TECHNICAL BULLETIN

INCOLOY® ALLOY 945®: HIGH STRENGTH AND CORROSION RESISTANCE FOR DEMANDING OIL & GAS APPLICATIONS

SPECIAL METALS
A PCC COMPANY

INCOLOY® ALLOY 945®

945® 09945 - -

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945

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945 0175 / 15156-3 -450

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. Typical mechanical properties of various size rods are shown in Table 7. Limiting mechanical properties of alloy 945, 925 and 718 are presented in Table 8. In addition, cold worked and directly aged products are available with even higher levels of strength for applications such as shafting. Typical mechanical properties are given in Table 11. Limiting mechanical properties for shafting are reported in Table 12. INCOLOY alloy 945 can be easily extruded and cold worked. Typical properties of seamless tubes manufactured by extrusion in combination with pilgering / drawing are shown in Table 13 and limiting properties are shown in Table 14.

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 and HA 121. Copies are available by contacting the Special Metals Research and Technology Department.

Table 1: 945 %

	46 5-48 0
	19 5-23 0
	3 00-4 00
	2 80-3 50
	1 50-3 00
	0 50-2 50
	0 01-0 70
	1 00
	0 50
	0 010
	0 020
0 005	0 040

Table 2: 945

/ 3	0 296
/ 3	8 2
	2317-2510
	1270-1377
/	663
	1 10
200	15 9 / 1 003
10^6	29 1
	200 8

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.

Tables and Figures

Table 3: Coefficient of thermal expansion. The values are mean coefficient of linear expansion between 77ºF (25ºC) and the listed temperature.

Temperature		Coefficient of thermal expansion	
ºF	ºC	In/in/ºF·10⁻⁶	cm/cm/ºC·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

4.

Temperature		Specific Heat	
ºC	ºF	J/kg·ºC	BTU/lb·ºF
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

5:

Temperature		Thermal Conductivity	
°C	°F	W/m·°C	BTU·in/ft2·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

6: E

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

Image 1: INCOLOY alloy 945 flapper for a sub- surface safety valve.

945 - - -
3 -
3 - -
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945 7 8
22 559 22 559
- 9 10 945

945
11 12

945 / 13
14 - 945 500° 160°
15 945 1

945 :
:1850° -1950° 1010° -1066° 4
:1300° -1350° 704° -732° /6-8 50° -100° 26-56 ° / 1125° - 1175°
607° – 635° 6-8

Table 7:Typical mechanical properties of annealed and aged round bar of INCOLOY alloy 945. Tensile properties are in longitudinal orientation at room temperature. Impact strength was determined at -75°F. Impact strength for the rod size less than 3.5 inch diameter was determined in longitudinal orientation and for 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: 945 925 and718

Alloy	SMC Spec	Minimum Yield Strength		Minimum Tensile Strength		Minimum Elongation	Minimum Reduction of Area	Minimum Average Impact	Minimum Hardness	Maximum Hardness
		ksi	MPa	ksi	MPa	%	%	ft-lb	Rc	Rc
925	HA 46 Rev. 14	110	759	140	965	18	25	35	26	38
945	HA 119 Rev. 7	130	896	150	1034	18	25	40	32	42
718	HA 79 Rev.	125	861	150	1034	20	35	35	32	40

Table 9: 22 559 945 -75°

	YS, ksi	UTS, ksi	% El	% RA	Grain size, ASTM #	Impact toughness	120 – hardness range
Surface	140.1	169.9	29.4	46.9	2	-	37.8 - 40.0
Mid-radius	138.6	167.8	27.5	40.7	2.5	75/74.3/75.3	
center	139	170.7	28.7	52.3	2	-	

Table 10: 945 6 152

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

Table11: - 945

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 12: - 945

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	C
945	HA 121 Rev. 0	165	1138	180	1281	15	20	-	38	46

Table 13: 945

Tube Size	Heat Lot	Tensile Properties YS ksi	UTS ksi	El	RA	Hardness HRC	Impact Ft-lbs	ASTM Grain Size
9.37"OD	HW1260PK	133.4	176.2	31.6	52.4	34.2	60/63/64	4
0.595"W	131	127.6	171.4	34.1	50.4	38	67/68/68	
8.14"OD	HW1260PK	132.8	172.0	31.7	48.8	35.3	64/64/65	3.5
0.85"W	132	133.7	170.0	34.7	53.3	36	71/70/70	
8.50"OD	HW1260PK	132.9	175.7	30.6	48.8	36.1	62/60/63	4
0.72"W	133	131.2	171.1	35.1	55.0	38	69/69/69	
Anticipated minimum properties		125	150	18	25	42 max	50	2 or finer

Table 14: / 945

Alloy	SMC Spec	Minimum Yield Strength ksi	Minimum Yield Strength MPa	Minimum Tensile Strength ksi	Minimum Tensile Strength MPa	Minimum Elongation %	Minimum Reduction of Area %	Minimum Impact ft-lb (Joules)	Minimum Hardness Rc	Maximum Hardness C
945	HA 124 Rev. 1	125	862	150	1034	18	25	40 (54)	34	42

Table 15: - 945.

Alloy	180°F	225°F	250°F	300°F	350°F	400°F	450°F	500°F
945	0.99	0.97	0.97	0.91	0.90	0.89	0.88	0.88

Listed values are typically of average of 5 samples from different heat/lots except 180°F, 225°F, and 250°F, where averages of duplicate tests are listed.

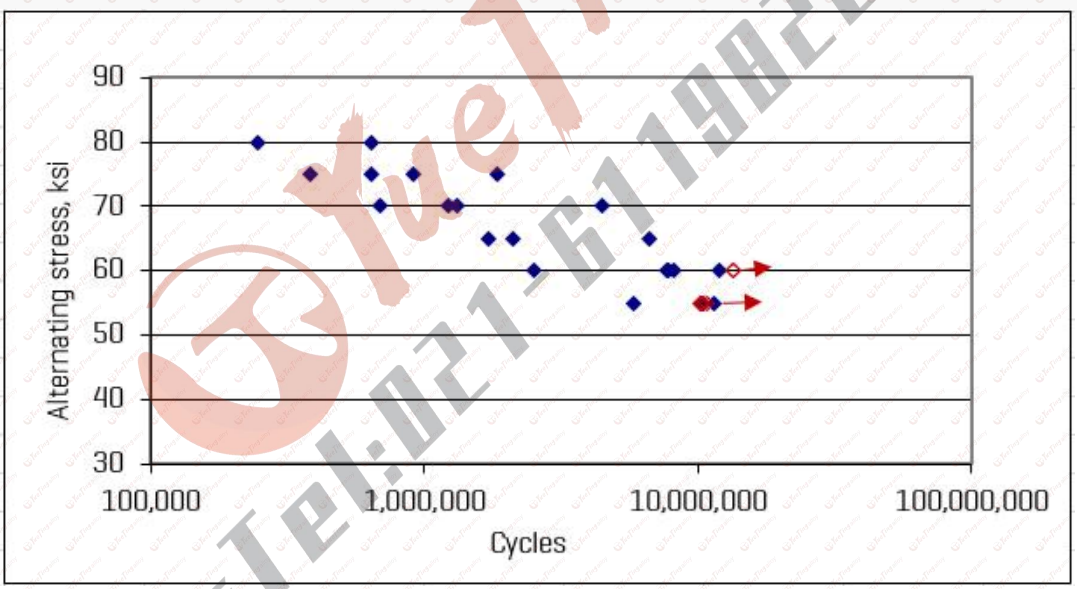

Figure 1: 945 1
100 - -1 The arrows indicate discontinued tests.

0175/ 15156-3: 2003 945
16

Table 16: 0175/ 15156: 2003

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

2 -

0175 / 15156-3 -450

17 18

0177-2004 - 2 51 0 15 3 8

0 95 24 1 20

Table 17: - 3500 508 2 3500 508

225 % 150 000 / 205 401 100%

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 18: - -450 :3500 508 2 3500 508

220 % 120 000 / 232 450 100%

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

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.

19: 0177-2004 -
90%

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: 0177-2004 -
90%

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

5% 0 5%
24 75 2 100 2 7 3 6

Image 2: A forging for a tubing hanger of alloy 945.

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 shows significantly better resistance than the stainless steel.

21: 123 -
25% 225 108 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: 36 -
45% 2 310 155

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

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 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

945 workability is -
945 1700 2100 930 1150 945
718 945 40%
2 945 -500 304 718
945 -500

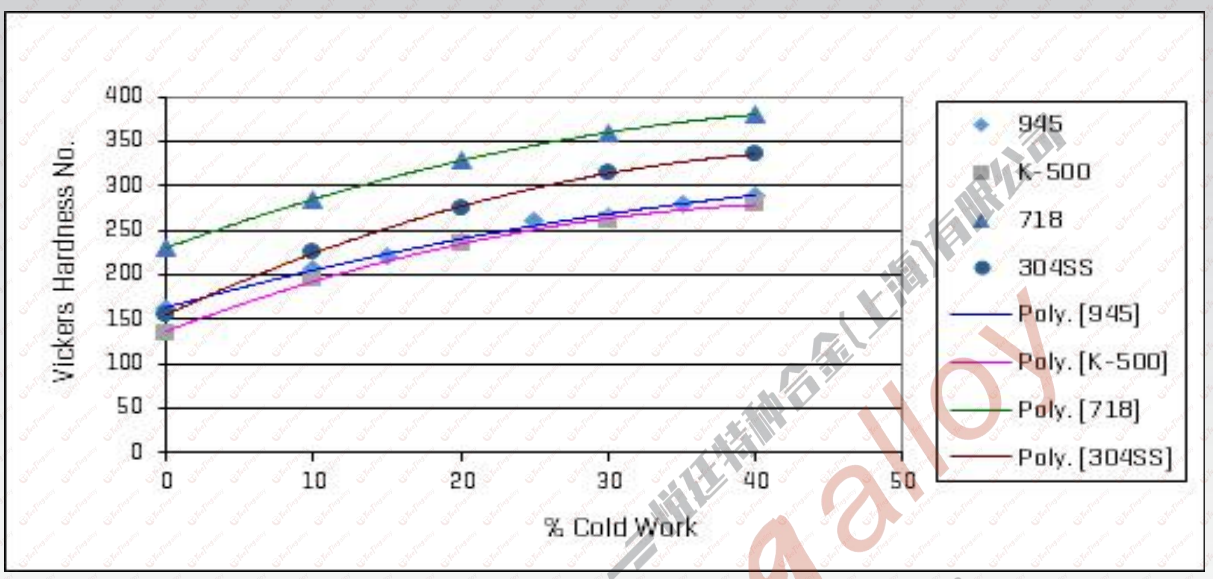

Figure 2:

Alloy 945 can be annealed in the temperature range of 1750ºF (954ºC) to 1950ºF (1066ºC). For optimum microstructure and properties, the alloy should be annealed in the range of 1850ºF (1010ºC) to 1950ºF (1066ºC). Figure 3 shows grain size and hardness versus annealing temperature. The samples were annealed at temperature for 1 hour and water quenched. A plot of grain size versus annealing temperature for a number of different mill products is shown as Figure 4.

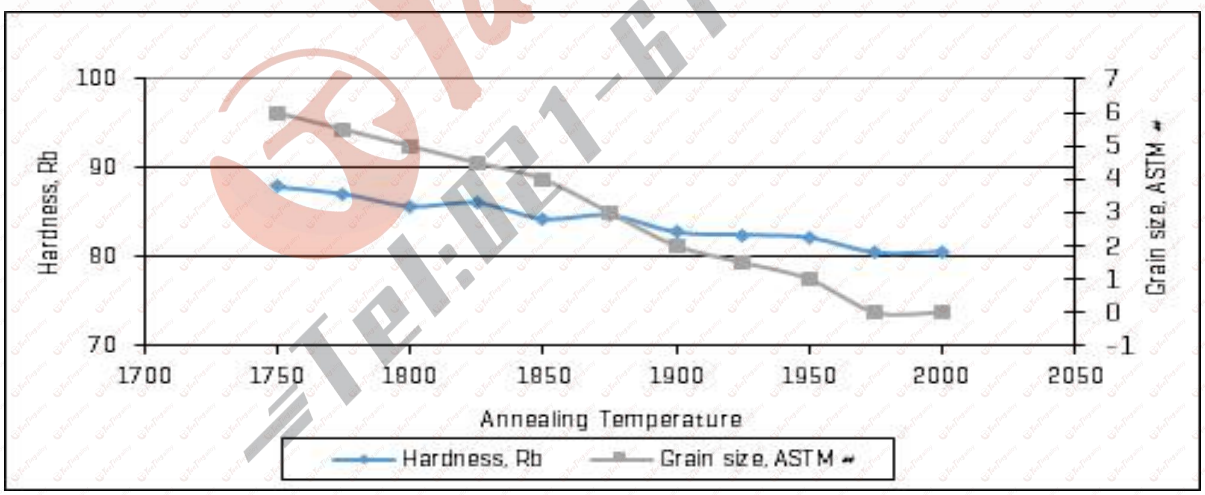

Figure 3: 945

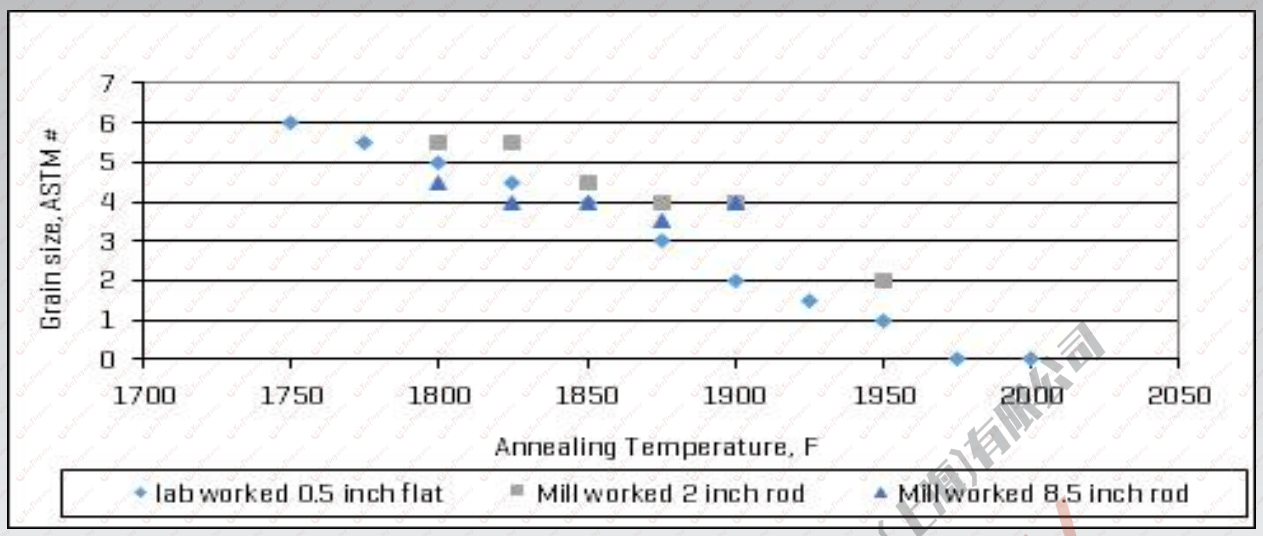

Figure 4: 945

The recommended age hardening treatment of alloy 945 is 1300ºF-1350ºF (704ºC-732ºC)/6-8 hours, furnace cool 50ºF-100ºF (26-56ºC)/hour to 1125ºF-1175ºF (607ºC-635ºC), hold at temperature for 6-8 hours, air cool. Figure 5 shows hardness of annealed material exposed for 8 hours at the age-hardening temperature.

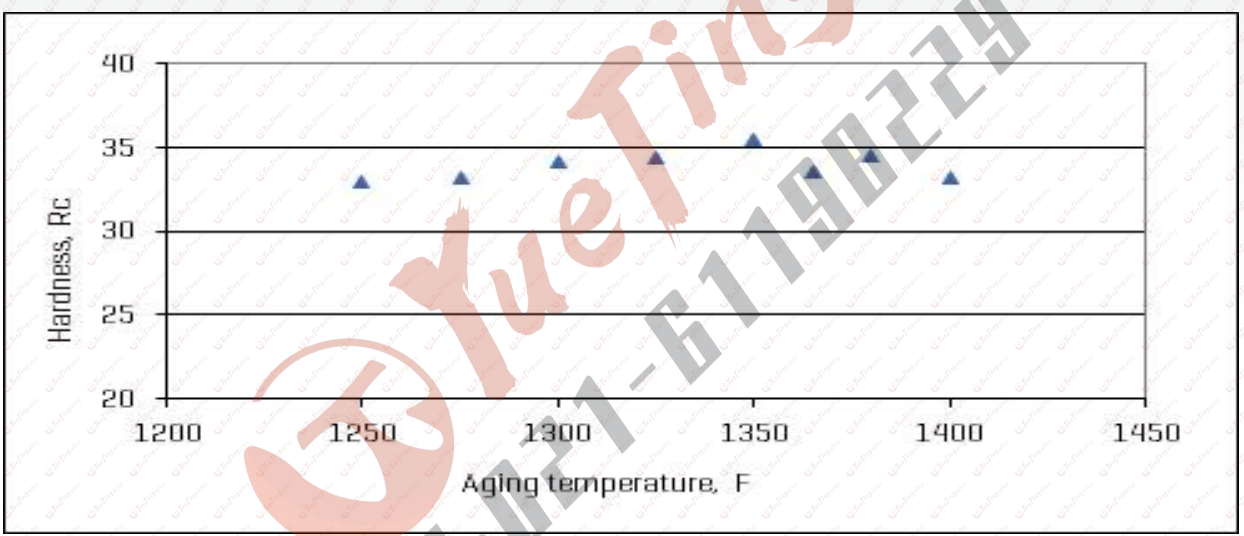

Figure 5: 945 8

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) or short time immersion etch using Kallings etchant (Methanol - 100ml, Cupric Chloride - 5gm, and Hydrochloric acid - 100ml). The typical microstructure of annealed and aged material is shown in Figure 6. Age-hardening heat treatment of annealed material precipitates sub-micron size Ni3 (TiNbAl)-type gamma prime and Ni3 (NbTiAl)-type gamma double prime, which are responsible for the high strength of alloy 945. Figure 7 is a Time-Temperature-Transformation (TTT) Diagram for alloy 945. This TTT diagram was generated using a mill produced rod.

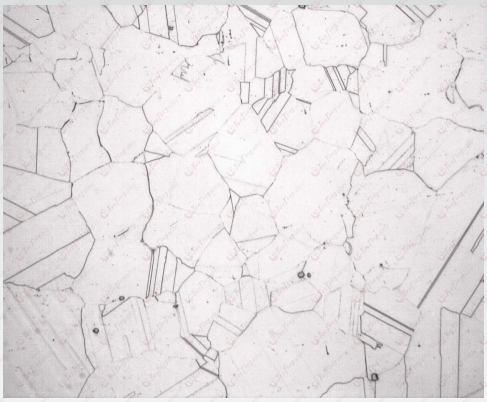

Figure 6: Typical microstructure of annealed and aged INCOLOY alloy 945 bar.

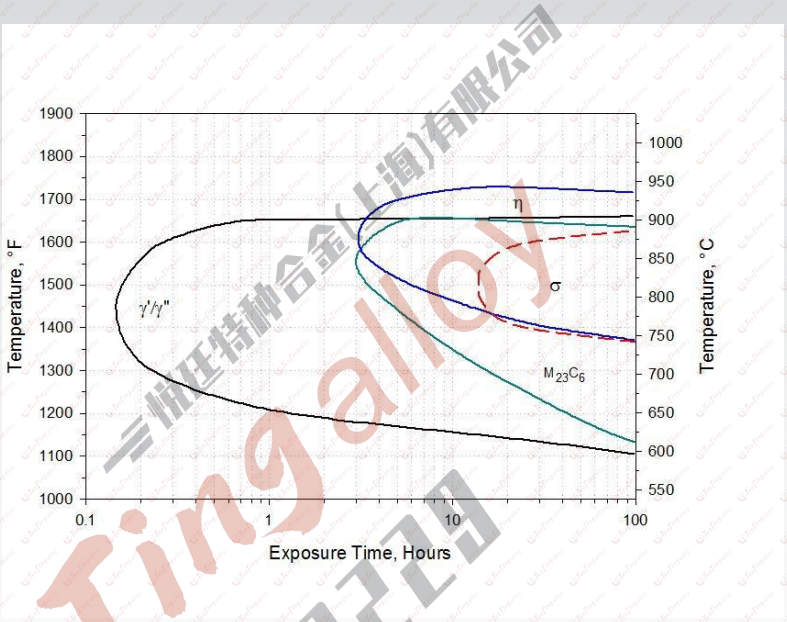

Figure 7: Time-Temperature-Transformation Diagram of Alloy 945, Sarwan Mannan, 7th International Symposium on Superalloy 718 and Derivatives, October 10-13, 2010, Pittsburgh, PA.

945 - - - - -
- 725 a 945 ® -
185 -
- - 945 24
945 - 725 25
- 945
26 945 945
26 945

27 350° -75°
945 -

Table 24: Mechanical properties of cross weld specimens of alloy 945 welded with INCO-WELD 725 NDUR filler metal. All tests fractured 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: 945 - 725
-75

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: 945 945

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

Table 27: 945 945X -
75° 50 7 - 68 7

Welding Process	Test Temperature	Yield Strength		Tensile Strength		Elongation	Reduction of Area
		ksi	MPa	ksi	MPa	%	%
GTAW	Room Temp	139	958	176	1214	29.0	51.0
	350°F	133	917	164	1131	19.0	48.0

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. INCOLOY alloy 945 can generally be machined using the same tools and procedures established for machining INCONEL alloy 718.

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-450ºF. Properties of alloy 945 are defined in the Special Metals Corporation internal specifications HA 119 Rev 7. Properties for shaft-grade bar are defined in specifications HA 121 Rev 0. Properties of seamless tubing is defined in specification HA 124 Rev 1.

Alloy 945 is available as round bar, forging stock, and tubing. Other forms are possible with consultation with SMC sales/ technical group.

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