# INCOLOY® alloys 945 / 945X

SPECIAL METALS
A PCC Company

# Contents



INCOLOY alloy 945 machined bars and forgings intended for fabrication of high performance components for service in aggressive environments in the oil and gas industry.

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 chorides. 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-450ºF 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, ºF | 2317-2510 |
| ºC | 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 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 |

**Table 4** – Specific Heat

| 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 |

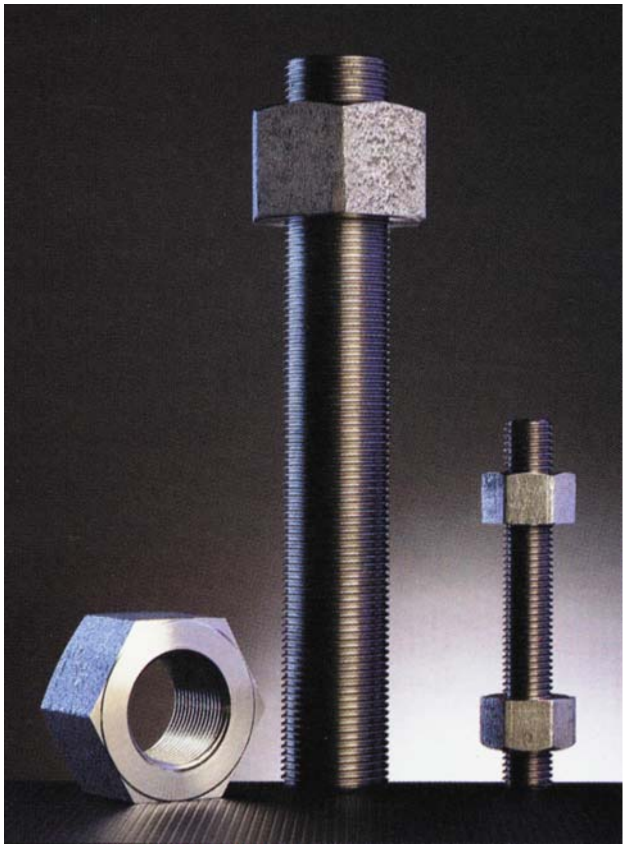
**Table 5** – Thermal Conductivity

| Temperature | | Thermal Conductivity | |
|---|---|---|---|
| ºC | ºF | W/m•ºC | BTU•in/ft$^2$•h•ºF |
| 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 |
|---|---|---|---|
| ºF | $10^3$ 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 |

| ºC | 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 it contents of niobium, titanium, and aluminum. The precipitation hardening (age hardening) heat treatment induces the formation of $Ni_3$(TiNbAl)-type (gama prime) and $Ni_3$(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 450ºF 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 - 1850ºF-1950ºF (1010ºC-1066ºC) for ½ to 4 hours, water quench.

Age Hardening - 1300ºF-1350ºF (704ºC-732ºC / 6-8 hours, furnace cool at 50ºF-100ºF (26ºC-56ºC) /hour to 1125ºF-1175ºF (607ºC-635ºC), 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 -75ºF. 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 -75ºF. 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-garde 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.

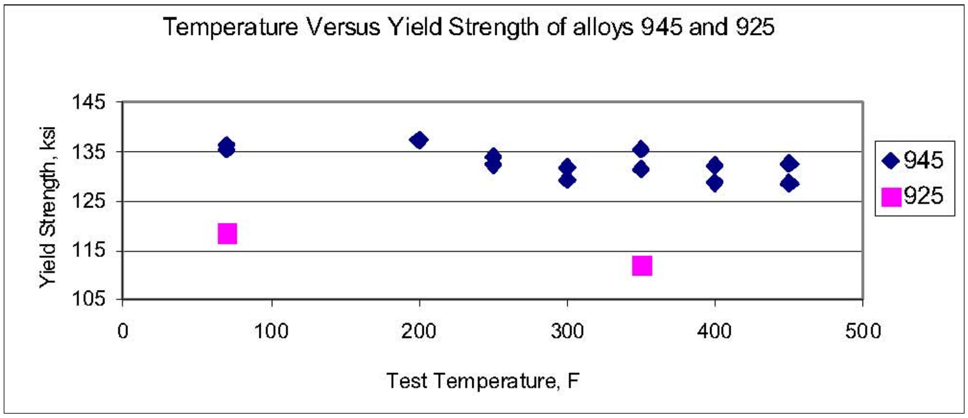
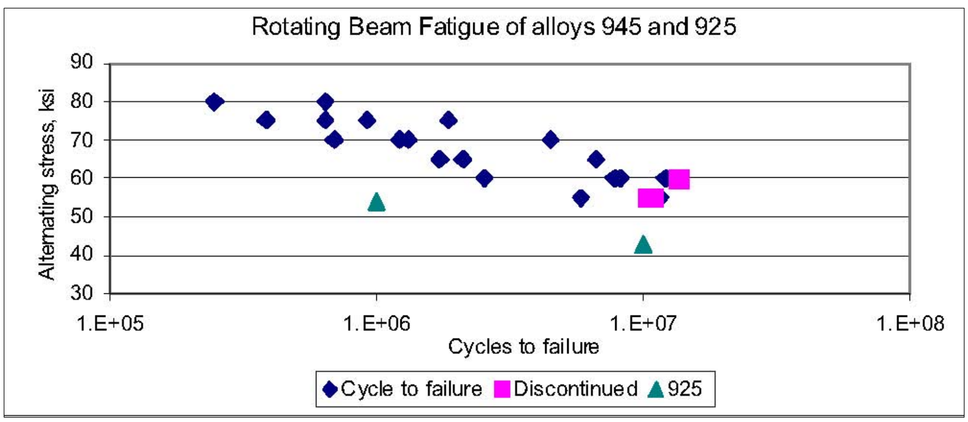



**Figure 2.** Rotating beam fatigue strength of INCOLOY alloys 945 and 925. Testing was done at $K_t$ of 1, at a frequency of 100Hz, and R-value of -1.



## 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 $H_2S$-Containing Environments:

Test results of triplicate samples from three commercial heats in NACE MR0175 / ISO 15156-3 for levels VII and VI-450º 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) $H_2S$, 3500 kPa (508 psia) $CO_2$, 25 wt% (150,000 mg/1 C1) NaC1, at 205ºC (401ºF). 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-450ºF. The environmental conditions were: 3500 kPa (508 psia) $H_2S$, 3500 kPa (508 psia) $CO_2$, 20 wt% (120,000 mg/1 C1) NaC1, at 232ºC (450ºF). 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 250ºF (121ºC) and 300ºF (149ºC) 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 $H_2S$ at room temperature, strain rate 4.0 X $10^{-6}$ $s^{-1}$.

| 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.

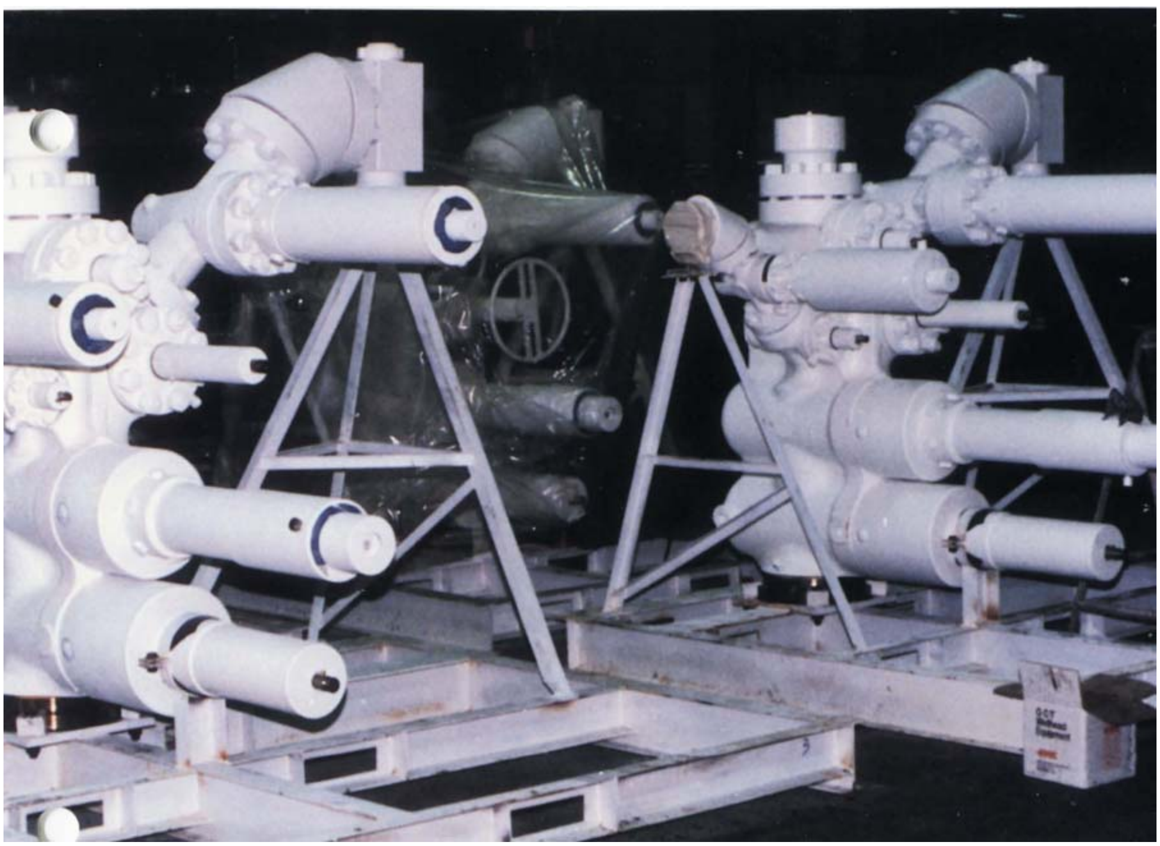
**Table 19** – Testing for GHSC was done in accordance with TM0177-2004, method A – Tensile test, in NACE solution A[a]. Samples were coupled to steel via the stressing bolt and were stressed to 90% of actual yield strength.

| 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 (24ºC, 75ºF) 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 225ºF (108ºC) 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% $MgCl_2$ at 310ºF (155ºC).

| 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, ºC |
|---|---|
| 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 1700ºF to 2100ºF (930ºC to 1150ºC). 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.

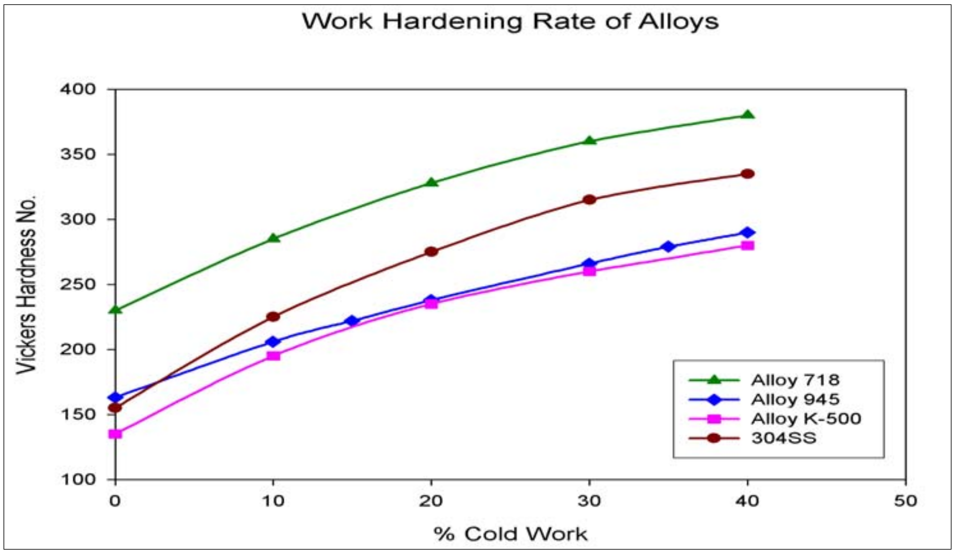



**Figure 3.** Work hardening rate of various alloys.

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 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 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.

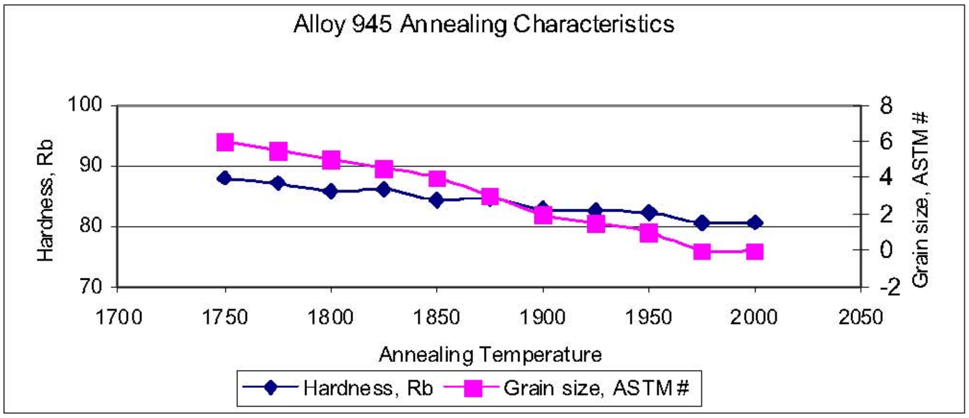



**Figure 4.** Hardness and grain size versus annealing temperature for alloy 945.

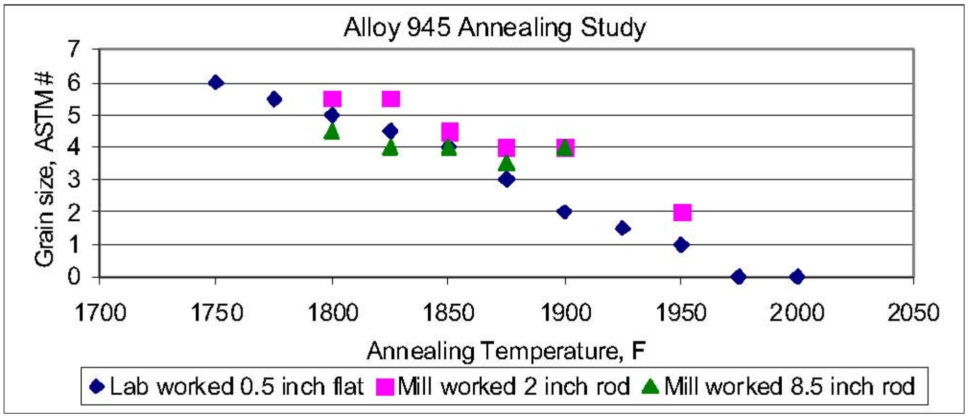



**Figure 5.** Grain size versus annealing temperature of alloy 945. The data showing a band of grain size is generated using various product forms.

The recommended age hardening treatment of alloy 945 is 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 6 shows hardness of annealed material exposed for 8 hours at the age-hardening temperature.

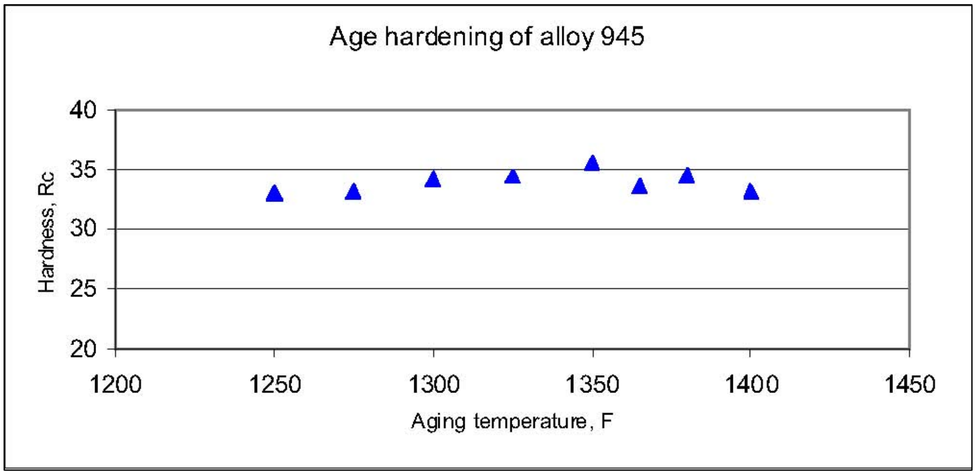



**Figure 6.** Age hardening of INCOLOY alloy 945. The material was annealed and exposed at the aging temperature for 8 hours.

## 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 $Ni_3$ (TiNbAl)-type gamma prime and $Ni_3$ (NbTiAl)-type gamma double prime, which are responsible for the high strength of alloy 945.

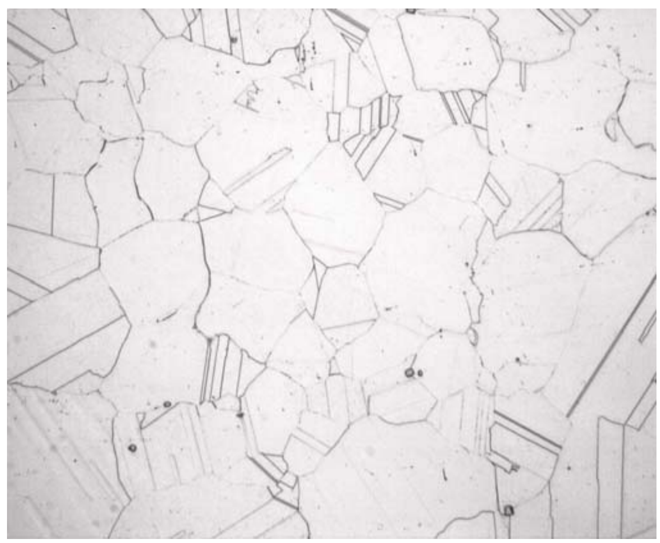


**Figure 7**. Optical photograph of alloy 945. The original photograph was taken at 100X.

## 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 |
| | 350ºF | 115 | 793 | 149 | 1030 | 20 | 41 |
| P-GMAW | Room Temp | 123 | 850 | 159 | 1098 | 19 | 39 |
| | 350ºF | 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 -75ºF. 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 |
| | 350ºF | 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-450ºF. 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.

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www.specialmetals.com

## U.S.A.

**Special Metals Corporation**

**Billet, rod & bar, flat & tubular products**
3200 Riverside Drive
Huntington, WV 25705-1771
Phone +1 (304) 526-5100
+1 (800) 334-4626
Fax +1 (304) 526-5643

**Billet & bar products**
4317 Middle Settlement Road
New Hartford, NY 13413-5392
Phone +1 (315) 798-2900
+1 (800) 334-8351
Fax +1 (315)798-2016

## United Kingdom

**Special Metals Wiggin Ltd.**
Holmer Road
Hereford HR4 9SL
Phone +44 (0) 1432 382200
Fax +44 (0) 1432 264030

**Special Metals Wire Products**
Holmer Road
Hereford HR4 9SL
Phone +44 (0) 1432 382518
Fax +44 (0) 1432 353995

## Germany

**Special Metals Deutschland Ltd.**
Postfach 20 04 09
40102 Düsseldorf
Phone +49 (0) 211 38 63 40
Fax +49 (0) 211 37 00 81

## Hong Kong

**Special Metals Pacific Pte. Ltd.**
Unit A, 17th Floor, On Hing Bldg
1 On Hing Terrace
Central, Hong Kong
Phone +852 2439 9336
Fax +852 2530 4511

## India

**Special Metals Services Ltd.**
No. 60, First Main Road,
First Block
Vasantha Vallabha Nagar
Subramanyapura Post
Bangalore 560 061
Phone +91 (0) 80 2666 9159
Fax +91 (0) 80 2666 8918

## The Netherlands

**Special Metals Service BV**
Postbus 8681
3009 AR Rotterdam
Phone +31 (0) 10 451 44 55
Fax +31 (0) 10 450 05 39

## China

**Special Metals Pacific Pte. Ltd.**
Room 1409
United International Building
No. 19 DongSanHuanNanLu
Chaoyang District
Beijing 100021, China
Phone +86 21 3229 0011
Fax +86 21 6288 1811

**Special Metals Pacific Pte. Ltd.**
Room 2001, Long Tai
International Building
No. 198 Zhongshan East Road
Nanjing 210002, Jiangsu Province
Phone +86 25 8440 1722
Fax +86 25 8451 1822

## Singapore

**Special Metals Pacific Pte. Ltd.**
24 Raffles Place
#27-04 Clifford Centre
Singapore 048621
Phone +65 6532 3823
Fax +65 6532 3621

## Affiliated Companies

**Special Metals Welding Products**
1401 Burris Road
Newton, NC 28658, U.S.A.
Phone +1 (828) 465-0352
+1 (800) 624-3411
Fax +1 (828) 464-8993

**Controlled Products Group**
590 Seaman Street, Stoney Creek
Ontario L8E 4H1, Canada
Phone +1 (905) 643-6555
Fax +1 (905) 643-6614

**A-1 Wire Tech, Inc.**
**A Special Metals Company**
4550 Kishwaukee Street
Rockford, IL 61109, U.S.A.
Phone +1 (815) 226-0477
+1 (800) 426-6380
Fax +1 (815) 226-0537

**DAIDO-*SPECIAL METALS* Ltd.**
**A Joint Venture Company**
Daido Shinagawa Building
6-35, Kohnan 1-chome
Minato-ku, Tokyo 108-0057, Japan
Phone +81 (0) 3 5495 7237
Fax +81 (0) 3 5495 1853