PROPERTIES OF ULTRA-HIGH-STRENGTH

CUSTOM AGE 625 PLUS® ALLOY

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Abstract

Custom Age 625 PLUS® alloy is a highly-corrosion-resistant, nickel-based alloy designed to be age-hardened to high-strength levels without warm or cold working. However, direct aging after cold working has been found to result in ultra-high strength levels making the alloy a candidate for high-strength, corrosion-resistant fasteners. The mechanical properties and corrosion resistance of cold-worked and aged bars of Custom Age 625 PLUS alloy and alloys 718 and MP35N** are compared. Results from fabrication of high-strength fasteners show that Custom Age 625 PLUS alloy is highly cold-formable and has mechanical properties similar to or higher than those of alloy 718.

Introduction

Custom Age 625 PLUS alloy (UNS N07716) is a highly-corrosion-resistant, nickel-based alloy that can be age-hardened to high strength levels without warm or cold working. The alloy combines the excellent corrosion resistance of alloy 625 with age-hardening capability similar to that of alloy 718. Yield strength levels of 120 ksi (827 MPa) and above can be obtained even in large section sizes using solution and age-hardening treatments. A review of the development, metallurgy, and properties of solution-treated and aged 625 PLUS alloy was presented at the previous 718/625 symposium (1).

Although 625 PLUS alloy and alloy 718 do not depend on cold-working operations for strengthening in most applications, cold-working and direct aging of alloy 718 bar and wire products has been used to obtain tensile strength levels exceeding 220 ksi (1517 MPa), primarily in fastener applications (2). The practical upper limit of tensile strength in cold-worked and aged alloy 718 is about 250 ksi (1724 MPa) because of reduced ductility accompanying higher strength levels. When higher strength levels are needed along with good ductility and excellent corrosion resistance at temperatures up to about 750°F (399°C), cobalt-base alloy MP35N is frequently used. However, the cost of MP35N alloy is significantly higher than that of alloy 718 because of a cobalt content of about 34%. Custom Age 625 PLUS alloy does not contain cobalt and has been found to have higher ductility and toughness compared to alloy 718 at the same strength level (3).

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Superalloys 718, 625, 706 and Various Derivatives
Edited by E.A. Loria
The Minerals, Metals & Materials Society, 1994

This study was undertaken to determine the mechanical properties and corrosion resistance of cold-worked and aged bar of 625 PLUS alloy and to compare these results with similar properties of 718 and MP35N alloys. The formability and mechanical properties of high-strength fasteners of 625 PLUS alloy and alloy 718 were also compared.

Procedure

Materials

Annealed 0.692-inch (17.6-mm) diameter bar representing a double vacuum-melted production heat of 625 PLUS alloy was obtained. The bars were cold drawn 38% to 0.547-inch (13.9-mm) diameter to produce material capable of a minimum tensile strength of 260 ksi (1793 MPa) in the aged condition. The cold-drawn bars were straightened and centerless ground to a finish size of 0.535-inch (13.6-mm) diameter.

Cold-drawn bars of 718 and MP35N alloys were obtained for comparison testing. Alloy 718 bars were cold drawn 26% to 0.758-inch (19.3-mm) diameter and test samples were given a conventional double-aging treatment of 1325°F (718°C)/8 hours/furnace cool to 1150°F (621°C)/8 hours/AC. Bars of MP35N alloy were cold drawn 52% and centerless ground to 0.649-inch (16.5-mm) diameter and test samples were given a typical aging treatment of 1050°F (566°C)/4 hours/AC. The chemical compositions of the three alloys are listed in Table I.

High-strength fasteners of 625 PLUS alloy were fabricated from 0.255-inch (6.5-mm) diameter bar. The bars were cold drawn 44%, straightened from coil, and ground to the finished size.

Table I. Chemical Compositions (Wt%) of Alloys Tested

	Custom Age 625 PLUS Alloy	Alloy 718	MP35N Alloy
C	0.009	0.030	0.007
Cr	21.05	18.41	20.53
Mo	8.18	3.07	9.45
Ni	60.64	52.50	34.75
Co	<0.01	0.78	34.05
Nb	3.42	5.34	0.01
Ti	1.31	0.99	0.75
Al	0.20	0.56	-
Fe	4.97	17.60	0.42

Mechanical Testing of Bar

Samples of cold-drawn bar of 625 PLUS alloy were heat treated for 4 hours at temperatures ranging from 1050°F (566°C) to 1400°F (760°C) to determine aging response. Single-aged samples were additionally treated 1075°F (579°C)/4 hours/AC to determine the effects of double-aging treatments. Aged samples were hardness tested and several treatments were selected for tensile testing at room temperature (0.350-inch/8.9-mm gage diameter specimens).

A double-aging treatment of 1200°F (649°C)/4 hours/furnace cool to 1075°F (579°C)/4 hours/AC was selected for evaluation of mechanical properties and corrosion resistance of ultra-high strength 625 PLUS alloy bar. Room-temperature tensile properties of notched and unnotched specimens of the three alloys were evaluated. Charpy V-notch impact tests were done at room temperature. Elevated-temperature tensile tests of ground 0.250-inch (6.4-mm) gage diameter specimens were conducted at temperatures of 600-1200°F (316-649°C). Stress-rupture tests of ground 0.178-inch (4.5-mm) gage diameter combination smooth-notched (K_t=3.8) specimens were conducted at 1000°F (538°C) using a stress level of 95 percent of the yield strength at that temperature.

Double-aged bar samples of 625 PLUS alloy were exposed for 1000 hours at 800-1200°F (427-649°C) and for 2000 hours at 1000°F (538°C) to determine effects of elevated-temperature exposure. Hardness and room-temperature tensile properties of exposed samples were evaluated.

Corrosion Testing of Bar

The crevice corrosion resistance of the three alloys was evaluated using simulated seawater (ASTM D1141-substitute seawater) and two solutions commonly used to rank the resistance to chlorides, 6 w/o $FeCl_3$ + 1 w/o HCl and 4 w/o NaCl + 0.1 w/o $Fe_2(SO_4)_3$ + 0.01 M HCl (yellow death). Ground cylinders, 0.500-inch diameter x 1.50-inch long (12.7 x 38.1-mm) were fitted with 0.375-inch (9.5-mm) diameter rubber O-rings to form a crevice. Crevice corrosion temperature tests were done in both solutions using 72- or 96-hour exposures at each temperature. Specimens were ground between exposures and temperature was increased in 5°C intervals until crevice corrosion was detected at 20X. Weight loss was determined after 72-hour exposures in 6 w/o $FeCl_3$ + 1 w/o HCl at 40°C and 55°C and after a 30-day exposure in simulated seawater acidified with HCl to an initial pH of 1.

Slow-strain-rate tensile (SSRT) tests were used to evaluate the stress-corrosion cracking resistance of the three alloys. The environment was simulated seawater prepared according to ASTM D1141. Because all three alloys contain sufficient nickel to provide excellent resistance to stress-corrosion cracking, the severity of this environment was increased using a higher temperature of 300°F (149°C) and by acidifying with HCl to a pH of 1.5. Inert reference tests were done in glycerol at 300°F (149°C). Test specimens measured 1.0-inch (25.4-mm) gage length and 0.200-inch (5.1-mm) gage diameter.

Slow-strain-rate tensile tests were conducted on a direct drive, 5-ton capacity, gear-driven machine. Environmental and inert reference tests were strained to failure at an extension rate of 4.0 x 10^{-6} in/in/sec. Time-to-failure, elongation, and reduction of area were obtained using duplicate tests in glycerol (inert) and the simulated seawater environment. Environmental degradation was expressed as a ratio of the inert test results. The elongation values were determined using punch marks on the shoulders of the specimens. Reliable elongation measurements were possible because the specimens resisted general corrosion and the fracture halves could be reassembled. The time-to-failure values are considered less reliable because the testing prior to reaching the proportional limit was included.

Fabrication and Testing of Fasteners

Cold-drawn 0.255-inch (6.5-mm) diameter bar of 625 PLUS alloy was used to fabricate 0.250-inch (6.4-mm) diameter protruding head fasteners. The heading operation was done with no external heat applied. The headed fasteners were aged, ground, thread rolled and coated with Hikote™ 1. Because preliminary tests showed the shear strength to be high (>140 ksi/965 MPa), an overaging cycle of 1350°F (732°C)/4 hours/AC was applied to facilitate thread rolling. The fasteners were heated to 400-600°F (204-316°C) for thread rolling to minimize die wear.

Mechanical testing of the finished fasteners included tensile, double shear, tension-tension fatigue and head ductility tests. Double shear tests of the shank sections were done to MIL-STD-1312, method 13 except that sharp blades (0.005-inch/0.127-mm maximum radius) were used. Axial fatigue tests were done using a maximum stress level of approximately fifty percent of the tensile strength and an R-factor of 0.1. The head ductility test involved loading fasteners onto a bearing surface with an angle of 3° and examining for fracture or cracking. The mechanical tests were the same as those used for alloy 718 fasteners.

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Results and Discussion

Table I lists the chemical compositions of the Custom Age 625 PLUS alloy, 718, and MP35N alloy bars evaluated in this study. Compared to alloy 718, 625 PLUS alloy contains lower carbon, aluminum and niobium and higher chromium, molybdenum and nickel to significantly improve corrosion resistance at a slightly lower level of strength (solution treated and aged condition). Compared to MP35N alloy, 625 PLUS alloy is cobalt-free (nickel-base) and contains 3.4% niobium to promote age hardening without prior cold working.

Mechanical Properties of Bar

Figure 1 shows the effect of aging temperature on age-hardening response of 0.535-inch (13.6-mm) diameter cold-worked bar of 625 PLUS alloy. Maximum hardness was obtained during 4-hour aging treatments at 1250-1275°F (677-691°C). A secondary-aging treatment at a lower temperature of 1075°F (579°C) resulted in a further increase in hardness.

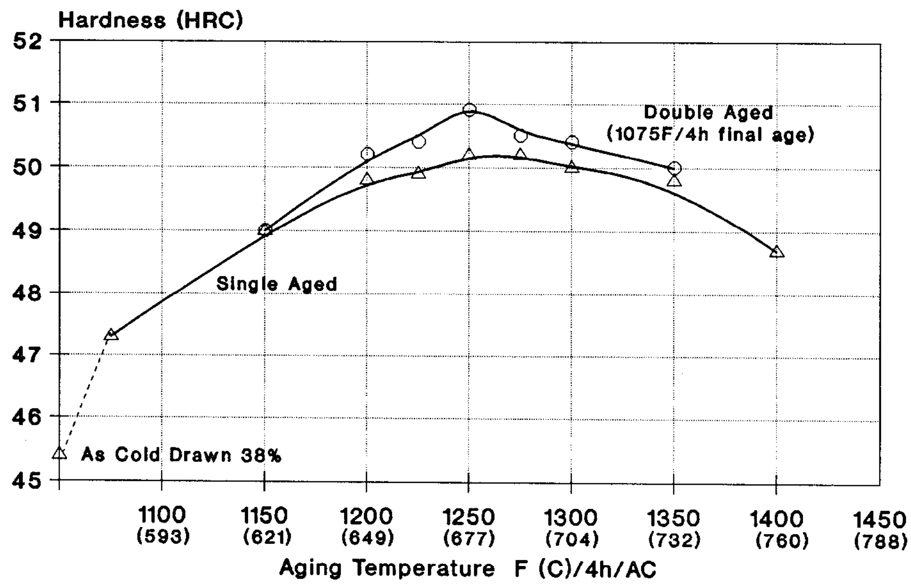

Figure 1. Effect of Aging Treatment on Hardness of 0.535-in (13.6-mm) Round Cold-Worked Bar of Custom Age 625 PLUS Alloy

Table II contains the room-temperature tensile properties of cold-worked 625 PLUS alloy bar after various single and double-aging treatments. Tensile strength levels of 260 ksi (1793 MPa) and above were obtained along with about 9% elongation. Cold working prior to aging resulted in a doubling of the yield strength and an 80-90 ksi (552-621 MPa) increase in tensile strength compared to the solution-treated and double-aged condition (3).

Results in Table II show that single aging resulted in a 25-35 ksi (172-241 MPa) increase in tensile strength of cold-drawn bar of 625 PLUS alloy. Double aging (1075°F/4-hour final age) increased strength by an additional 5 to 10 ksi (34-69 MPa) without significantly reducing ductility. A double-aging cycle of 1200°F (649°C)/4 hours/furnace cool to 1075°F (579°C)/4 hours/AC resulted in the best combination of strength and ductility. The longer 1325/1150°F (718/621°C) double-aging cycle commonly used for alloy 718 resulted in similar strength but slightly lower ductility. Increased grain boundary precipitation, which occurred with primary-aging temperatures above 1200°F (649°C), may be responsible for the lower ductility levels.

Table II. Effect of Aging Treatment on Room-Temperature Tensile Properties of Cold-Worked 625 PLUS Alloy (0.535-in./13.6-mm diameter bar)

Aging Treatment	0.2% Y.S. ksi	(MPa)	U.T.S. ksi	(MPa)	Elong. %-4D	R.A. %	Hardness HRC
As Cold Drawn	184	(1269)	234	(1613)	12.5	52	45.5
1200°F (649°C)/4h/AC	257	(1772)	264	(1820)	9.4	39	50
1275°F (691°C)/4h/AC	260	(1793)	268	(1848)	8.8	38	50
1350°F (732°C)/4h/AC	250	(1724)	260	(1793)	9.1	33	50
1200°F (649°C)/4h/FC* to 1075°F (579°C)/4h/AC	264	(1820)	270	(1862)	9.0	37	50
1250°F (677°C)/4h/FC* to 1075°F (579°C)/4h/AC	269	(1855)	275	(1896)	8.4	35	51
1325°F (718°C)/8h/FC* to 1150°F (579°C)/8h/AC	262	(1806)	271	(1869)	8.2	32	51

*FC = furnace cooled 100°F (56°C) per hour
Averages of duplicate tests at room temperature
Condition: annealed and cold drawn 38% prior to aging

The room-temperature tensile properties of cold-worked and aged 625 PLUS bar after long-term exposures at 800-1200°F (427-649°C) are listed in Table III. Thermal exposure at these temperatures resulted in slightly higher strength and lower ductility. The microstructures of these samples are currently being evaluated.

Table III. Effects of Thermal Exposure on Room-Temperature Tensile Properties of Cold-Worked and Aged 625 PLUS Alloy (0.535-in./13.6-mm diameter bar)

Thermal Exposure	0.2% Y.S. ksi	(MPa)	U.T.S. ksi	(MPa)	Elong. %-4D	R.A. %	Hardness HRC
None	264	(1820)	270	(1862)	9.0	37	50
800°F (427°C)/1000 hours	267	(1841)	273	(1882)	8.8	36	50
900°F (482°C)/1000 hours	274	(1889)	278	(1917)	8.3	37	50.5
1000°F (538°C)/1000 hours	272	(1875)	280	(1931)	8.0	35	51
1000°F (538°C)/2000 hours	276	(1903)	282	(1944)	7.7	34	51
1100°F (593°C)/1000 hours	279	(1924)	287	(1979)	6.7	29	51.5
1200°F (649°C)/1000 hours	265	(1827)	279	(1924)	7.0	27	50.5

Averages of duplicate tests at room temperature
Condition: cold drawn 38% and aged 1200°F/4h/FC to 1075°F/4h/AC

Table IV compares the room-temperature tensile properties of cold-worked and aged bar of 625 PLUS alloy to those of alloys 718 and MP35N. Tensile strength values above 260 ksi (1793 MPa) along with 8% minimum elongation were obtained with 625 PLUS alloy and MP35N alloy. The alloy 718 bar was cold drawn and aged to a lower tensile strength level of 251 ksi (1731 MPa) because ductility is significantly reduced at higher strength levels. The ratio of notched to unnotched tensile strength of alloy 718 was significantly lower than that of 625 PLUS alloy and MP35N alloy (1.1 vs. 1.3).

Table V contains Charpy V-notch impact data for the three alloys. The impact energy of 625 PLUS alloy was between that of the lower-strength alloy 718 and the higher-strength MP35N alloy.

Table IV. Room-Temperature Tensile Properties of Cold-Worked and Aged Bars

Alloy	0.2% Y.S. ksi (MPa)	U.T.S. ksi (MPa)	Elong. %-4D	R.A. %	Notch T.S.* ksi (MPa)	NTS/UTS Ratio
625 PLUS	264 (1820)	270 (1862)	9.0	37	356 (2455)	1.32
718	235 (1620)	251 (1731)	10.4	28	281 (1937)	1.12
MP35N	281 (1937)	287 (1979)	9.4	47	379 (2613)	1.32

* stress concentration factor of notch, K_t = 8
Averages of duplicate tests at room temperature
Alloy Conditions:
625 PLUS: 0.535-in.(13.6-mm) rd. - CD 38% and aged 1200°F/4h/FC to 1075°F/4h/AC
718: 0.758-in.(19.3-mm) rd. - CD 26% and aged 1325°F/8h/FC to 1150°F/8h/AC
MP35N: 0.649-in.(16.5-mm) rd. - CD 52% and aged 1050°F/4h/AC

Table V. Charpy V-Notch Impact Energy of Cold-Worked and Aged Bars

Alloy	U.T.S. ksi	(MPa)	Impact Energy ft-lb	(J)
625 PLUS	270	(1862)	14.3	(19.4)
718	251	(1731)	7.3	(9.9)
MP35N	287	(1979)	18.5	(25.1)

Averages of duplicate tests at room temperature
Alloy Conditions:
625 PLUS: 0.535-in.(13.6-mm) rd. - CD 38% and aged 1200°F/4h/FC to 1075°F/4h/AC
718: 0.758-in.(19.3-mm) rd. - CD 26% and aged 1325°F/8h/FC to 1150°F/8h/AC
MP35N: 0.649-in.(16.5-mm) rd. - CD 52% and aged 1050°F/4h/AC

The elevated-temperature tensile properties of the three alloys in the cold-worked and aged condition are listed in Table VI. All three alloys showed lower strength levels with increasing temperature and a ductility minimum at about 1000°F (538°C). While MP35N bar had the highest strength levels at room-temperature, the 625 PLUS bar had similar strength levels at 800°F and 1000°F along with higher ductility.

Table VII contains stress-rupture data for the three alloys tested at 1000°F (538°C) at a stress level of 95 percent of the yield strength. The stress-rupture life of 625 PLUS alloy was similar to that of alloy 718 and higher than that of MP35N alloy. It should be noted that the aging treatment applied to the cold-worked 625 PLUS alloy was selected based on room-temperature properties and microstructure rather than high temperature properties.

Table VI. Elevated-Temperature Tensile Properties of Cold-Worked and Aged Bars

Temperature °F	Custom Age 625 PLUS Alloy 0.2%Y.S. ksi	U.T.S. ksi	Elong. %-4D	R.A. %	Alloy 718 0.2%Y.S. ksi	U.T.S. ksi	Elong. %-4D	R.A. %	MP35N 0.2%Y.S. ksi	U.T.S. ksi
75	263	267	9.7	38	234	249	12.2	31	282	287
600	227	238	10.0	37	-	-	-	-	238	249
800	220	234	8.3	27	196	227	12.6	33	225	238
1000	211	231	6.9	17	195	221	10.2	31	219	233
1100	204	231	16.2	42	191	217	18.6	46	-	-
1200	184	209	32.1	52	166	197	36.5	58	-	-

Averages of duplicate tests at each temperature.
Alloy Conditions:
625 PLUS: 0.535-in. (13.6-mm) rd. - CD 38% and aged 1200°F/4h/FC to 1075°F/4h/AC
718: 0.758-in. (19.3-mm) rd. - CD 26% and aged 1325°F/8h/FC to 1150°F/8h/AC
MP35N: 0.649-in. (16.5-mm) rd. - CD 52% and aged 1050°F/4h/AC

Table VII. Stress-Rupture Properties of Cold-Worked and Aged Bars

Alloy	Diameter in.	(mm)	Condition	1000°F (538°C) Stress Rupture Stress* ksi	(MPa)	Life hours	Elong. %-4D	R.A. %
625 PLUS	0.535	(13.6)	CD 38%+1200°F/4h/FC to 1075°F/4h/AC	200	(1379)	93	17	31
718	0.758	(19.3)	CD 26%+1325°F/8h/FC to 1150°F/8h/AC	185	(1276)	82	21	37
MP35N	0.649	(16.5)	CD 52%+1050°F/4h/AC	210	(1448)	28	23	28

* 95% of 0.2% offset yield strength at 1000°F (538°C)
Averages of duplicate tests for each alloy

Corrosion Resistance of Bar

Crevice corrosion resistance is important for materials used for high-strength fasteners because localized attack can provide initiation sites for stress-corrosion cracks. Results of crevice corrosion tests in chloride-containing solutions are listed in Tables VIII and IX. The temperatures at which crevice corrosion initiated on 625 PLUS alloy were significantly higher than those of alloy 718 and approaching those of MP35N alloy. Similar trends were observed in weight loss tests in 6 w/o $FeCl_3$ + 1 w/o HCl at higher temperatures of 40°C and 55°C (see Table IX). The higher level of corrosion resistance of 625 PLUS alloy and MP35N alloy compared to alloy 718 is attributed to higher chromium and molybdenum contents.

None of the alloys showed significant attack during 30-day exposures to simulated seawater at a slightly elevated temperature of 35°C although one of the alloy 718 specimens did show light attack.

The SSRT results are listed in Table X. The 625 PLUS alloy and MP35N alloy displayed good resistance to the hot simulated seawater environment with time-to-failure and ductility ratios exceeding 0.9. In contrast, the cold-worked and aged 718 specimens were severely embrittled and ductility ratios were 0.2-0.3.

Table VIII. Crevice Corrosion Temperature Test Results for Cold-Worked and Aged Bars

Alloy	Diameter in.	(mm)	Condition	Crevice Corrosion Temperature - °C: 6 w/o $FeCl_3$+1 w/o HCl 72-h exposures	Yellow Death* 96-h exp.
625 PLUS	0.535	(13.6)	CD 38%+1200°F/4h/FC to 1075°F/4h/AC	35/30/30	35/35
718	0.758	(19.3)	CD 26%+1325°F/8h/FC to 1150°F/8h/AC	≤0/≤0	5/10
MP35N	0.649	(16.5)	CD 52%+1050°F/4h/AC	40/35	35/35

* 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 ground between exposures; crevices examined at 20X
Specimens: 0.500-in. diameter x 1.50-in. long (12.7 x 38.1 mm) cylinders with 0.375-in. (9.5-mm) ID rubber O-rings

Table IX. Crevice Corrosion Weight Loss Results for Cold-Worked and Aged Bars

Alloy	Crevice Corrosion Weight Loss (mg/cm^2) 6 w/o $FeCl_3$+1 w/o HCl 40°C/72h	6 w/o $FeCl_3$+1 w/o HCl 55°C/72h	Synthetic Seawater (pH=1) 35°C/30 days
625 PLUS	3.0	9.4	0.0 (No Attack)
	3.9	11.1	0.0 (No Attack)
718	41.1	68.3	0.0 (No Attack)
	42.6	72.5	0.1 (Light Attack)
MP35N	0.0	0.0	0.0 (No Attack)
	0.0	0.3	0.0 (No Attack)

Alloy Conditions:
625 PLUS: 0.535-in. (13.6-mm) rd. - CD 38% and aged 1200°F/4h/FC to 1075°F/4h/AC
718: 0.758-in.(19.3-mm) rd. - CD 26% and aged 1325°F/8h/FC to 1150°F/8h/AC
MP35N: 0.649-in.(16.5-mm) rd. - CD 52% and aged 1050°F/4h/AC
Specimens: 0.500-in. diameter x 1.50-in. long (12.7 x 38.1 mm) cylinders with 0.375-in. (9.5-mm) ID rubber O-rings

Table X. Slow-Strain-Rate Tensile (SSRT) Results for Cold-Worked and Aged Bars

Alloy	Condition	Environment*	Time to Fail (hours)	Elong. (% in 1")	R.A. (%)
625 PLUS	CD 38% + 1200°F/4h	Seawater	10.5	7.8	31.1
	FC to 1075°F/4h/AC	Inert	11.2	7.9	33.8
		Ratio	0.93	0.98	0.92
718	CD 26% + 1325°F/8h	Seawater	6.8	1.6	6.3
	FC to 1150°F/8h/AC	Inert	12.2	8.1	26.6
		Ratio	0.55	0.20	0.24
MP35N	CD 52% + 1050°F/4h/AC	Seawater	10.5	7.0	44.1
		Inert	10.3	6.8	43.3
		Ratio	1.02	1.03	1.02

*Environment:
Simulated Seawater (ASTM D1141) acidified to pH=1.5 using HCl and tested at 300°F(149°C)
Inert - Glycerol at 300°F (149°C)
Specimens: 0.200-in (5.1-mm) gage diameter x 1.0-in (25.4-mm) gage length
Values represent averages of duplicate tests

Table XI. Mechanical Properties of 0.250-Inch (6.4-mm) Diameter Fasteners of 625 PLUS Alloy

Tensile Strength	280 ksi (1931 MPa)
Double Shear Strength*	133 ksi (917 MPa)
Axial Fatigue**	>130,000 cycles
Head Ductility (3° Wedge)	No cracking

* shear tested to MIL-STD 1312, #13 with sharp blades
** Max. stress approx. 50% of UTS; R-factor = 0.1
Averages of a minimum of two tests at room temperature.
Material Condition - CD 44%, aged 1200°F/4h/FC to 1075°F/4h/AC + 1350°F/4h/AC, and thread rolled

Fabrication and Properties of Fasteners

No cracking occurred during cold heading of the 625 PLUS alloy fasteners. In contrast, both 718 and MP35N alloys require heating to avoid cracking. The results of tensile, double shear, axial fatigue, and head ductility tests are listed in Table XI. The level of properties is similar to or higher than that typically obtained in alloy 718 fasteners.

Summary

Custom Age 625 PLUS alloy is a highly-corrosion-resistant, cobalt-free, nickel-based alloy that can be age hardened to high strength levels. Tensile strength levels above 260 ksi (1793 MPa) along with good ductility can be obtained in the alloy by cold working prior to direct aging. Cold worked and aged 625 PLUS alloy offers a higher strength/ductility capability and improved corrosion resistance compared to cold-worked and aged alloy 718. Compared to MP35N alloy, 625 PLUS alloy offers similar ultra-high strength levels and excellent resistance to corrosion in a cobalt-free matrix. Fasteners of 625 PLUS alloy can be readily cold headed while similar fasteners of 718 and MP35N alloys must be heated for heading.

References

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