ALLOY 718 FOR THE OIL AND GAS INDUSTRY

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Abstract

This paper examines some of the properties of Alloy 718 required by the oil and gas industry for the completion of corrosive wells. The properties of interest include strength, toughness, pitting and general corrosion resistance, hydrogen embrittlement resistance, and stress corrosion cracking resistance. The effects of heat treatment on some of these properties are discussed.

Heat treatment temperatures can affect each property differently. Thus high aging temperatures may improve hydrogen embrittlement resistance while low aging temperatures may improve toughness and corrosion resistance. The stress corrosion cracking performance determines the limits for use in the most aggress environments containing elemental sulfur.

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Introduction

Alloy 718 is used as a corrosion-resistant alloy in the oil and gas industry because of its combination of high-strength, corrosion resistance, and ability to be heat treated to various strength levels. While Alloy 718 was developed for high-temperature use, it's properties have been modified for the oil industry through processing and heat treatment. The properties of most interest to the oil and gas industry are corrosion resistance, strength, toughness, hydrogen embrittlement resistance, and stress corrosion cracking resistance. Since Alloy 718 can be heat treated to the required strength levels, it finds use as thick sections and complicated shapes for downhole and surface components. This paper will discuss some of the oil industry uses of Alloy 718, the corresponding mechanical properties and heat treatments, the corrosion resistance in typical oil field environments.

Applications of Alloy 718 in the Oil and Gas Industry

Alloy 718 is used where high strength and corrosion resistance are required. While a number of alloys can provide high strength and corrosion resistance, many are strengthened only by cold work and, therefore, are not suitable for thick sections or complicated shapes. Other alloys, such as carbon and low-alloy steels, do not have sufficient corrosion resistance, although they may have the desired mechanical properties. Thus, for thick sections or complicated shapes, an alloy must be heat treated rather than cold worked to the desired mechanical properties. An additional advantage of heat-treatable alloys is inventory reduction since one inventory can supply materials for applications requiring different strength levels. In thick sections, heat-treatable alloys such as Alloy 718 provide more uniform mechanical properties through the cross section as compared to cold-worked materials. The cold-worked materials in thick sections often possess high residual stresses, thus increasing difficulty in maintaining tolerances during machining. For these reasons, heat-treatable alloys are often selected for downhole and surface equipment which is machined to final dimensions.

A frequent application of Alloy 718 is in valve stems. These stems are often used in service which is slightly corrosive. Low corrosion rates are needed for low torque to open and close valves, thus, Alloy 718 valve stems are used in combination with noncorrosion resistant alloys. Figure 1 shows a cutout of a valve with parts typically manufactured from Alloy 718. A common use is in gates and seats for corrosion-resistant applications. Alloy 718 valve stems, gates, seats, set screws, and other fasteners requiring high strength have been used for a number of years. Other common applications include springs and components in downhole safety valves which require high tolerances, for example, flappers and seals for downhole safety valves. Alloy 718 components for side-pocket mandrels (chemical injection valves) have been used. These applications constitute the bread-and-butter usage of Alloy 718 in the petroleum industry.

Newer applications of Alloy 718 are found in extremely corrosive wells using only corrosion-resistant alloy equipment. These wells have very high downhole temperatures, high pressures, and high concentrations of both carbon dioxide and hydrogen sulfide. While tubular products in corrosion-resistant alloy completions are cold worked nickel-based alloys, Duplex stainless steels, or 13-chrome stainless steels, these completions require increased use of Alloy 718. Alloy 718 has been used as tubing hangers, bodies for safety valves, downhole polished bore receptacles, chemical injection valves, downhole packers, landing nipples, and extension seals

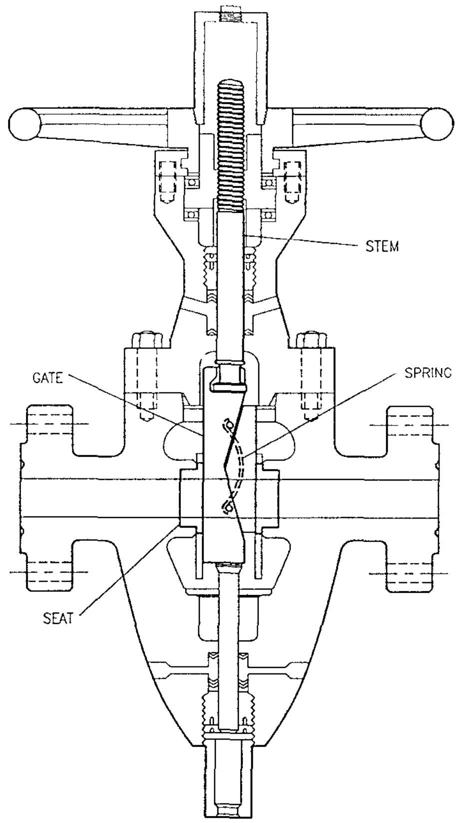

Figure 1. Schematic drawing of a valve showing common Alloy 718 components used in corrosive service.

(1). A large number of these safety valves has been manufactured to date. These constitute the larger equipment constructed from Alloy 718.

Mechanical Properties

The yield strength of precipitation-hardened, corrosion-resistant alloys required for the oil and gas industry ranges from 65,000 to 160,000 psi (450-1100 MPa). The range for Alloy 718 is usually from 110,000 psi (758 MPa) to approximately 150,000 psi (1100 MPa). The NACE specification MR0175 (specification to control hydrogen embrittlement) limits the maximum hardness of Alloy 718 to HRC 40. Thus, the very high-strength levels used in the aviation and aerospace industry are not required nor permitted in oil and gas applications. Therefore, the heat treatments are different from those for high-temperature applications. Consequently, the double-aging treatments used to maximize the strength and creep resistance of Alloy 718 are not used; rather, single-aging treatments are preferred.

In addition to the strength requirement, alloy toughness is extremely important. A Charpy v-notch toughness of 20 to 40 foot-pounds for corrosion-resistant alloys is often specified. This also limits the maximum strength of Alloy 718. Thus, the processing and heat treatment of Alloy 718 should provide the necessary strength and good toughness. In addition, Alloy 718 is heat treated to provide adequate hydrogen embrittlement resistance and stress corrosion cracking resistance. These will be discussed in later sections.

Single-step aging treatments are used to develop the mechanical properties in oil and gas applications. The annealing temperatures are usually in the range 1850 to 1950 F (1210 to 1265 C) followed by a one-step age at 1200 to 1450 F (648 to 988 C). This achieves yield strengths of 130,000 to 140,000 psi (896 to 965 MPa). Figure 2 displays the yield strength and toughness of Alloy 718 and Alloy PH3 after solution annealing and aging between 1200 and 1400 F (648 to 760 C). The strength can be achieved either by underaging near 1275 F (690 C) or overaging near 1400 F (760 C). Depending on the requirements, either of these heat treatments are used for a given yield strength. The toughness (2,3) decreases with increasing aging temperature, although the yield strength reaches a peak between 1200 and 1400 F (648 to 760 C). Thus, for best toughness, underaging may be preferable. There are other considerations for developing toughness in Alloy 718. For example, grain boundary precipitation may affect toughness, as is indicated by either the ductile (4) or intergranular nature of fracture surfaces obtained in toughness tests (5). These factors will not be considered in detail.

The political metallurgical requirement of NACE Specification MR0175 permits the use of Alloy 718 to maximum hardness of HRC 40. It is necessary, for some applications, to obtain the highest yield strength achievable with the imposed maximum HRC 40 hardness. Table 1 shows that under these restrictions, a minimum yield strength of 140,000 psi (965 MPa) can be attained. Alloy 718 as shown in Table 1 has been supplied and installed in oil field applications for corrosive environments. The use at these very high strength levels is contrary to the justification for the recent changes made in NACE Specification MR0175. The increase in the Rockwell hardness to HRC 40 in MR0175 was justified by easier manufacturing of Alloy 718 to the 120,000 minimum yield strength (827 MPa).

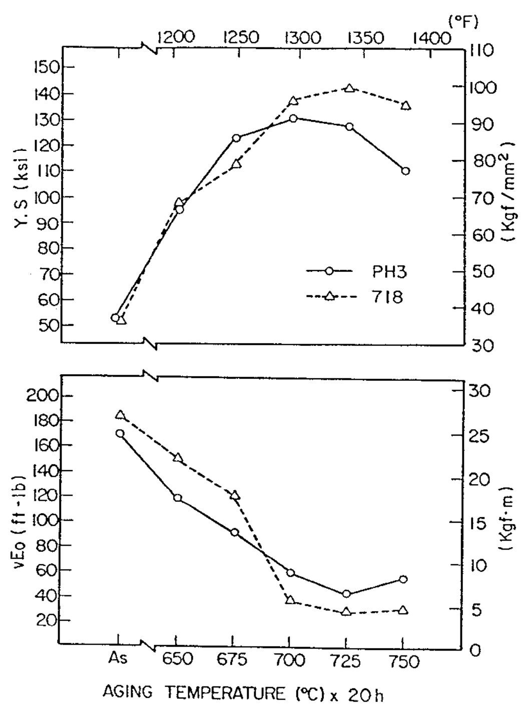

Figure 2. Comparison of aging behavior of PH3, 718,

TABLE 1
ALLOY 718 WITH
SPECIFIED MAXIMUM HARDNESS HRC 40

Yield Strength ksi	Yield Strength MPa	Tensile Strength ksi	Tensile Strength MPa	RA %	Charpy V-Notch foot-lbs	Hardness HRC
148	(1020)	183	(1262)	21	79/80/80	39
151	(1041)	183	(1262)	45	69/72/74	40
148	(1020)	188	(1296)	44	68/69/77	39

This paper has not addressed the use of multiple heat treatments which may be detrimental in providing the mechanical properties necessary for the oil field. However, the user should be aware that most of Alloy 718s applied to the market are destined for high-temperature use. These are heat treated to the "standard" two step aging treatments. Reheat treating of these alloys may not provide the required properties for oil and gas applications since the heat treatment history (not only to the last heat treatment) has an effect on the microstructure. For example, grain boundary precipitates or second phases can remain in the grain boundaries to subsequently coarsen in future heat treatments. Therefore, the oil and gas industry should take into consideration heat treatment history. Further study is necessary in this area.

Corrosion Resistance of Alloy 718

Alloy 718 is used for oil and gas applications because of its good corrosion resistance. Since downhole environments are totally deaerated, the likelihood of either general corrosion or pitting corrosion in production environments is low (6). Alloy 718 has been found to be highly resistant to carbon dioxide, hydrogen sulfide, and acetic acid containing environments as shown in Table 2. Corrosion rates of less than 1 mil per year (.025 mm/y) are encountered to high temperatures. Only with acid, oxygen, or elemental sulfur does corrosion of Alloy 718 become significant. Therefore, the pitting corrosion resistance is considered only in the most severe environments encountered in the industry. Figure 3 shows the pitting potentials of alloys used in the industry. These alloys are considered to be corrosion resistant in most production environments. Alloy 718 has pitting corrosion resistance equivalent to duplex stainless steels. Alloys such as 410 stainless steel, nine-chrome one-moly, 304 stainless steel, CA6NM, F6NM, and 17-4 PH stainless steel are limited in use because of their corrosion resistance. Alloy 718 applications are generally not limited by corrosion resistance.

TABLE 2
CORROSION RESISTANCE OF ALLOY 718
IN SIMULATED PRODUCTION ENVIRONMENTS

Environment	Temperature	Gas	Corrosion Rate mpy	(mm/y)
3% NaCl	400 F (204 C)	1% H_2S + 50% CO_2 + 49% CH_4, 1000 psi	0.1	(.0025)
Seawater	240 F (115 C)	CO_2, 250 psi	0.2	(.0050)

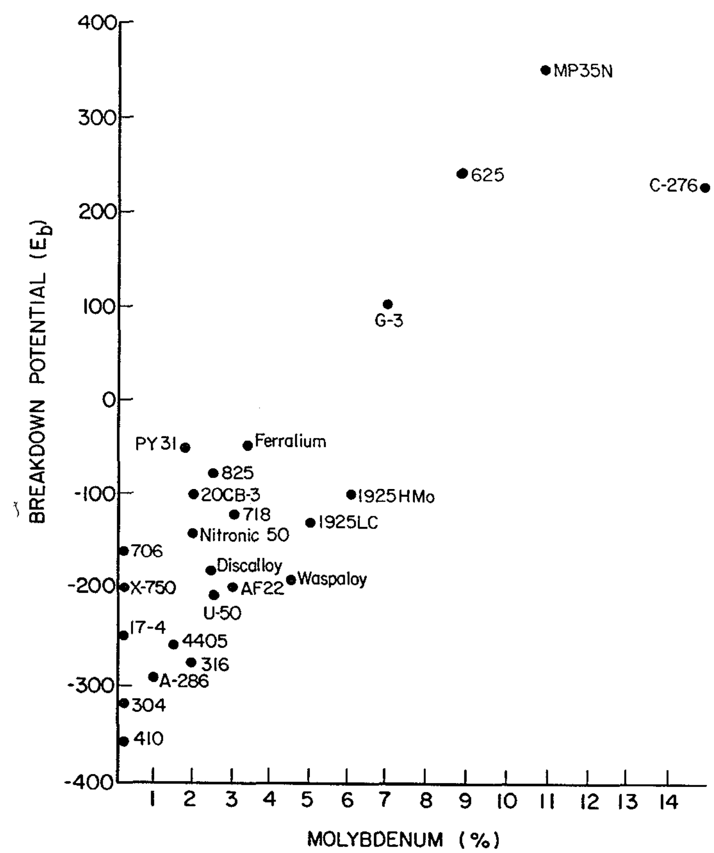

Figure 3. Pitting breakdown potentials of alloys used in the oil and gas industry. Eleven percent NaCl, 250 F, 500 psi CO_2 (after Paul J. Kovach, Vetco Gray).

Both the general corrosion resistance and the pitting corrosion resistance of Alloy 718 are affected by heat treatment. Table 3 shows the influence of aging temperature on the pitting corrosion resistance in the "Yellow Death Solution." In this test, increasing pitting temperatures reflect improved corrosion resistance. The reproducibility of this test is within 5 C. Heat treatments to 1350 F (732 C) do not have a detrimental effect on the pitting temperature in the "Yellow Death Solution." However, heat treatment at 1450 F (788 C) affects the pitting corrosion resistance. The reduction in pitting corrosion resistance can be attributed to both the precipitation of carbides and to the segregation of alloying elements during the precipitation hardening treatments. The trend shows that higher annealing temperatures are detrimental to pitting corrosion resistance of Alloy 718. However, except in the most severe cases, pitting corrosion resistance is not a limiting property, even in the 1450 F heat-treated conditions shown in Table 3. Table 4 shows a corresponding decrease in the general corrosion resistance of Alloy 718 with increasing temperature of heat treatment. This corrosion is associated with the chromium depletion in localized regions due to heat treatment. Thus, both the localized corrosion and generalized corrosion resistance decrease with increasing temperature aging treatments.

TABLE 3
ALLOY 718

Pitting Temperature in "Yellow Death Solution"
4% NaCl + 0.1% $Fe_2(SO_4)_3$ + 0.01M HCl
24-Hour Test

Conditions	Temperature Where Pitting Was Observed C
Mill Annealed	45
8 Hr/1250 F (677 C)	45
8 Hr/1350 F (718 C)	45
8 Hr/1450 F (788 C)	40
168 Hr/1450 F (788 C)	30

TABLE 4
CORROSION RESISTANCE OF ALLOY 718

Conditions	Boiling 5% H_2SO_4 mpy (mm/y)	Boiling 50% H_2SO_4 + 2.5% $Fe_2(SO_4)_3$ mpy (mm/y)
Mill Annealed	81 (2.1)	14 (.36)
8 Hr/1250 F (677 C)	77 (1.8)	58 (1.5)
8 Hr/1325 F (718 C)	62 (1.6)	200 (5.1)
8 Hr/1450 F (788 C)	56 (1.4)	280 (7.1)
168 Hr/1450 F (788 C)	77 (2.0)	3600 (9.1)

Alloy 718 possesses sufficient resistance to corrosion in acidizing environments. Table 5 shows relative corrosion rates of alloys in 10 percent boiling hydrochloric acid. This acid is uninhibited and shows maximum corrosion rates expected for short-term exposures. Alloy 718 corrodes at 4 mils (0.10 mm) per day, even in the uninhibited acid. The corrosion resistance is comparable to Alloys 825, SM2550, or G3, which are a likely combination with Alloy 718 in the most severe completions. From a practical standpoint, the corrosion resistance of Alloy 718 in oil field acidizing environments is adequate, especially since these environments will contain corrosion inhibitors to reduce the corrosion rates even further. The effect of heat treatment on corrosion resistance of Alloy 718 in hydrochloric acid has not been examined. The effects of H_2S on acidizing have also not been examined.

TABLE 5
CORROSION RESISTANCE OF ALLOYS

Uninhibited 10% HCl Acidizing Solution
Boiling Test, 24-Hours

Alloy	Corrosion Rate mpy	(mm/y)
304 Stainless Steel	>20,000	(>500)
Duplex Stainless Steel (2205)	>20,000	(>500)
Alloy 718	1,500	(38)
Alloy SM 2550	1,150	(29)
Alloy G-3	1,050	(27)
Alloy 825	1,000	(25)
Alloy C-276	230	(5.8)

Hydrogen Embrittlement Resistance of Alloy 718

Alloy 718 is susceptible to hydrogen embrittlement (7,8), especially in the high strength heat-treated conditions. However, most of the investigations of hydrogen embrittlement have been performed with high strength (170,000 psi (1172 MPa) yield) materials. Thus, the results from work with these high strength materials for the aerospace industry may not be relevant in predicting the likelihood of failure in oil field applications (9,10). However, the effects of heat treatment or other environmental parameters may still be relevant to oil industry use. High temperature aging treatments (11) near 1400 F (760 C) improve the hydrogen embrittlement resistance of Alloy 718. Table 6 shows the effect of heat treatment on the hydrogen embrittlement resistance in high-pressure hydrogen at room temperature (12). As shown, Heat Treatment No. 1 provides the highest resistance to hydrogen embrittlement. Other work has shown that grain boundary precipitation (13) is detrimental to hydrogen embrittlement

TABLE 6
EFFECT OF HEAT TREATMENT ON
HYDROGEN EMBRITTLEMENT RESISTANCE OF
ALLOY 718, 1,000 PSI PRESSURE OF GAS

Heat Treatment	Strength Ratio H_2/He in Tensile Tests
1900 F/20 min/AC/1400 F/11 hr/1200 F/9 hr	.91
1800 F/1 hr/AC/1325 F/8 hr/1180 F/12 hr	.66
1950 F/1 hr/AC/1350 F/9 hr/1200 F/11 hr	.51

resistance. Fine grained structures are more resistant to embrittlement (14). The hot-worked plus direct-aged condition has better hydrogen embrittlement resistance than hot-rolled + solution-annealed + aged condition. This may be interpreted as an effect of grain boundary precipitation (15) on the hydrogen embrittlement resistance of Alloy 718.

The resistance to sustained crack growth is relatively independent of temperature between ambient and minus 100 F. There is some evidence that the gamma double prime precipitate is more resistant to hydrogen embrittlement than the gamma prime precipitate in nickel-based alloys. Also solution-annealed + cold-worked condition is more susceptible to hydrogen embrittlement (16) than precipitation-hardened Alloy 718. This susceptibility to embrittlement is especially enhanced after well-aging (17) treatments at 400 to 600 F (204 to 315 C).

In spite of the proven susceptibility of Alloy 718 to hydrogen embrittlement at high strength levels, it shows high resistance to cracking at strength levels used in the oil industry (18). Various laboratories have shown that, even at a hardness of HRC 40, Alloy 718 is not susceptible to delayed failure in the NACE TM0177 tests containing hydrogen sulfide and acetic acid, even when coupled to carbon steel and in the well-aged condition (19). Table 8 demonstrates the resistance to delayed failure in the TM0177 tests. These results imply that hydrogen embrittlement of Alloy 718 in properly heat treated conditions does not pose the primary limitation for use in oil field applications. This applies for constant temperature exposures as well as cycling between high and low temperature environments, as is shown in Table 7. Since the strength level is the critical parameter which determines sulfide stress corrosion cracking resistance, controlling the strength level to acceptably low values minimizes the risk for sulfide stress cracking in the oil field. Thus, the HRC 40 maximum hardness appropriately reduces the risk of hydrogen embrittlement in the oil and gas applications to low values.

Stress Corrosion Cracking of Alloy 718

Alloy 718 is susceptible to stress corrosion cracking in high temperature waters (20), in caustic solutions, and in high-temperature chloride solutions (16,21) containing hydrogen sulfide or acids. Most of the stress corrosion cracking investigations performed for the aerospace industries (water or caustic environments) are not relevant to the oil and gas industry applications because of the specificity of environments required for stress corrosion cracking. In deionized water and caustics (22), the

TABLE 7*
RESISTANCE OF ALLOY 718 TO
HYDROGEN EMBRITTLEMENT IN THE NACE
TM-01-77 TEST SOLUTION, ROOM TEMPERATURE,
5 PERCENT NaCl + 1/2 PERCENT ACETIC ACID + 1 ATMOSPHERE H_2S

720 Hours

Alloy Condition	Hardness, HRC	Test Condition
1875 F/1 hr/WQ/1425 F/12 hr/AC/1490 F/8 hr AC	38	U-Bend
1875 F/1 hr/WQ/1475 F/12 hr AC	40	U-Bend
1750 F/1hr WQ/1325 F/8 hr FC/1150 F/8 hr AC	41	NACE Tensile
1950 F/1 hr/WQ/1325 F/8 hr FC/1150 F/8 hr AC	41	C-Ring + Steel Couple $\sigma = \sigma_y$
1925 F/1 hr/WQ/1450 F/1 hr/AC	32	C-Ring + Steel Couple $\sigma = \sigma_y$
1750 F/1 hr/WQ/1325 F/8 hr FC/1150 F/8 hr/AC	43	NACE Tensile Steel Couple
Cold Roll + 1325 F/8 hr/FC/1150 F/8 hr/AC	46	Bent Beam Steel Couple
1925 F/1 hr/AC/1400 F/10 hr/FC/1200 F/20 hr AC	45	TM0177

*Data From Reference (19).

TABLE 8
AVERAGE CRACKING TIME FOR COMMERCIAL Fe-Ni-Cr ALLOYS EXPOSED IN BOILING $MgCl_2$ at 154 C*

Alloy Designation	Nickel Concentration (wt. pct.)	Average Time to Cracking (minutes)++
Type 304	9	590
Type 310	20	600
Alloy 800	32	1,800
Alloy 825	42	6,700
Alloy 718	53	10,000

*Specimens 0.38 mm diameter wires, vacuum annealed and rapidly cooled, stressed at 90% of 0.2% offset yield strength.

++Each value the average of ten specimens.

Reference 31.

stress corrosion cracking resistance improves with increased aging temperature similar to that for hydrogen embrittlement. It is not known whether this is relevant to the stress corrosion cracking in high-temperature chloride solutions typical of oil and gas field environments. The effect of heat treatment on the chloride stress corrosion cracking resistance of Alloy 718 in oil field environments has not been thoroughly examined. This is ironical since the stress corrosion cracking behavior limits the application in the most severe environments. Alloy 718 is susceptible to chloride cracking in boiling magnesium chloride (23) solution at 154 C (309 F) (Table 8) and other high-temperature environments containing chloride, sulfur (24), oxygen, or acids. Although not specific to Alloy 718, the presence of hydrogen sulfide greatly accelerates the high-temperature chloride stress corrosion cracking of nickel-based alloys.

High-temperature chloride stress corrosion cracking limits the maximum environmental temperature for Alloy 718 in the oil industry. While Alloy 718 exhibits good resistance to chloride stress corrosion cracking in many high-temperature chloride containing solutions, it is very susceptible in the presence of elemental sulfur (25) (Table 9). Elemental sulfur is found in environments with high H_2S partial pressures. Therefore, in the presence of elemental sulfur, the maximum temperature limit for Alloy 718 is estimated to be 250 to 300 F (121-149 C). In fact, wellhead temperatures and temperatures of safety valves are controlled below 260 F (127 C) in some applications.

TABLE 9
EFFECT OF ELEMENTAL SULFUR ON STRESS CORROSION CRACKING

C-Shaped Samples, Like Alloy Holders
Deaerated 25% NaCl + 1 g/l Sulfur (No Acid Added)
ANNEALED ALLOYS
Time to Failure, Months, 12-Month Exposure

	350 F 100 psi H_2S pH = 4.5	450 F 100 psi H_2S pH = 4.5
Duplex Stainless Steel	1, 1, 1	1, 1, 1
Alloy 28	1, 2, 2	1, 1, 1
Alloy 925, Aged	1, 1, 1	1, 1, 1
Alloy 718 (Heat Treated HRC 45)	1, 1, 1	1, 1, 1
Alloy 825	2, 2, 2	1, 1, 2
Alloy G-3	7, 8, 8	1, 2, 3
Alloy C-276	NC, NC, NC	NC, NC, NC

NC - No Cracking

Some investigations have shown the gamma double prime alloys to be less susceptible to stress corrosion cracking than gamma prime alloys similar to findings on hydrogen embrittlement. While the data are sparse on Alloy 718, information on other precipitation hardenable alloys similar to 718 suggest that higher-temperature heat treatments and the absence of grain boundary precipitation is beneficial for chloride stress corrosion cracking resistance. Consequently, as a practice, where stress corrosion cracking limitations apply, higher-temperature aging treatments are used to prolong life and improve resistance to chloride stress corrosion cracking.

Selection of Precipitation Hardenable Alloys for the Oil and Gas Industry

Only a few highly corrosion-resistant precipitation hardenable alloys are considered for use in the oil and gas industry. Among these alloys are 17-4 PH stainless steel, Custom 450 stainless steel, A-286, Alloy K500, Alloy 718, Alloy 925, Alloy 625, Alloy Custom-Aged 625+, and a new Alloy PH3. The Alloy X750 has been used historically but is finding less usage because of its susceptibility to hydrogen embrittlement and stress corrosion cracking. The first few alloys are of lower-cost and are used as environmental considerations permit. However, these alloys are more highly susceptible to sulfide stress corrosion cracking and are not considered for the severe applications. In the severe applications, the alloys include 925, 718, PH6, 625, and Custom-Aged 625+. Of these alloys, only Alloy 718 can achieve the very high-yield strengths (140,000 psi minimum yield) for application requiring these strength levels. Table 10 displays the yield

TABLE 10
MECHANICAL PROPERTIES OF HEAT TREATABLE ALLOYS USED FOR CORROSION RESISTANT APPLICATIONS IN PETROLEUM PRODUCTION

Alloy	Heat Treatment	Yield Strength Solution Annealed + Aged ksi	(MPa)	Tensile Strength ksi	(MPa)
625	1700 F/1 hr/WQ/1200 F/16 hr	88	(607)	146	(1007)
925	1800 F/1 hr/WQ/1400 F/8 hr FC/ 1150 F/8 hr/AC	114	(786)	170	(1172)
Custom Age 625	1800 F/4 hr/WQ/1375 F/8 hr/ FC 1250 F/8 hr/AC	126	(869)	182	(1255)
PH6	1960 F/WQ/1275 F/20 hr/AC	133	(917)	160	(1103)
718	1875 F/2 hr/WQ/1425 F/8 hr/AC	142	(979)	184	(1269)

strengths obtainable and typical values used in the industry. In this respect, Alloy 718 has the advantage over the other alloys. However, for the most severe applications, the Alloy 625, Custom-Aged 625+, and PH6 alloys exhibit higher chloride stress corrosion cracking resistance (26-30) and, therefore, are considered for the highest severity environments.

Subsurface safety valves require alloys with higher strength than those in production tubing because design stress levels are lower. Since the restriction of the I.D. bore should be minimized, the strength requirement for complicated parts is pushed to higher levels. Therefore, one of the most critical components in high-pressure gas wells, a subsurface safety valve, presently imposes the greatest restrictions for material usage in severely corrosive applications. Alloy 718 remains the material of choice for the severe sour applications.

Conclusions

1. The stress corrosion cracking resistance of Alloy 718 determines the limits of application in the most severely corrosive high-pressure sour gas wells.

2. Alloy 718 is susceptible to hydrogen embrittlement in the extremely high-strength levels. However, for oil field applications, the limit of HRC 40 maximum hardness provides good resistance to hydrogen embrittlement.

3. Increasing aging temperatures result in lower toughness in Alloy 718. Toughness is an important material selection criteria for this alloy.

4. Increasing aging temperatures reduce both the general corrosion resistance and the pitting corrosion resistance of Alloy 718.

5. The heat treatment of Alloy 718 is necessarily customized for applications in the oil industry, and heat treatments historically used for high-temperature applications are generally not suitable for general oil field usage. High temperature aging treatments are preferred for improved resistance to environmental embrittlement.

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