# CUSTOM AGE 625 PLUS®ALLOY - A HIGHER STRENGTH ALTERNATIVE TO ALLOY 625

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## Abstract

Highly-corrosion-resistant, age-hardenable alloys are needed in severely-corrosive environments such as those encountered in deep sour-gas wells. Age-hardenability is important because high strength levels (120 ksi/827 MPa minimum 0.2% yield strength) are required in large section sizes. Custom Age 625 PLUS® alloy was developed to provide higher strength levels than those attainable with alloy 625 along with similar corrosion resistance (more corrosion-resistant than alloy 718). The development and metallurgy of 625 PLUS alloy are reviewed. The mechanical properties and corrosion resistance of 625 PLUS, 625, and 718 alloys are compared.

**Superalloys 718, 625 and Various Derivatives**
**Edited by Edward A. Loria**
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## Introduction

Within the last ten years, there has been a high level of interest in highly-corrosion-resistant, age-hardenable alloys. Production of deep sour-gas wells has been the primary driving force for this interest. Age-hardenable alloys are desirable because high strength levels can be obtained in large section sizes (>4-inch or 102-mm diameter) which are very difficult to strengthen by cold or warm working. Existing age-hardenable nickel-base alloys such as alloys 718 and X-750 have been used in oil-field applications but have insufficient corrosion resistance in the most severe environments which contain chlorides and sulfides at high pressures and temperatures up to about 450°F (232°C). Nickel-base alloys 625 and C-276 have excellent corrosion resistance in many severe environments but must be cold worked to obtain high strength levels.

Custom Age 625 PLUS alloy was developed to combine the excellent corrosion resistance of alloy 625 with age-hardening capability similar to that of alloy 718. This paper summarizes the development and metallurgy of 625 PLUS alloy including the mechanical properties and corrosion resistance of the alloy. The alloy development, mechanical properties, corrosion resistance, heat treatment, and welding metallurgy of 625 PLUS alloy have been the subjects of previous papers (1-4).

## Alloy Development/Composition

A review of the literature indicated that a nickel-base alloy with high levels of chromium and molybdenum would be required to resist pitting corrosion, crevice corrosion, and stress-corrosion cracking (SCC) in chloride/sulfide-containing environments such as those encountered in deep sour-gas wells. Additions of columbium, titanium and aluminum could be used to promote age hardening. However, the alloy would require a critical balance of these elements to provide high strength and excellent corrosion resistance without precipitation of deleterious phases.

Corrosion tests used to evaluate the experimental compositions included pitting and crevice corrosion tests in chloride environments, sulfide-stress-cracking tests in the NACE TM0177 environment* (steel coupled at ambient temperature) and chloride-stress-cracking tests at 155°C. In addition, the alloys were evaluated for SCC resistance in a simulated deep-well environment containing 25% NaCl, 0.5 g/l elemental sulfur and 1400 psig (9.7 MPa) $H_2S$ at 400-500°F (204-260°C). Stressed samples were exposed for 4-6 weeks in autoclaves. Room-temperature tensile properties, Charpy V-notch impact toughness and microstructure were also evaluated.

Figure 1 summarizes the effects of chromium and molybdenum on properties of the experimental nickel-base alloys after solution treating and double aging to yield strengths of 120-140 ksi (827-965 MPa). Minimum levels of chromium and molybdenum were required to obtain the desired level of corrosion resistance. Excessive chromium and molybdenum reduced corrosion resistance, hot workability and toughness. Extensive precipitation of chromium and molybdenum-rich phases contributed to the reduction in properties at high chromium and/or molybdenum contents. An excellent combination of properties was obtained using 18% to 22% Cr and 7.5% to 11% Mo provided that the sum of the two elements did not exceed 31%.

Figure 2 summarizes the effects of columbium and titanium on properties of the experimental nickel-base alloys after solution treating and double

*5% NaCl + 0.5% Acetic acid purged with $H_2S$

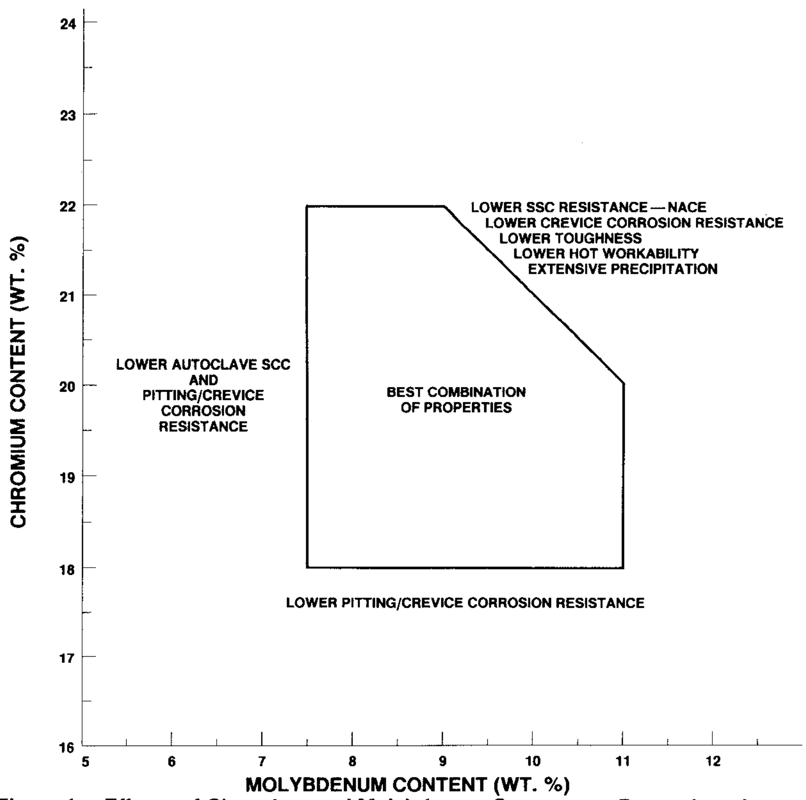


*Figure 1*—Effects of Chromium and Molybdenum Contents on Properties of Experimental Age-Hardenable Nickel-Base Alloys

*Base Analysis:* 0.015% C, 59–63% Ni, 3% Cb, 1.25% Ti, 0.25% Al, Bal. Fe

*Condition:* 1900°F/1h/AC + 1350°F/8h/FC to 1150°F/8h/AC to obtain 120–140 ksi Y.S.

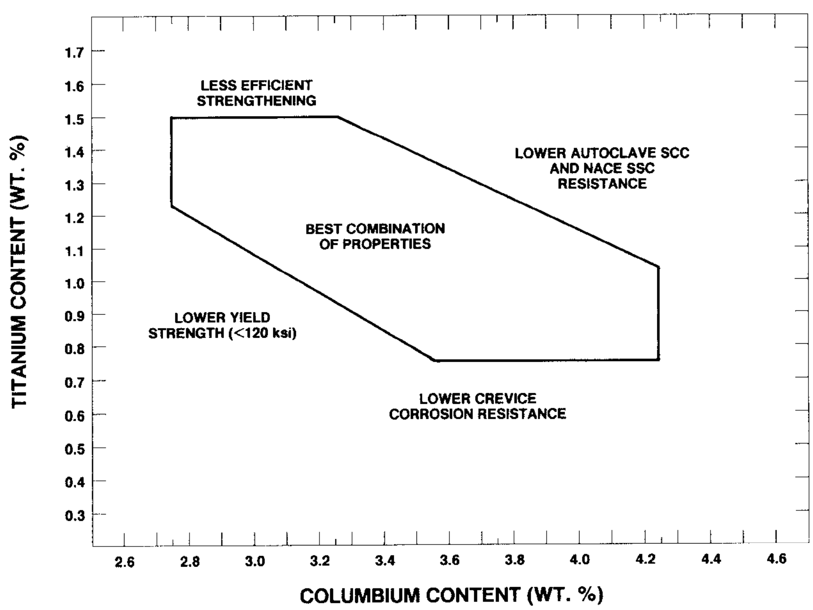


*Figure 2*—Effects of Columbium and Titanium Contents on Properties of Experimental Age-Hardenable Nickel-Base Alloys

*Base Analysis:* 0.015% C, 19% Cr, 9% Mo, 59–63% Ni, 0.25% Al, Bal. Fe

*Condition:* 1900°F/1h/AC + 1350°F/8h/FC to 1150°F/8h/AC aging. It was found that alloys strengthened with columbium and titanium had significantly better properties than alloys strengthened with titanium or titanium and aluminum. Thus, only compositions strengthened with columbium and titanium are shown in Figure 2.

Figure 2 shows that the best combination of properties was obtained using 2.75% to 4.25% Cb and 0.75% to 1.5% Ti. Alloys with less than about 0.75% Ti had much lower resistance to crevice corrosion than alloys with higher titanium contents. Within the ranges stated, minimum levels of columbium and titanium were needed to permit age-hardening to a yield strength of 120 ksi (827 MPa). On an atomic percent basis, columbium was more effective than titanium in increasing strength so compositions with more than about 1.5% Ti were not preferred. While higher levels of columbium and titanium provided yield strengths of 140 ksi (965 MPa) and above, resistance to stress-corrosion cracking was reduced. Aluminum participates in the age-hardening reaction used to strengthen these alloys and also stabilizes the hardening precipitate. However, aluminum was a far less effective strengthener than columbium and titanium in these alloys and, for this reason, was kept below 0.35%.

In experimental alloys with yield strengths of 120-140 ksi (827-965 MPa), it was found that a nickel content of at least 60% provided good resistance to stress-corrosion cracking in boiling 45% $MgCl_2$. Low-carbon contents resulted in highest strength and best corrosion resistance and minimized precipitation of intergranular carbides during aging.

Many of the compositions discussed above had corrosion resistance similar to alloy 625 (better than alloy 718) and were age-hardenable to yield strengths of 120 ksi and above. Subsequent evaluations of production heats revealed that the nominal composition listed in Table I provided an excellent combination of mechanical properties and corrosion resistance. UNS N07716 has been assigned to the alloy which is called Custom Age 625 PLUS.

Table I Chemical Compositions (Wt%) of 625 PLUS, 625 and 718 Alloys

| | Custom Age 625 PLUS | | | |
|---|---|---|---|---|
| | Ranges | Nominal | Alloy 625 | Alloy 718 |
| Carbon | 0.03 max. | 0.01 | 0.04 | 0.04 |
| Chromium | 19.00-22.00 | 21 | 22 | 18 |
| Molybdenum | 7.00-9.50 | 8 | 9 | 3 |
| Nickel | 59.00-63.00 | 61 | 62 | 52.5 |
| Columbium | 2.75-4.00 | 3.4 | 3.7 | 5.2 |
| Titanium | 1.00-1.60 | 1.3 | 0.2 | 1.0 |
| Aluminum | 0.35 max. | 0.2 | 0.2 | 0.6 |
| Iron | Balance | 5 | 2.5 | 19 |

Compared to nominal alloy 625, 625 PLUS alloy has a higher titanium content, a lower carbon content and optimized levels of chromium, molybdenum, and iron to increase age-hardening response while maintaining or improving corrosion resistance. Compared to alloy 718, 625 PLUS alloy has lower carbon, aluminum and columbium contents and higher chromium, molybdenum and nickel contents to provide a yield strength capability of 120 ksi (827 MPa) minimum as opposed to the 150 ksi (1034 MPa) minimum level typical of alloy 718 and to significantly improve corrosion resistance.

## Heat Treatment and Physical Metallurgy

Custom Age 625 PLUS alloy is solution treated and aged to obtain uniform mechanical properties and corrosion resistance in a range of product sizes. Figure 3 shows the effect of solution-treatment temperature on mid-radius hardness of two 0.78-in. (20-mm) round hot-rolled bars (finished at different temperatures) and a 6-in. (152-mm) round forged bar. Figure 4 shows the same effect at various locations within the cross-section of a 6.25-in. (159-mm) round forged bar. These figures illustrate that a solution treatment in the range of 1875-1925°F (1024-1052°C) resulted in similar hardness for various products despite differences in section size and finishing temperature. Variations in hardness within the cross-section of larger forged bars were also minimized. A solution treatment at 1875-1925°F resulted in a recrystallized grain structure of ASTM 3 or finer. Solution treatment at temperatures above about 1925°F (1052°C) results in coarse grain structures and lower strength. Treatment at temperatures below 1800°F (982°C) can result in unrecrystallized or mixed grain structures in some products.

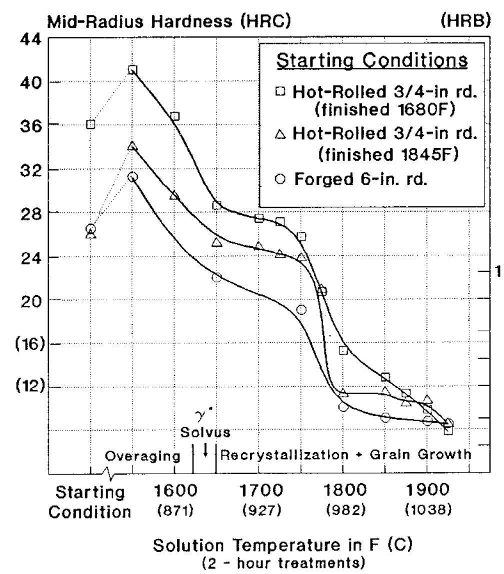


Figure 3 - Effect of Solution-Treating Temperature on Hardness of Hot-Finished Bars of 625 PLUS Alloy

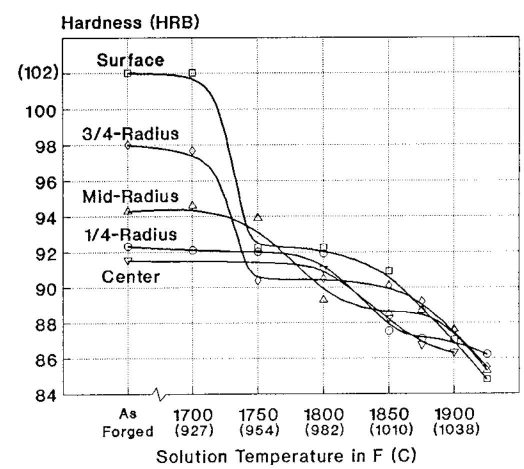


Figure 4 - Effect of Solution-Treating Temperature on Hardness of 6.25-in. (159-mm) Round Forged Bar of 625 PLUS Alloy (treated 2 hours/air cooled)

Because of the low carbon and nitrogen contents of this alloy, few primary carbide or nitride particles (columbium/titanium-rich) are present in the as-cast condition. However, fine globular columbium/titanium-rich carbides (MC) precipitate at temperatures of about 1800°F (982°C) or above. This type of precipitation is beneficial because the alloy is partially stabilized and intergranular precipitation of undesirable chromium and molybdenum-rich carbides ($M_{23}C_6$, $M_6C$) during a subsequent aging treatment is minimized. Because of the high activities of chromium and molybdenum in this alloy and the lower solubility of carbon in nickel-base alloys, it is not possible to prevent precipitation of chromium and molybdenum-rich carbides during aging at 1350°F (732°C) or above, even at carbon levels as low as 0.004 weight percent.

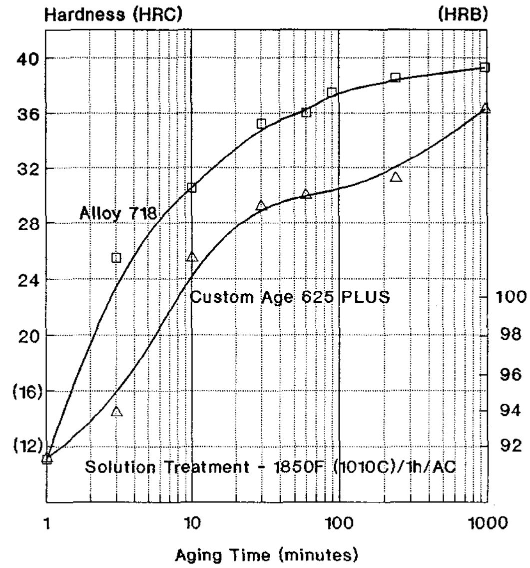


Figure 5 - Comparison of Aging Responses of 625 PLUS Alloy and Alloy 718 at 1350F (732C)

Aging response curves in Figure 5 show that the initial hardening rate and the actual hardness values of 625 PLUS alloy were lower than those of alloy 718 after treatment at 1350°F (732°C). 625 PLUS alloy has lower columbium and lower total hardener contents compared to alloy 718 to provide a 120 ksi (827 MPa) minimum yield strength capability rather than the 150 ksi (1034 MPa) minimum capability of alloy 718. Both alloys age-harden slower than nickel-base alloys strengthened with titanium and aluminum (e.g. Waspaloy* and alloy 41) and therefore exhibit greatly reduced susceptibility to strain-age cracking during processing or welding.

The hardener elements (Cb,Ti) in 625 PLUS alloy were balanced to provide hardness values within the 35-40 HRC range (approx. 120-140 ksi 0.2% Y.S.) using a double-aging treatment similar to one commonly used for alloy 718. The effects of double-aging treatment times and temperatures on hardness and the extent of intergranular precipitation are shown in Figure 6. Double-

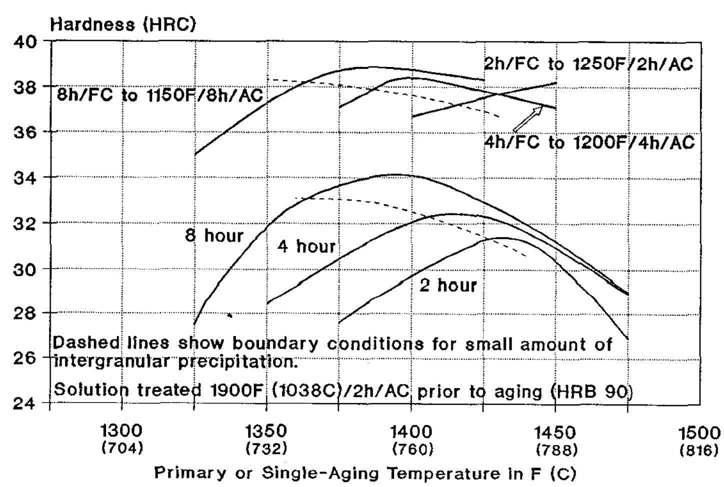


Figure 6 - Effect of Single and Double-Aging Treatments on Hardness of Solution-Treated 3/4-in. Sq. Bar of 625 PLUS Alloy

*trademark of United Technologies Corporation aging treatments (furnace cooling between steps) resulted in a 5-6 HRC point increase in hardness over that of the single-aging treatments with little or no additional intergranular precipitation. The double 8-hour cycle provided slightly higher hardness compared to the double 4 or 2-hour cycles. Underaging during the primary-aging treatment minimized intergranular carbide precipitation. A double-aging treatment of 1350°F (732°C)/8h/FC 100°F(55°C) per hour to 1150°F (621°C)/8h/AC resulted in highest hardness with minimal intergranular precipitation.

Custom Age 625 PLUS alloy is hardened by precipitation of a very fine gamma double- prime phase ($Ni_3Cb,Ti,Al$) during aging, the same phase responsible for hardening in alloy 718. Gamma double-prime ($\gamma''$) is an ordered body-centered tetragonal phase which forms in a disc-shaped morphology. In the standard heat-treated condition, the average diameter of the disc-shaped particles is 20 nm and the average thickness is 5.5 nm.

Although the nickel and columbium contents of 625 and 625 PLUS alloys are similar, the higher titanium content of 625 PLUS greatly accelerates the aging response. Thus, yield strengths of 120 ksi (827 MPa) or above can be obtained by aging for 24 hours or less while much longer aging times (>70 hours) would be required to obtain similar strength levels in annealed alloy 625 (5).

## Mechanical Properties

Table II contains typical room-temperature tensile properties for 625 PLUS, 625, and 718 alloys. Results show that alloy 625 cannot be hardened to obtain yield strengths above 120 ksi (827 MPa) without cold working or using very long aging treatments. Warm working combined with long aging times have been used to strengthen smaller section sizes of alloy 625 to yield strengths above 120 ksi (827 MPa) but warm or cold working becomes less practical as section size increases. Yield strengths of 120 to 140 ksi (827 to 965 MPa) can be obtained in 625 PLUS alloy using an 18-hour double-aging treatment similar to that used for aerospace alloy 718. Because strengthening of 625 PLUS is not dependent on warm or cold working, a full solution treatment is used to obtain best uniformity. Similar strength levels are obtained in alloy 718 by overaging at about 1450°F (788°C) following solution treatment at 1875°F (1025°C). The solution/overage treatment for alloy 718 provides better uniformity and toughness compared to the standard aerospace treatment of 1750°F (955°C)/1h/AC + 1325°F (718°C)/8h/FC to 1150°F(621°C)/8h/AC albeit at a lower strength level (6).

Table III shows the effects of specimen orientation and location on room-temperature tensile and Charpy V-notch impact properties of 625 PLUS, 625, and 718 alloys. Yield strengths of 120 to 140 ksi (827 to 965 MPa), along with high ductility and toughness, were obtained for 625 PLUS alloy at various locations throughout a 6-in. (152-mm) round bar. Solution treated and aged 625 PLUS alloy had similar tensile properties and impact energies in the longitudinal and transverse orientations while cold worked alloy 625 and aged alloy 718 had lower properties in the transverse orientation.

Table IV shows that the room-temperature tensile properties of 6-in. (152-mm) round forged bars of 625 PLUS alloy were uniform from end to end after heat treating in production furnaces. Table V shows that room-temperature tensile properties of heat-treated bars of 625 PLUS, ranging in diameter from 1.00 to 7.25-in. (25 to 184-mm), were similar which indicates that strengthening is not dependent on section size.

Table II. Typical Room-Temperature Tensile Properties of 625 PLUS, 625, and 718 Alloys

| Alloy | Size in. (mm) | Solution Treatment | Aging Treatment | 0.2% Y.S. ksi (MPa) | U.T.S. ksi (MPa) | Elong. (%-4D) | R.A. (%) |
|---|---|---|---|---|---|---|---|
| 625 PLUS | 6 (152) Round | 1040°C/2h/AC | 730°C/8h/FC to 620°C/8h/AC | 133 (917) | 183 (1262) | 32 | 53 |
| 625 | 6 (152) Round | 925°C/1h/AC | 640°C/64h/AC | 80 (552) | 141 (972) | 46 | 58 |
| | 2.25(57) Round | 885°C/1h/AC | 650°C/70h/AC | 126 (869) | 172 (1186) | 31 | 37 |
| | 0.5 (13) Plate | 1150°C/0.5h/AC | Cold Rolled 25% (No Age) | 129 (889) | 152 (1048) | 29 | 59 |
| 718 | 6 (152) Round | 1025°C/2h/WQ | 788°C/8h/AC | 132 (910) | 178 (1227) | 26 | 33 |
| | 5 (127) Round | 970°C/1h/AC | 720°C/8h/FC to 620°C/8h/AC | 174 (1200) | 203 (1400) | 16 | 30 |

Averages of longitudinal, mid-radius tests

[a] average values from both ends of 13 bars (3 heats) heat treated in production furnaces (3.4% Cb, 1.3% Ti, 0.2% Al)

[b] from reference 5 (3.26% Cb, 0.24% Ti, 0.19% Al)

[c] from reference 5 (3.39% Cb, 0.24% Ti, 0.22% Al)

[d] average values from 13 heats treated in production furnaces

Table III Effects of Specimen Location and Orientation on Mechanical Properties

| Alloy | Specimen Orient. | Test Location | Room-Temperature Tensile 0.2% Y.S. ksi (MPa) | U.T.S. ksi (MPa) | Elong. in 4D (%) | R.A. (%) | Charpy V-Notch Impact Energy[a] ft-lb (J) |
|---|---|---|---|---|---|---|---|
| 625 PLUS | Long. | Center | 126 (869) | 180 (1241) | 35 | 52 | 75 (102) |
| | Long. | Mid-Radius | 129 (889) | 183 (1262) | 33 | 56 | 74 (100) |
| | Trans. | Mid-Radius | 128 (883) | 179 (1234) | 31 | 54 | 68 ( 92) |
| | Long. | Surface | 139 (958) | 190 (1310) | 31 | 55 | 69 ( 94) |
| 625 | Long. | -- | 132 (910) | 154 (1062) | 27 | 61 | 88 (119) |
| | Trans. | -- | 127 (876) | 148 (1020) | 24 | 47 | 46 ( 62) |
| 718 | Long. | Mid-Radius | 142 (979) | 184 (1269) | 28 | 48 | 58 ( 79) |
| | Trans. | Mid-Radius | 141 (972) | 183 (1262) | 25 | 39 | 32 ( 43) |

averages of duplicate tests at room temperature.
[a] notch orientation - radial for 625 PLUS and short transverse for 625.
Alloy Conditions:
625 PLUS: 6-in. (152-mm) rd. bar - 1040°C/2h/AC + 730°C/8h/FC to 620°C/8h/AC
625: Cold Rolled 24% - 0.5-in. (13-mm) thick plate from 5.5-in. (140-mm) rd. bar.
718: 6-in. (152-mm) rd. bar - 1025°C/2h/WQ + 775°C/8h/AC.

Table IV Uniformity of Room-Temperature Tensile Properties of 6-in. (152-mm) Rd. Bar of 625 PLUS Alloy

| Sample Location[a] | | 0.2% Y.S. ksi (MPa) | U.T.S. ksi (MPa) | Elong. (%-4D) | R.A. (%) |
|---|---|---|---|---|---|
| Bar 1 | End 1 | 132 (910) | 180 (1241) | 33 | 53 |
| " | End 2 | 132 (910) | 181 (1248) | 33 | 55 |
| Bar 2 | End 1 | 135 (931) | 181 (1248) | 32 | 53 |
| " | End 2 | 136 (938) | 185 (1276) | 31 | 54 |
| Bar 3 | End 1 | 136 (938) | 183 (1262) | 31 | 52 |
| " | End 2 | 138 (952) | 185 (1276) | 32 | 51 |

[a] longitudinal, mid-radius tests of 4-m long bars heat treated 1040°C/2h/AC + 730°C/8h/FC to 620°C/8h/AC in production furnaces

Table V Room-Temperature Tensile Properties of Various Bar Sizes of 625 PLUS Alloy

| Bar Size in. (mm) | No. of Bars | No. of Tests | 0.2% Y.S. ksi (MPa) | U.T.S. ksi (MPa) | Elong. (%-4D) | R.A. (%) |
|---|---|---|---|---|---|---|
| 7.25 (184) | 1 | 6 | 132 (910) | 185 (1276) | 32 | 51 |
| 6.00 (152) | 13 | 25 | 133 (917) | 183 (1262) | 32 | 53 |
| 5.00 (127) | 2 | 4 | 135 (931) | 183 (1262) | 32 | 53 |
| 4.00 (102) | 2 | 4 | 134 (924) | 186 (1282) | 33 | 54 |
| 2.75 (70) | 1 | 1 | 125 (862) | 181 (1250) | 35 | 53 |
| 1.50 (38) | 3 | 5 | 130 (896) | 186 (1282) | 31 | 56 |
| 1.00 (25) | 3 | 3 | 133 (917) | 190 (1310) | 33 | 55 |

averages of longitudinal, mid-radius tests except center tests for 1.00-in. (25-mm) rd. bar
Heat Treatment: 1040°C/2h/AC (production furnaces) + 730°C/8h/FC to 620°C/8h/AC (production furnaces except for 1.50, 2.75 and 7.25-in. rd. bars)

## Corrosion Resistance

### Stress-Corrosion Cracking Resistance

Autoclave environments containing elemental sulfur and high pressure $H_2S$ in saturated brine at 400°F (204°C) were used to simulate severe conditions expected in some deep sour-gas wells. Stress-corrosion cracking results for C-ring and U-bend samples of age-hardened 625 PLUS and 718 alloys and cold-worked alloy 625 are listed in Table VI. Samples of 625 PLUS alloy with yield strengths up to 139 ksi (958 MPa) resisted cracking at 400°F (204°C) for 28 days. For comparison, one of the nine alloy 625 samples cracked and three of the four alloy 718 samples cracked.

Steel-coupled tensile, U-bend, and double-cantilever beam specimens were tested in the NACE TM0177 environment (5% NaCl + 0.5% acetic acid purged with $H_2S$) to evaluate resistance to sulfide stress-cracking/hydrogen embrittlement at ambient temperature. Results in Table VII show that transverse tensile (stressed at 100% of 0.2% Y.S.) and U-bend specimens of 625 PLUS alloy resisted cracking at yield strength levels of 120 to 139 ksi (827 to 958 MPa). No crack growth was observed in any of the fatigue pre-cracked DCB samples with final stress intensities of 53 to 68 ksi $\sqrt{in.}$ (58 to 75 MPa $\sqrt{m}$). Based on the excellent stress-cracking resistance demonstrated in ambient temperature and 400°F (204°C) tests, 625 PLUS alloy in the solution-treated and aged condition (HRC 40 maximum hardness) has been included in the NACE MR0175 document.

Table VI Autoclave SCC Test Results

Environment: 25% NaCl + 0.5 g/l S + 1400 psig (9.7 MPa) $H_2S$ at 400°F (204°C) for 28 days (672 hours)

| Alloy | Size in. (mm) | Condition[a] | 0.2% Y.S. ksi (MPa) | Results: Number Cracked/Number Tested C-Rings | U-Bends |
|---|---|---|---|---|---|
| 625 PLUS | 6.25 (159) Round | 1040°C/2h/AC + 718°C/8h/FC to 621°C/8h/AC | 121 (834) | -- | 0/2 |
| | | 1040°C/2h/AC + 732°C/8h/FC to 621°C/8h/AC | 130 (896) | 0/2 | 0/2 |
| | | 1040°C/2h/AC + 746°C/8h/FC to 621°C/8h/AC | 139 (958) | 0/2 | 0/2 |
| 625 | 0.18 (4.6) Plate | Cold Rolled 24-25% | 120 (827) | -- | 1/6 |
| | | | 126 (869) | 0/1[b] | -- |
| | 0.32 (8.2) Plate | Cold Rolled 32% | 141 (972) | -- | 0/2 |
| 718 | 6.0 (152) Round | 1025°C/2h/WQ + 788°C/8h/AC | 132 (910) | 1/2 | 2/2 |

[a]well aged in air at 500°F (260°C) for 720 hours after heat treatment or cold rolling.
[b]cold rolled to 0.5-in. (13-mm) plate.

Specimens: C-Rings - 1.50-in. OD x 1.25-in. ID x 0.375-in. wide (38.1 x 31.8 x 9.5-mm) stressed to 100% of 0.2% Y.S.
U-Bends - 0.125-in. thick x 0.375-in. wide x 3-in. long (3.2 x 9.5 x 76-mm) stressed beyond yield strength (radial orientation).
Stressed transversely using C-276 fasteners without insulators, stressed area at mid-radius.

## Pitting and Crevice Corrosion Resistance

Pitting and crevice corrosion tests were performed in several chloride-containing solutions as shown in Tables VIII and IX. The modified green death solution is a simulated service environment while the yellow death solution has been useful in ranking the pitting resistance of a wide range of alloys. 625 PLUS alloy displayed pitting and crevice corrosion resistance similar to that of alloy 625 and superior to that of alloy 718.

Table VII Effect of Aging Treatment on Sulfide Stress-Cracking Resistance of 625 PLUS Alloy (6.25-in./159-mm round bar)

Environment: 5% NaCl + 0.5% Acetic Acid + $H_2S$ (NACE TM0177) at 75°F (24°C)

| Aging Treatment[a] | 0.2% Y.S. ksi (MPa) | Hardness (HRC) | SCC Results Tensile[b] | U-Bend[c] | DCB[d] | DCB[e] |
|---|---|---|---|---|---|---|
| 718°C/8h/FC to 621°C/8h/AC | 120 (827) | 35/36 | – | NC,NC | NC,NC | NC |
| 732°C/8h/FC to 621°C/8h/AC | 130 (896) | 38 | NC | NC,NC | NC,NC | NC |
| 746°C/8h/FC to 621°C/8h/AC | 139 (958) | 39/40 | NC | NC,NC | NC | NC |

NC = no environmental cracking
[a] solution treated 1900°F (1038°C)/2h/AC prior to aging as shown; well aged in air at 500°F (260°C) for 720 hours after heat treatment.
[b] 0.252-in.(6.4 mm) gage diameter tensiles coupled to steel, stressed to 100% of 0.2% Y.S. and exposed for 720 hours; transverse, radial orientation.
[c] 0.125 x 0.375 x 3-in.(3.2 x 9.5 x 76-mm) transverse, radial U-bends coupled to steel, stressed beyond yield strength and exposed for 1000 hours.
[d] 4 x 1 x 0.188-in. thick (102 x 25.4 x 4.8-mm) slotted sample with chevron notch, pre-cracked, coupled to steel, wedge loaded, stressed transversely at mid-radius to 53-56 ksi $\sqrt{in.}$, 58-61 MPa $\sqrt{m}$ and exposed for 672 hours.
[e] DCB samples cut, prepared and exposed as in footnote d except that sample thickness was 0.250-in. (6.4-mm) and stress intensity was 62-68 ksi $\sqrt{in.}$ (68-75 MPa $\sqrt{m}$).

Table VIII Pitting Temperature Test Results for 625 PLUS, 625 and 718 Alloys

| Alloy | Size in. (mm) | Condition | Pitting Temperature (°C) 6 w/o $FeCl_3$ + 1 w/o HCl (24-h exposures)[a] | Modified Green Death (96-h exposures)[b] |
|---|---|---|---|---|
| 625 PLUS | 6.25(159) Round | 1040°C/2h/AC + 732°C/ 8h/FC to 621°C/8h/AC | >98, >98 | 75, 80 |
| 625 | 0.18(4.6) Plate | Cold Rolled 24-25% | >98, >98 | 80, 90 |
| 718 | 6.0 (152) Round | 1025°C/2h/WQ + 788°C/8h/AC | 56, 62 | 45, 45 |

[a] temperature increased in 2.5°C intervals; no preparation of specimens between exposures.
[b] modified green death = 7 v/o $H_2SO_4$ + 3 v/o HCl + 5 w/o $CuCl_2 \cdot 2H_2O$ + 5 w/o $FeCl_3 \cdot 6H_2O$; temperature increased in 5°C intervals and specimens wet ground between exposures.
Specimens: 1 x 2 x 1/8-in. thick (25.4 x 50.8 x 3.2 mm) longitudinal,mid-rad

Table IX Crevice Corrosion Test Results for 625 PLUS, 625, and 718 Alloys

| Alloy | Size in. (mm) | Condition | Crevice Corrosion Weight Loss ($mg/cm^2$)[a] 6 w/o $FeCl_3$ + 1 w/o HCl (40°C/72h) | (55°C/72h) | Crevice Temperature-°C Yellow Death 96-h exposures[b] |
|---|---|---|---|---|---|
| 625 PLUS | 6.25(159) Round | 1040°C/2h/AC + 732°C 8h/FC to 621°C/8h/AC | 1.2 | 6.0 | 40, 40 |
| 625 | 0.18(4.6) Plate | Cold Rolled 24-25% | 3.7 | 13.7 | 35, 40 |
| 718 | 6.0(152) Round | 1025°C/2h/WQ + 788°C/8h/AC | 35.0 | 47.2 | <25, <25 |

[a] higher weight loss in duplicate tests.
[b] yellow death = 4 w/o NaCl + 0.1 w/o $Fe_2(SO_4)_3$ + 0.01 M HCl; temperature increased in 5°C intervals and specimens wet ground between exposures.
Specimens: 1 x 2 x 1/8-in. thick (25.4 x 50.8 x 3.2 mm) with ASTM G48 crevices (Teflon cylinders with crossed rubber O-rings).

## Weld Properties

Custom Age 625 PLUS alloy will require welding in some applications and may also provide a higher-strength alternative to alloy 625 weldments. The effect of heat treatment on room-temperature tensile properties of all-weld-metal samples of 625 PLUS alloy can be found in Table X. The standard solution plus double-aging treatment provided yield strength and ductility in the weld similar to that of the base metal. Direct double aging resulted in slightly lower properties although a yield strength of about 120 ksi (827 MPa) was still obtained.

Table XI contains corrosion test results for autogenous welds of 625 PLUS alloy in various heat-treated conditions. As-welded and welded plus solution-treated/aged samples exhibited sulfide stress-cracking resistance and intergranular corrosion resistance similar to that of the base metal. Direct double aging (no solution treatment) of the weld resulted in sulfide stress cracking in the heat-affected zones (HAZ) and increased intergranular corrosion in the weld and HAZ. The reduced corrosion resistance of the direct-aged weld and HAZ has been attributed to extensive intergranular carbide precipitation. Solution treating at 1900°F (1038°C) prior to aging eliminated stresses and stabilized carbon as (Cb,Ti)C. Both factors minimize intergranular precipitation of chromium and molybdenum-rich carbides during the aging treatment.

## Summary

Custom Age 625 PLUS is a nickel-base alloy strengthened by precipitation of gamma double-prime [$Ni_3$(Cb,Ti,Al)] during aging. Large section sizes can be age-hardened to yield strengths (0.2%) above 120 ksi (827 MPa) without cold or warm working. Excellent ductility and toughness are retained following age-hardening. Solution treating before aging results in uniform properties and microstructures for a variety of product sizes as well as throughout the cross-sections of larger-diameter bars.

Table X Effect of Heat Treatment on Room-Temperature Tensile Properties of GTA Welds of 625 PLUS Alloy[a]

| Condition[b] | 0.2% Y.S. ksi (MPa) | U.T.S. ksi (MPa) | Elong. (%-4D) | R.A. (%) |
|---|---|---|---|---|
| As Welded | 74 (510) | 120 ( 827) | 41 | 48 |
| Direct Aged | 123 (848) | 163 (1124) | 22 | 34 |
| Sol'n + Aged (Weld) | 127 (876) | 177 (1220) | 26 | 51 |
| Sol'n + Aged (Base metal) | 130 (896) | 185 (1276) | 31 | 55 |

[a]0.460-in. (11.68-mm) thick plate with 60° V-groove GTA welded in 13 passes using matching filler metal; 0.252-in. (6.40-mm) gage diameter all-weld-metal tensile specimens
[b]Sol'n = 1038°C/1h/AC; Age = 732°C/8h/FC to 621°C/8h/AC

Table XI Effect of Heat Treatment on Corrosion Resistance of Autogenous Welds of 625 PLUS Alloy

| Condition[a] | Pitting Temp.[b] (°C) | Intergranular Attack Depth (μm)[c] Base | HAZ | Weld | Sulfide Stress Cracking - NACE TM0177 (Room Temp./1000h) |
|---|---|---|---|---|---|
| Sol'n + Weld + Age | 97/>99 | 41 | 246 | 84 | HAZ Cracks |
| Sol'n + Weld + Sol'n + Age | -- | 31 | 13 | 36 | No Cracking |
| Sol'n + Age + Weld | 97/>99 | 28 | 0 | 28 | No Cracking |
| Sol'n + Age (Base Metal) | 97/>99 | 20 | - | - | No Cracking |

[a]Sol'n = 1038°C/1h/AC; Age = 732°C/8h/FC to 621°C/8h/AC
Stress-cracking test specimens were also "well aged" 288°C/30 days.
[b]24-hour exposures in 6 w/o $FeCl_3$ + 1 w/o HCl; temperature increased in 2.5°C increments, no preparation between exposures.
[c]24-hour exposure in boiling ferric sulfate/50% sulfuric acid (ASTM G28, method A)

The chemical composition of 625 PLUS alloy was optimized to provide corrosion resistance similar to that of cold-worked alloy 625 and superior to that of age-hardened alloy 718 in many environments. The alloy is highly-resistant to pitting and crevice corrosion by chlorides; sulfide stress cracking in the NACE TM0177 environment; and stress-corrosion cracking in environments containing brine, hydrogen sulfide and elemental sulfur at high pressures and temperatures. Because of its high strength and resistance to corrosive environments, 625 PLUS alloy is being used in oil-field and marine applications.

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