#### FATIGUE AND CORROSION FATIGUE PROPERTIES

OF ALLOYS 625 PLUS, 718, 725 AND K-500

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#### Abstract

The mechanical, fatigue, and corrosion fatigue properties of precipitation-hardened Ni-Cr-Mo-Cb-Ti alloys, Custom Age 625 PLUS®, ALLVAC 716, and INCONEL 725®, in bar product, were determined to assess their suitability for use as high-strength fasteners in marine applications. These alloys are intended for Ni-Cu-Al Alloy K-500 replacement. The evaluation of the alloys included tensile tests, hardness tests, Charpy V-notch impact tests, and high-cycle corrosion fatigue tests using rotating beam-type specimens. The notch used in the fatigue specimens was a machined, circumferential V-groove to result in a theoretical stress concentration factor,  $K_t \approx 3$ . The results showed that the mechanical and fatigue properties of the precipitation-hardened Ni-Cr-Mo-Cb-Ti alloys, Custom Age 625 PLUS®, ALLVAC 716, and INCONEL 725®, met or exceeded the comparative properties of Alloy K-500 in all the tests conducted. The precipitation-hardened Ni-Cr-Mo-Cb-Ti alloy types exhibited these properties over a range of bar diameters from 1 to 5 inches. The corrosion fatigue properties were compared to results for Alloy 718, as well as alloy K-500, and assessed in terms of marine fastener fatigue performance.

## Introduction

# **Background**

High-performance marine equipment, particularly with direct exposure to seawater, have utilized nickel-copper-aluminum alloy K-500 (MONEL® K-500, UNS N05500) to QQ-N-286, where high-strength fasteners are required in bolted joints. The alloy has extensive service use, but the limitations of the material are becoming evident in regard to marine exposures where (1) fasteners are required for bolted joints to alloys more noble than Alloy K-500 in seawater and (2) in areas of intense cathodic polarization. Service failures of alloy K-500 bolts have occurred due to intergranular (hydrogen) cracking in cathodically protected equipment [1,2]. In corrosion studies conducted of Alloy 625 components bolted together with Alloy K-500 fasteners immersed in seawater, the Alloy K-500 fasteners lost an average of 40% of their original weight in one year due to galvanic corrosion [3]. Alternate high-strength fastener alloys with yield strength of 100 ksi (690 Mpa) or greater for seawater immersion service are required, and high-performance propulsion equipment requires fastener alloys of 150 ksi (1035 Mpa) minimum yield strength.

Candidate alloys for high-strength marine fastener applications included high-strength nickel-base alloys and titanium alloys. Most were developed for high temperature and/or aerospace applications, and data regarding their performance in seawater service is scarce. For fastener applications, data on mechanical properties, fatigue and corrosion fatigue properties, notch sensitivity, galling resistance, machinability, thread-forming operations, in addition to galvanic, crevice, and stress corrosion performance, are required for the evaluation of candidate materials. High-performance bolt alloys with yield strength greater than 690 MPa, high fatigue and corrosion-fatigue strength, good seawater corrosion resistance, availability in diameters from ½ to 6 inches, and some fastener application experience were surveyed. The precipitation-hardened Ni-Cr-Mo-Cb-Ti alloys and Alloy 718 were selected for evaluation.

#### **Bolt Fatigue**

Initial alloy selection criteria for bolts and fasteners in marine applications are strength and corrosion resistance. Since fasteners may experience some level of cyclic loading, the fatigue and corrosion fatigue strength must also be considered. Bolt fatigue failures usually occur in the first or second threads, where stress concentration and load pickup is highest, or in the shank-to-head fillet [4]. Metal-to-metal seals, such as bolt head seating in blade hole recess facing, will not reliably keep out seawater, and even effective sealing arrangements are prone to improper installation. Therefore, a bolt alloy with adequate notched, corrosion fatigue resistance is a prudent selection.

Preload is applied to the bolts to minimize the magnitude of cyclic load passing through the bolts [4]. There is an optimum preload for maximum fatigue strength above which the cyclic bolt load component cannot be further reduced. A high-strength alloy allows a high preload level in a slender bolt for the optimum fastener design against fatigue. However, high-strength alloys can be notch sensitive and special thread-forming operations may be required for optimum performance [4].

#### Scope

The precipitation-hardened Ni-Cr-Mo-Cb-Ti alloys, INCONEL® Alloy 725 (UNS N07725), Custom Age 625 PLUS® (UNS N07716), and ALLVAC 716 PH (UNS N07716), are galvanically compatible with Alloy 625 in sea water applications, since they are based on the same alloy system. This paper presents the evaluation of the mechanical and fatigue properties of Custom Age 625 PLUS®, ALLVAC 716 PH, and INCONEL® 725. For comparison, the fatigue properties of Alloy K-500 and Alloy 718 are also included.

# Materials Investigated

Precipitation-hardened Ni-Cr-Mo-Cb-Ti alloys were procured in the form of rod or bar product over a range of diameters from 1 to 6¼ inches (25 to 160 mm). The product range was intended to maximize the variety of composition, processing, heat treatment, and grain size. For Alloy K-500 and Alloy 718 fatigue tests had previously been conducted using plate product. However, large diameter bar of these alloys were procured to supplement the available data. Fatigue tests of high-strength Ni-Cr-Fe-Cb-Mo-Ti Alloy 718 [5] showed that fatigue and corrosion fatigue strength were dependent on grain size. Thus, it was important to evaluate these alloys in the range of section sizes typical for marine fastener manufacture to determine if grain size was a significant factor.

## Test Procedures

## **Mechanical Properties**

The mechanical properties of the high-strength nickel alloys were evaluated using the following test procedures:

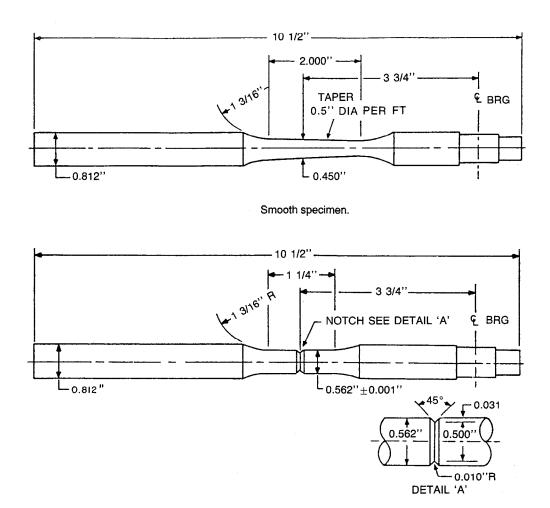
- Tensile tests were conducted using standard, 0.505-inch diameter round specimens, conducted in accordance with ASTM Standard Test Method E8 for Tension Testing of Metallic Materials.
- Hardness tests were conducted by ASTM Method E18 for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials using the C-scale, on a cross-section of each bar, traversing the diameter.
- Charpy V-notch (CVN) impact tests were conducted for each bar in the longitudinal (L-R) direction in accordance with ASTM Standard Test Method E23 for Notched Bar Impact Testing of Metallic Materials.

## Rotating-Beam, High-Cycle Fatigue Tests

Fatigue and corrosion fatigue tests were conducted on smooth and circumferentially notched rotating cantilever-beam (McAdam-type) specimens [6], as shown in Figure 1. The specimens were machined in the longitudinal direction of the bars.

Prior to fatigue testing, the smooth specimens were circumferentially and longitudinally polished to a metallographic grade finish, using a standardized polishing procedure [6]. The notch used was a machined, circumferential V-groove to result in a theoretical stress concentration factor,  $K_t = 3.2$ , as determined from the graphs of Peterson [7]. The notched

specimens were tested in as-machined condition after optical inspection of the notch dimensions for conformity to requirements. The stress concentration for machined screw threads of standard form was determined to be in a range of  $K_t = 3$  to 4 [7].



V-notch specimen,  $K_t = 3$ .

Figure 1 - Smooth and notched rotating cantilever-beam specimens (McAdam-type).

In the fatigue tests, cyclic loading was obtained by applying a constant, deadweight load at the bearing end of the specimen while rotating at 1750 rpm. The maximum, nominal reversed stress was calculated from the applied deadweight load and the dimensions of the specimens, disregarding notch effects. The rotating cantilever-beam tests were performed in air and in saltwater, with the test section being continuously wetted with Severn River water, a brackish water having about one-third the salt content of natural seawater. All tests were conducted at an ambient room temperature. Failure in all tests was defined as complete fracture of the specimen.

## Results and Discussion

### Composition and Mechanical Properties

The chemical compositions and mechanical properties of each rod or bar lot included in the evaluation are given in Tables I through V in the following order: Table I - compositions of Custom Age 625 PLUS® bars, Table II - compositions of ALLVAC 716 PH (UNS N07716) bars, Table III - compositions of INCONEL® Alloy 725 bars, Table IV - compositions of Alloy 718 (UNS N07718) bars, and Table V - compositions of Alloy K-500 (UNS 05500) bars. The compositions of all the products verified that given by producers and were within the required limits of the respective ASTM compositions for the alloys. The microstructures of the products did not show a consistent relationship between bar diameter and grain size, and many of the bars exhibited a mixed or duplex grain size.

Results of tensile tests are given in Tables I and II for the UNS N07716 bars and in Table III for the UNS N07725 bars. In general, yield strengths were typically above 130,000 psi and tensile strengths were above 180,000 psi for all bar diameters. All of the products exhibited good ductility, with elongation greater than 30% and reduction of area greater than 45%. Average Rockwell C-scale hardness (HRC) for each bar is given in Tables I to V. For UNS N07716 and N07725 bars, note that the average hardness values did not significantly vary with producer or bar diameter. Hardness values were higher than that measured and typical for Alloy K-500 and similar to Alloy 718 bars. For most alloys, hardness is related to the ultimate tensile strength.

Table I. Chemical composition and mechanical properties of UNS N07716 (CustomAge 625 PLUS) bars.

GSO GTO GSV  Code  GSO GTO GTH	Bar Size	CHEMICAL COMPOSITION (weight %)												
	(in)	Ni	Cr	Mo	Cb	Fe	C	Mn	Si	P	s	Al	Ti	Co
GSO	1	60.86	20.96	8.00	3.36	rem	0.015	0.09	0.06	0.006	0.001	0.18	1.31	0.04
GTO	11/2	60.65	21.05	8.18	3.57	rem	0.009	0.01	0.02	0.003	0.001	0.20	1.31	0.01
GTH	2	60.82	20.99	7.99	3.26	rem	0.011	0.03	0.04	0.005	0.001	0.19	1.29	0,01
GTI	21/2	60.82	20.99	7.99	3.26	rem	0.011	0.03	0.04	0.005	0.001	0.19	1.29	0.01
GSV	3	60.71	20.98	8.07	3.41	rem	0.014	0.03	0.05	0.008	0.001	0.22	1.31	0.01
Code	Bar Size	MECHANICAL PROPERTIES												
GSO GTO GTH GTI GSV Code		Yield Tensile Strength Strength		Elong	Elongation Reduction of Area			n Hardness		Charpy V-notch Impact Energ (ft-lb)			nergy	
	(in)	(ksi	)	(ksi)	(%	<b>b</b> )	(%)		(HRC)	0 (	F	75 °F	2	00 oF
GSO	1	144	ı	191	30	)	48		33	-		54		56
GTO	11/2	139	)	188	33	3	49		37	-		60		70
GTH	2	132	2	181	34	4	58		36	10	9	113		109
GTI	$2\frac{1}{2}$	132	2	181	34	1	56		35	92	2	91		100
GSV	3	134	1	185	34	1	54		34	75	5	75		78

Table II. Chemical composition and mechanical properties of UNS N07716 (Allvac 716) bars.

Code	Bar	CHEMICAL COMPOSITION (weight %)													
	Size (in)	Ni	Cr	Мо	Cb	Fe	C	Mn	Si	P	s	Al	Ti	Co	
GSR	61/4	61.65	19.89	8.44	3.38	4.87	0.007	0.09	0.01	0.005	0.001	0.22	1.36	-	
GSR Code 1	Bar MECHANICAL PROPERTIES Size														
		Yield Strength		Tensile Strength	Elongation		Reduction of Area		ardness	Charpy V-notch Impact Energy (ft-lb)				ergy	
	(in)	(ks	i)	(ksi)	(%	6)	(%)	1	(HRC)	0 (	F	75 °F	2	90 oF	
GSR	61/4	143	3	182	3	0	45		35	83	3	73		84	

The heat treatment of UNS N07716 and N07725 alloys includes a solution anneal and age-hardening treatment. The solution anneal is conducted at 1900 °F followed by air cooling. The age-hardening treatment consists of heating to 1350 °F, hold for 8 hours, furnace cooling at a rate of 100 °F per hour to 1150 °F, hold for 8 hours, and air cooling. The yield strength of these alloys readily exceeds the minimum of 100 ksi required for hot finished and age-hardened Alloy K-500 by this heat treatment schedule.

Charpy V-notch impact test results are given in Tables I to V, and showed that impact toughness of these alloys was insensitive to temperature, as expected for nickel alloys, with toughness typically exceeding that of Alloy K-500, 30 to 35 ft-lb at room temperature.

Table III. Chemical composition and mechanical properties of UNS N07725 (INCONEL 725) bars.

Code	Bar	CHEMICAL COMPOSITION (weight %)													
	Size (in)	Ni	Cr	Мо	Cb +Ta	Fe	C	Mn	Si	P	s	Al	Ti	Co	
GTM	1	56.12	20.16	7.54	3.51	10.03	0.02	0.16	0.09	0.011	nil	0.28	1.68	-	
GTN	31/4	56.13	20.17	7.53	3.51	10.02	0.02	0.15	0.08	0.010	nil	0.29	1.69	-	
GUJ	5	56.33	20.92	8.02	3.55	9.22	0.01	0.10	0.04	0.002	0.002	0.19	1.62	-	
Code	Bar Size					M	ECHANIC	CAL P	ROPERT	TES					
		Yield Strength		Tensile Strength	Elongation		Reduction of Area		lardness	Charpy V-notch Imp (ft-lb)			pact Ei	pact Energy	
	(in)	(ksi	i)	(ksi)	(%	<b>6</b> )	(%)		(HRC)	0 0	F	75 °F		200 oF	
GTM	1	128	8	184	3	2	43		35	40	5	47		53	
GTN	31/4	126	5	182	3	2	42		34	5:	5	58		61	
GUJ	5	130	)	181	3	1	46		35	69	7	68		70	

Table IV. Chemical composition and mechanical properties of UNS N07718 (INCONEL 718) bars.

Code	Bar Size	CHEMICAL COMPOSITION (weight %)												
	(in)	Ni	Cr	Мо	Cb +Ta	Fe	C	Mn	Si	Cu	s	Al	Ti	Со
DTW FGH	1 3	53.19 53.27	18.88 17.98		5.36 5.17	17.00 18.24	0.06 0.04	0.31 0.15	0.29 0.26	0.17 0.12	0.007 0.003	0.55 0.63	1.03 0.97	- 0.15
Code	Bar Size	MECHANICAL PROPERTIES												
	(in)	Yiel Stren (ksi	gth	Tensile Strength (ksi)	Elong		Reduction of Area (%)		(HRC)		arpy V-1 0 of	otch Im (ft-lb) -120 °	•	ergy 80 °F
DTW FGH	1 3	175. 178.		207.4 204.9	1:		15 23		43 43	19 (12 <b>(-80</b>	2)	20 (12) (32 °F)		22 15

Table V. Chemical composition and mechanical properties of UNS N05500 (MONEL K-500) bars.

Code	Bar	CHEMICAL COMPOSITION (weight %)													
	Size (in)	Ni	Cr	Mo	Cu	Fe	C	Mn	Si	P	S	Al	Ti	Co	
DTN	1	64.61	_	_	30.35	0.76	0.14	0.57	0.14	-	0.006	2.95	0.45	_	
FGG	4	62.00	-	-	32.80	0.56	0.21	0.56	0.18	-	0.007	2.55	1.01	-	
Code	Bar Size	MECHANICAL PROPERTIES													
		Yield Strength		Tensile Strength	Elongation		Reduction of Area		Hardness		Charpy V-notch Impact Energy (ft-lb)				
	(in)	(ksi)		(ksi)	(ks	si)	(ksi)		(HRC)	-20	0 oF	-120 oF		80 oF	
DTN	1	105.8		158.3	30	)	45		30	3	7	37		35	
FGG	4	113.5		159.8	2:	5	42		30	(5 <b>(-80</b>	0) <b>0F)</b>	(49) ( <b>30 °F</b> )		52	

#### Fatigue and Corrosion Fatigue Properties

The results of the fatigue tests are presented in Figures 2 through 5. The results for smooth specimens in air and notched specimens in air and saltwater (SW) are plotted in Figures 2 and 3 for UNS N07716 and UNS N07725, respectively. The data are not noted as to bar diameter, since no trend in fatigue behavior was evident. In general, all the alloys show a fatigue strength at 10<sup>8</sup> cycles of approximately 60,000 psi, about 1/3 of the tensile strength. However, the number of tests in air of smooth specimens was small and the degree of scatter was greater than for the notched specimens. The notched fatigue strength of the UNS N07716 alloy at 10<sup>8</sup> cycles was approximately 38,000 psi, higher than that of UNS N07725.

The fatigue notch reduction factor,  $K_f$  [7], of the alloys was 1.6 for UNS N07716 and 1.8 for UNS N07725, where

$$K_{f} = \frac{Ss}{Sn} \tag{1}$$

Ss = fatigue strength of smooth specimens in air at N cycles, and

Sn = fatigue strength of notched specimens in air at N cycles.

This indicated a low notch sensitivity in fatigue, where the notch stress concentration factor, K<sub>t</sub>, was 3.2. All of the alloys showed a further reduction in fatigue strength due to the salt water environment. The notched corrosion fatigue strength of the UNS N07716 alloy at 10<sup>8</sup> cycles was approximately 28 ksi, while that of UNS N07725 and Alloy K-500 was about 20 ksi. However, the value is an extrapolation for the UNS N07725, since few long-life results support the value. In summary, the fatigue performance of the UNS N07716 alloy was slightly better than that of UNS N07725. However, both alloys were equal or superior to Alloy K-500 under all fatigue test conditions.

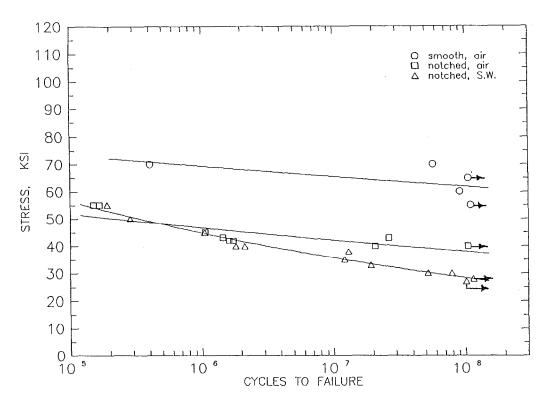


Figure 2 - Fatigue and corrosion fatigue test results for UNS N07716 alloy.

The results for smooth specimens in air and notched specimens in air and saltwater (SW) are plotted in Figures 4 and 5 for UNS N07718 and UNS N05500, respectively. The notched corrosion fatigue data for K-500 are not shown in Figure 5, since these would obscure the results for large diameter corrosion fatigue results with low corrosion fatigue strength.

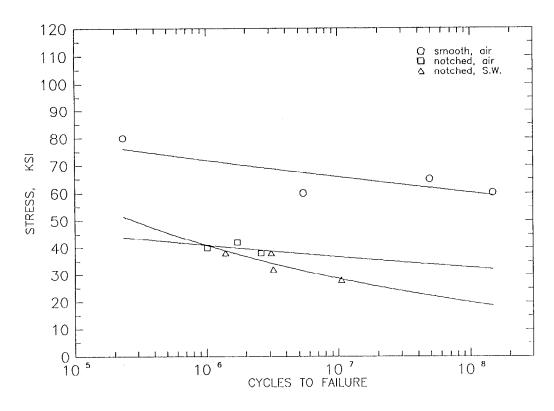


Figure 3 - Fatigue and corrosion fatigue test results for UNS N07725 alloy.

Table VI compares the notched corrosion fatigue strengths of the high-strength nickel fastener alloys. The notched corrosion fatigue strengths are based on best-fit curves to the data. The values for notched corrosion fatigue strength at  $10^8$  cycles ranged from 15 ksi for K-500 to 28 ksi for UNS N07716. A corrosion fatigue notch reduction factor,  $K_{\rm cf}$ , was calculated as the ratio of the fatigue strength in air (smooth specimens) to the notched fatigue strength in saltwater at the same fatigue life. Values of  $K_{\rm cf}$  were least for UNS N07716.

Table VI. Comparison of notched corrosion fatigue properties of high-strength nickel alloys.

Alloy	Yield Strength (ksi)	Tensile Strength (ksi)		d Corrosion ength at N cy (ksi) N = 10 <sup>7</sup>			on Fatigue n Factor (F N = 10 <sup>7</sup> 108	K <sub>cf</sub> ) at N	Fastener Fatigue Capacity (ksi)
Alloy 625+ UNS N07716	120	150	44.5	36	28	1.53	1.80	2.14	11.2
Inconel 725 UNS N07725	120	150	40.5	29	[20]	1.75	2.36	3.30	8.0
Alloy 718 UNS N07718	150	185	36	28	21	2.75	2.96	3.20	8.2
Monel K-500 UNS N05500	100	140	31.5	21	15	2.00	2.38	2.67	7.0

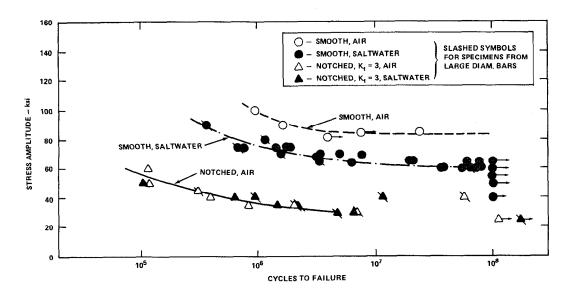


Figure 4 - Fatigue and corrosion fatigue test results for UNS N07718 alloy.

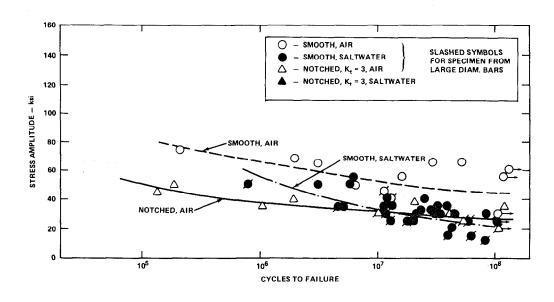


Figure 5 - Fatigue and corrosion fatigue test results for UNS N05500 alloy.

As previously noted, preload is applied to fasteners to minimize the magnitude of cyclic load transmitted to the fastener. The preload compresses the mating surfaces and may aid the bolt in resisting bending moments. It does not increase the static strength of the bolt, nor does it assist the bolted joint in withstanding tensile loads. However, preload increases the fastener fatigue resistance by decreasing the load range sensed by the bolt. A portion of the applied external load is always part of the total bolt load. It is proportional to the ratio of bolt-to-joint stiffness regardless of the amount of preload. There is an optimum preload for maximum fatigue strength above which the cyclic component of the bolt load cannot be further reduced. Preload levels above the optimum lead to lower fatigue lives because of high mean stress [8].

Thus, a fastener material must have adequate fatigue strength, particularly in machined threads. Bolt fatigue failures usually occur in the first or second threads, where stress concentration and load pickup is highest, or in the shank-to-head fillet. Metal-to-metal seals, such as bolt head seating in bolt hole recess facing, will not reliably keep out water; and even effective sealing arrangements are prone to improper installation. A bolt material with adequate notched corrosion fatigue resistance is a prudent selection for marine applications.

Since the alloys investigated in this study were of different strength levels, a ranking scheme was used, "fastener fatigue capacity," based on the Goodman equation [9] which describes the effect of mean stress on fatigue strength:

$$S_{eq} = \frac{S_a}{1 - \frac{S_m}{S_u}} \tag{2}$$

where  $S_{eq}$  = equivalent reversed stress amplitude (zero mean stress);

 $S_m$  = mean stress;

 $S_u$  = ultimate tensile strength; and

 $S_a$  = alternating stress at  $S_m$ .

For each alloy, the mean stress was selected equal to 75% of the minimum yield strength. This stress is recommended as the preload to avoid low-clamp-force problems, such as vibration loosening or fatigue. This is the maximum preload target when a torque wrench is used [8]. This value for  $S_m$ , the value of  $S_u$ , and  $S_{eq}$  as the notched corrosion fatigue strength at  $10^8$  cycles for each alloy (Table VI) gives a value of  $S_a$ , the fastener fatigue capacity at maximum recommended preload.

# Work-Hardened Fastener Threads

Cold-roll formed or roll-worked threads have long been a method of obtaining fatigue resistant fasteners. The process combines work hardening, compressive residual stress at the thread root, geometric factors (i.e. lower stress concentration factor for a rounded thread root profile versus a cut thread).

An analysis of cold rolling of threads using slip-line field and finite element analyses was conducted. The residual stress distribution around a plastically formed thread was mapped and showed an intense compressive region below the thread root compensated by a region of tensile residual stress to the side of the thread [10]. Experimental fatigue studies of roll-formed notches in Alloy 718 and K-500 were conducted to verify analytical conclusions. Rotating cantilever-beam fatigue tests used specimens with cold-roll formed notches of the same dimensions (depth, flank angle, root radius) as machined notches, Figure 1. The results of the fatigue tests of rolled versus machined notches are shown in Figure 6.

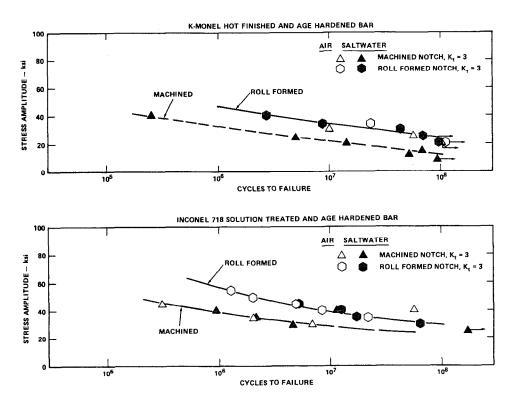


Figure 6 - Fatigue and corrosion fatigue test results for K-500 and Alloy 718 with machined and roll-formed notches.

The path of fatigue crack growth in the rolled notches was not perpendicular to the specimen axis with crack origin at the notch root as in the machined notches. Instead, initiation and growth was altered by the residual stress pattern predicted by analysis [10]. Fatigue cracks initiated in the wall of the rolled notches (the region of tensile residual stress) and grew at an angle to the specimen axis. This crack path resulted in considerably longer fatigue lives for the rolled notch.

Although work-hardening of the metal and improved geometry contribute to the improved fatigue resistance of roll-formed threads, the residual stress distribution was the primary beneficial factor. Thread forming by this process is beneficial to the optimum only if performed after all heat treatments necessary to obtain the required material properties. Thus, for materials of very high strength, considerable power and tooling development may be required. For materials of very high strength and limited ductility, roll-forming of full, deep threads may cause micro-cracking in the surface layers and degrade fatigue resistance. Root rolling of partially machined threads may be an option for high-strength, difficult to work metals. Fatigue tests of partial machining and root rolling were conducted on Alloy 718 specimens. Fatigue tests of partially machined and root-rolled-to-size, notched specimens was conducted. The results, shown in Figure 7, indicate that fatigue performance is better than for fully roll-formed notches. Such a process for bolt production would require development of parameters for different materials and thread sizes. Also, more steps in production are required. However, these results sugest that the process may result in the optimum for fatigue strength.

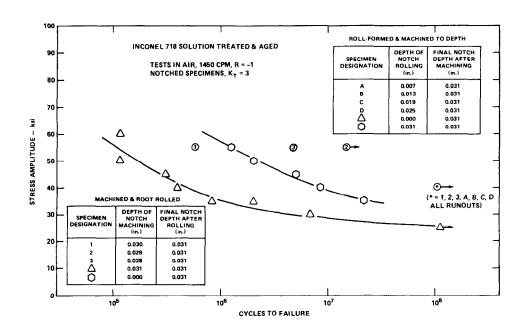


Figure 7 - Results of fatigue tests of Alloy 718 specimens with partially rolled and machined notches compared to machined and to roll-formed notches.

It is cautioned that fatigue tests with notched specimens are essentially qualitative, for comparison of various alloys, environmental factors, notch sensitivity, etc. The results may not be directly applicable in evaluating the performance of a full-size fastener.

#### Summary

The mechanical and fatigue properties of the precipitation-hardened Ni-Cr-Mo-Cb-Ti alloys, Custom Age 625 PLUS® and ALLVAC 716 PH (UNS N07716 alloys) and INCONEL® 725 (UNS N07725 alloy), meet or exceed the properties of K-500 (UNS N05500) in all the tests conducted, over a range of bar diameters from 1 to 6¼ inches. Alloy UNS N07716 had the highest notched corrosion fatigue strength, while large-diameter K-500 showed the lowest.

The notched corrosion fatigue strength of Alloy 718 and K-500 was increased by roll-forming notches. Fatigue tests of Alloy 718 with partially machined and root-rolled notches showed the highest fatigue resistance.

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