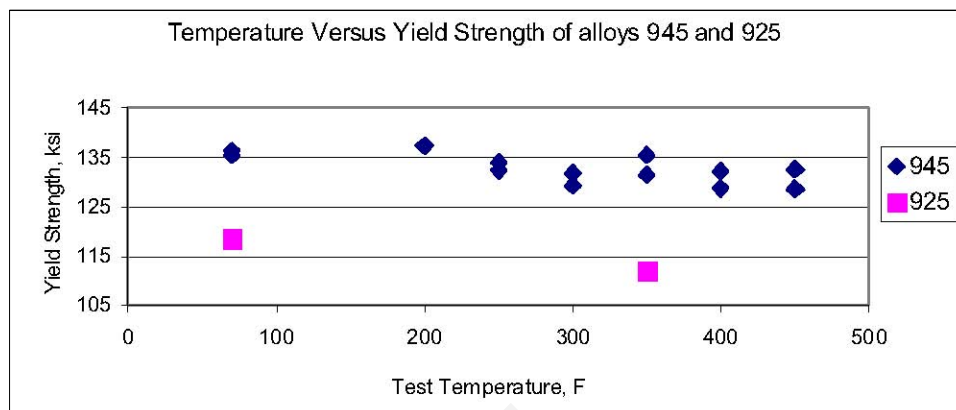
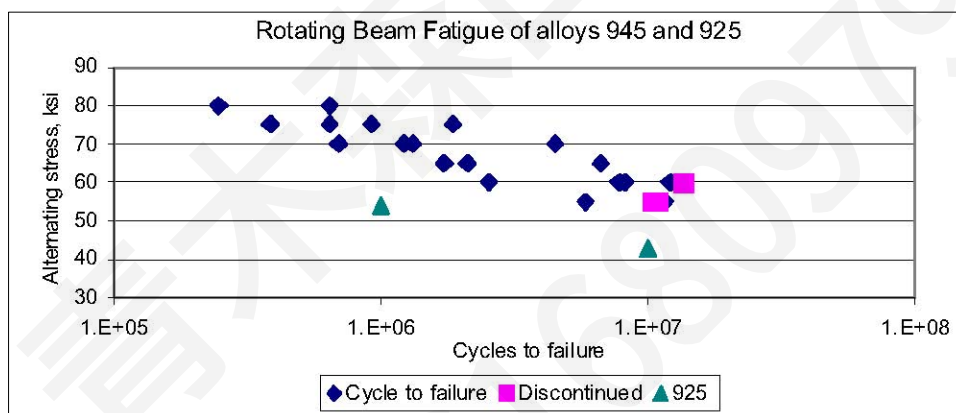


Figure 2. Rotating beam fatigue strength of INCOLOY alloys 945 and 925. Testing was done at K_t of 1, at a frequency of 100Hz, and R-value of -1.



Corrosion Resistance

Extensive testing was conducted to obtain NACE MR0175/ISO 15156-3: 2003 approval of INCOLOY alloy 945. Properties of the material used in the qualification program are seen in Table 15.

Table 15 – Mechanical properties of the heats used for NACE MR0175/ISO 15156: 2003 qualification.

Heat Number	Yield Strength		Ultimate Tensile Strength		Elongation	Reduction of Area	Hardness
	ksi	MPa	ksi	MPa	%	%	Rc
0019PY-12	135.5	920	172.0	1186	25.5	40.5	43
0019PY-11	134.2	925	168.6	1163	28.6	46.7	42
0022PK-1	141.0	972	171.7	1184	22.0	34.5	42

Stress Corrosion Cracking Resistance in H₂S-Containing Environments:

Test results of triplicate samples from three commercial heats in NACE MR0175 / ISO 15156-3 for levels VII and VI-450° qualification are given in Tables 16 and 17 respectively. Tests were conducted in accordance with NACE TM0177-2004, method C for C-Ring tests. The dimensions of the samples were 2 inch (51 mm) OD, 0.15 inch (3.8 mm) wall thickness and 0.95 inch (24.1 mm) width. The results were judged by visual examination at 20X.

Table 16 – C-ring test results in NACE level VII. The environmental conditions were: 3500 kPa (508 psia) H₂S, 3500 kPa (508 psia) CO₂, 25 wt% (150,000 mg/1 C1) NaCl, at 205°C (401°F). The applied stress was 100% of the yield stress.

Sample	Applied Stress		Results
	ksi	MPa	
0019PY-12(1)	135.5	920	No failure, 90 days
0019PY-12(2)	135.5	920	No failure, 90 days
0019PU-12(3)	135.5	920	No failure, 90 days
0019PY-11(1)	134.2	925	No failure, 90 days
0019PY-11(2)	134.2	925	No failure, 90 days
0019PY-11(3)	134.2	925	No failure, 90 days
0021PK-11(1)	141.0	972	No failure, 90 days
0021PK-11(2)	141.0	972	No failure, 90 days
0021PK-11(3)	141.0	972	No failure, 90 days

Table 17 – C-ring test results in NACE level VI-450°F. The environmental conditions were: 3500 kPa (508 psia) H₂S, 3500 kPa (508 psia) CO₂, 20 wt% (120,000 mg/1 C1) NaCl, at 232°C (450°F). The applied stress was 100% of the yield stress.

Sample	Applied Stress		Results
	ksi	MPa	
0019PY-12(1)	135.5	920	No failure, 90 days
0019PY-12(2)	135.5	920	No failure, 90 days
0019PU-12(3)	135.5	920	No failure, 90 days
0019PY-11(1)	134.2	925	No failure, 90 days
0019PY-11(2)	134.2	925	No failure, 90 days
0019PY-11(3)	134.2	925	No failure, 90 days
0021PK-11(1)	141.0	972	No failure, 90 days
0021PK-11(2)	141.0	972	No failure, 90 days
0021PK-11(3)	141.0	972	No failure, 90 days

Slow Strain Rate testing (SSRT) of alloy 945 was performed in a solution defined by ExxonMobil that is commonly used to rate nickel-base alloys. The material exhibited excellent environment-to-air ratios at 250°F (121°C) and 300°F (149°C) as shown in Table 18. The environmental conditions are described in the table. No secondary cracking was observed.

Table 18 – SSRT testing in 25 wt% NaCl + 0.50 wt% HAc, 100 psig H₂S at room temperature, strain rate $4.0 \times 10^{-6} \text{ s}^{-1}$.

Temperature	Time-to-Failure Ratio	% Elongation Ratio	Reduction of area Ratio	Secondary Cracking
250F (121C)	0.89	0.88	0.92	None
250F (121C)	0.88	0.87	0.90	None
250F (121C)	0.93	0.93	0.85	None
300F (149C)	0.92	0.92	0.93	None
300F (149C)	0.92	0.92	0.84	None
300F (149C)	0.94	0.94	0.94	None

Corrosion Resistance for GHSC and SSC:

Test results for GHSC and SSC tests are presented in Tables 19 and 20. Samples were nominally 0.15 inch (3.8 mm) diameter with a 1 inch (25.4 mm) gauge length. The results were judged by visual examination at 20X.

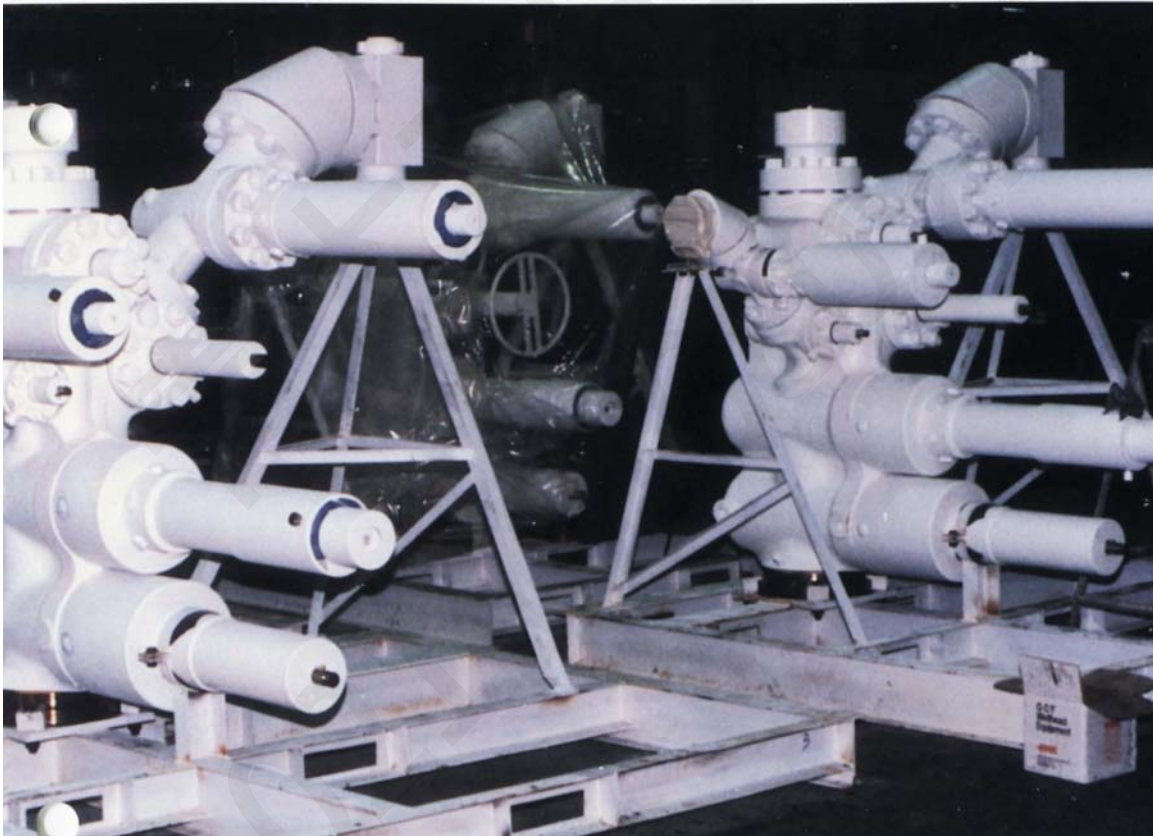
Table 19 – Testing for GHSC was done in accordance with TM0177-2004, method A – Tensile test, in NACE solution A^a. Samples were coupled to steel via the stressing bolt and were stressed to 90% of actual yield strength.

Sample	Applied Stress		Results
	ksi	MPa	
0019PY-12(1)	122.0	828	No failure, 30 days
0019PY-12(2)	122.0	828	No failure, 30 days
0019PU-12(3)	122.0	828	No failure, 30 days
0019PY-11(1)	120.8	833	No failure, 30 days
0019PY-11(2)	120.8	833	No failure, 30 days
0019PY-11(3)	120.8	833	No failure, 30 days
0021PK-11(1)	126.9	875	No failure, 30 days
0021PK-11(2)	126.9	875	No failure, 30 days
0021PK-11(3)	126.9	875	No failure, 30 days

Table 20 – SSC testing was performed in accordance with TM0177-2004, Method A – Tensile test, in NACE solution A^a. Samples were stressed to 90% of actual yield strength.

Sample	Applied Stress		Results
	ksi	MPa	
0019PY-12(1)	122.0	828	No failure, 30 days
0019PY-12(2)	122.0	828	No failure, 30 days
0019PU-12(3)	122.0	828	No failure, 30 days
0019PY-11(1)	120.8	833	No failure, 30 days
0019PY-11(2)	120.8	833	No failure, 30 days
0019PY-11(3)	120.8	833	No failure, 30 days
0021PK-11(1)	126.9	875	No failure, 30 days
0021PK-11(2)	126.9	875	No failure, 30 days
0021PK-11(3)	126.9	875	No failure, 30 days

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



Block gas well "Christmas" trees can be forged and machined from INCOLOY alloy 945
(Photo courtesy of FMC Petroleum Equipment Group).

Chloride Stress Corrosion Cracking Resistance:

The resistance of INCOLOY alloys 945 and 925 and AISI 304 stainless steel samples to chloride-induced stress corrosion cracking (SCC) was determined by the ASTM G123 and ASTM G36 test methods. The tests were performed by immersing pre-stressed samples in boiling sodium chloride and boiling magnesium chloride, respectively. Progress of testing was monitored by periodic visual observation during the test duration. Tables 21 and 22 show the results of these SCC tests. The nickel-base exhibit significantly better resistance than the stainless steel.

Table 21 – Sodium chloride stress corrosion cracking test per ASTM G123. Standard U-bent specimens, stressed over the yield strength, were exposed in boiling 25% NaCl at 225°F (108°C) at pH 1.5.

Alloy	Time to Observe Cracks
INCOLOY alloy 945	No cracks after 720 hours
INCOLOY alloy 925	No cracks after 720 hours
304 Stainless Steel	Cracks after 22 hours

Table 22 – Magnesium chloride stress corrosion cracking test per ASTM G36. Standard U-bent specimens, stressed over the yield strength, were exposed in boiling 45% MgCl₂ at 310°F (155°C).

Alloy	Time to Observe Cracks	Time to Failure
INCOLOY alloy 945	22 hours	142 hours
INCOLOY alloy 925	22 hours	70 hours
304 Stainless Steel	4 hours	13 hours

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. By virtue of its contents of chromium and molybdenum, alloy 945 offers excellent resistance to localized attack. The resistance of an alloy to localized corrosion 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 be 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 CPT for alloys 945 and 925 are reported in Table 23.

Table 23 – Resistance of Oilfield Alloys to Localized Corrosion

Alloy	CPT, °C
INCOLOY alloy 925	35
INCOLOY alloy 945	50

Hot & Cold Working

INCOLOY alloy 945 can be hot and cold worked similar to other conventional Ni-base superalloys. The hot working range of INCOLOY alloy 945 is 1700°F to 2100°F (930°C to 1150°C). Hot working characteristics of alloy 945 are very similar to INCONEL alloy 718. Alloy 945 can be easily cold worked for up to 40% cold work. Figure 3 shows the work hardening curve of alloys 945, MONEL alloy K-500, 304 stainless steel, and alloy 718. The work hardening rate of alloy 945 is similar to that of alloy K-500.

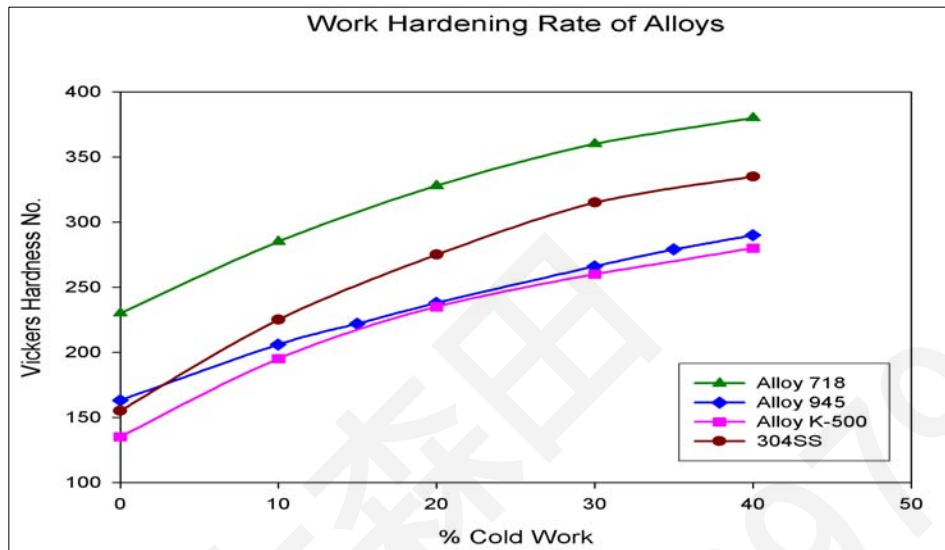


Figure 3. Work hardening rate of various alloys.



The excellent machinability of INCOLOY alloy 945 is a very important factor in the fabrication of complex gas well components (Photo courtesy of FMC Petroleum Equipment Group).

Heat Treating

Alloy 945 can be annealed in the temperature range of 1750°F (954°C) to 1950°F (1066°C). For optimum microstructure and properties, the alloy should be annealed in the range of 1850°F (1010°C) to 1950°F (1066°C). Figure 4 shows grain size and hardness versus annealing temperature. A plot of grain size versus annealing temperature for a number of different mill products is shown as Figure 5.

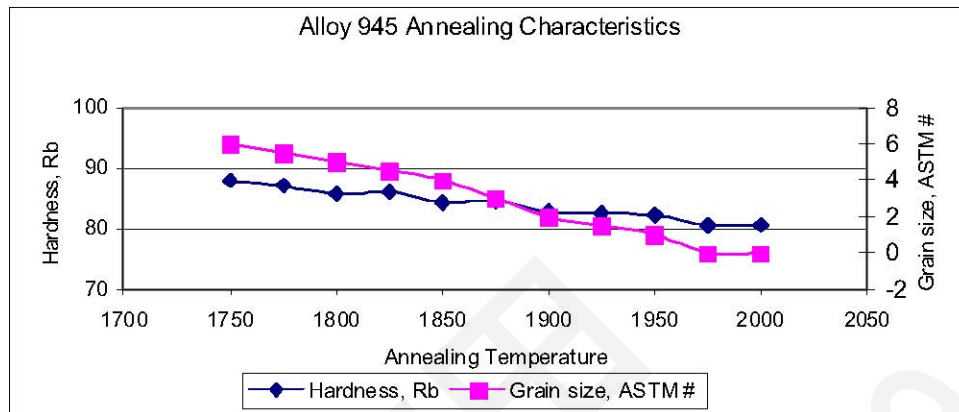


Figure 4. Hardness and grain size versus annealing temperature for alloy 945.

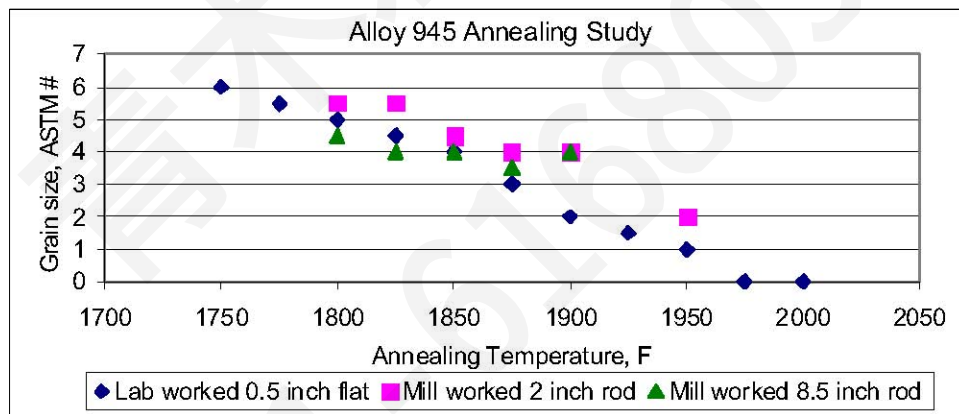


Figure 5. Grain size versus annealing temperature of alloy 945. The data showing a band of grain size is generated using various product forms.

The recommended age hardening treatment of alloy 945 is 1300°F-1350°F (704°C-732°C)/6-8 hours, furnace cool 50°F-100°F (26-56°C)/hour to 1125°F-1175°F (607°C-635°C), hold at temperature for 6-8 hours, air cool. Figure 6 shows hardness of annealed material exposed for 8 hours at the age-hardening temperature.

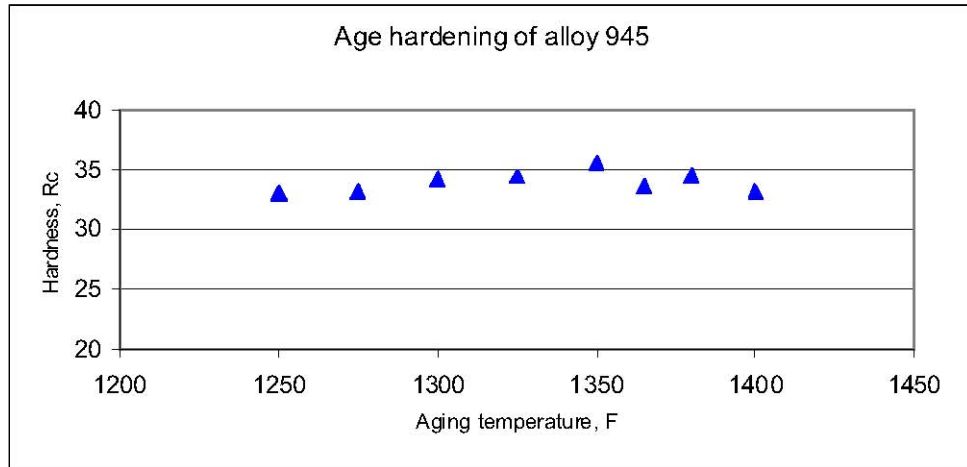


Figure 6. Age hardening of INCOLOY alloy 945. The material was annealed and exposed at the aging temperature for 8 hours.

Microstructure

Conventional grinding and polishing techniques for Ni-based alloys are adequate for INCOLOY alloy 945. To reveal the microstructure, the recommended procedure is to swab etch using Seven Acids etchant (Hydrochloric acid - 300ml, Nitric acid - 60ml, Phosphoric acid - 60ml, Hydrofluoric 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 - 100ml). The typical microstructure of annealed and aged material is shown in Figure 7. Age-hardening heat treatment of annealed material precipitates sub-micron size $\text{Ni}_3(\text{TiNbAl})$ -type gamma prime and $\text{Ni}_3(\text{NbTiAl})$ -type gamma double prime, which are responsible for the high strength of alloy 945.

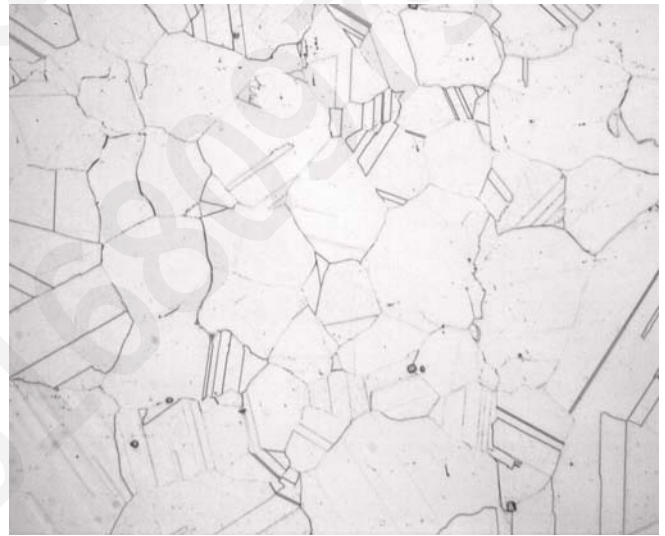


Figure 7. Optical photograph of alloy 945. The original photograph was taken at 100X.

Joining

INCOLOY alloy 945 can be readily joined by the gas-tungsten-arc welding (GTAW) and pulsed gas-metal-arc welding (P-GMAW) processes using matching composition filler metal or INCO-WELD® filler metal 725NDUR®. For best results, the current for P-GMAW process should not exceed 185 amperes for standard power sources in the “spray arc” metal transfer mode. Submerged-arc welding (SAW) and shielded-metal-arc welding (SMAW) are not recommended for alloy 945. Tables 24 and 25 show room temperature mechanical properties and impact strength for alloy 945 welded with INCO-WELD filler metal 725NDUR. Table 26 shows tensile properties of alloy 945 welded with INCOLOY filler metal 945. In these welding studies, the base plate was annealed prior to welding. Following welding, the material was re-annealed and aged using standard alloy 945 heat treatment procedures. The mechanical properties of filler metal 945 GTA weldments were found to be superior to those of filler metal 725NDUR deposits.

Table 24 – Mechanical properties of cross weld specimens of alloy 945 welded with INCO-WELD® 725 NDUR® filler metal. All tests failed in the weld metal. Values are the average of two tests.

Welding Process	Test Temperature	Yield Strength		Tensile Strength		Elongation	Reduction of Area
	%	ksi	MPa	ksi	MPa	%	%
GTAW	Room Temp	129	846	164	1128	23	35
	350°F	115	793	149	1030	20	41
P-GMAW	Room Temp	123	850	159	1098	19	39
	350°F	114	783	145	1001	19	37

Table 25 – Impact strength of alloy 945 welded with INCO-WELD 725 NDUR filler metal. Testing was done at -75°F. Values are the average of three tests.

Welding Process	Weld Center		Heat-Affected Zone	
	ft•lb	Joules	ft•lb	Joules
GTAW	75	101	80	109
P-GMAW	76	103	62	84

Table 26 – Mechanical properties of cross weld specimens of alloy 945 welded with filler metal 945. All tests failed in the base metal. Values are the average of two tests.

Welding Process	Test Temperature	Yield Strength		Tensile Strength		Elongation	Reduction of Area
	%	ksi	MPa	ksi	MPa	%	%
GTAW	Room Temp	139	958	176	1214	25.3	42.8
	350°F	130	896	163	1124	21.7	40.9

Machinability

INCOLOY alloy 945 exhibits good machinability in either the solution annealed or aged condition. Rigid tools with positive rake angles and techniques that minimize work hardening of the material should be used. Best results are obtained by rough machining components prior to age hardening and finishing after final heat treatment.

Specifications

INCOLOY alloy 945 is designated as UNS N09945. The alloy is approved for use in oil and gas applications by NACE MR0175 / ISO 15156-3 up to NACE level VII and to level VI-450°F. Properties of alloy 945 and 945X are defined in the Special Metals Corporation internal specification HA 119 and HA123, respectively. Properties for shaft-grade bar are defined in specifications HA 121 and HA 122.

Available Product Forms

Alloy 945 is available as round bar, forging stock, and tubing.