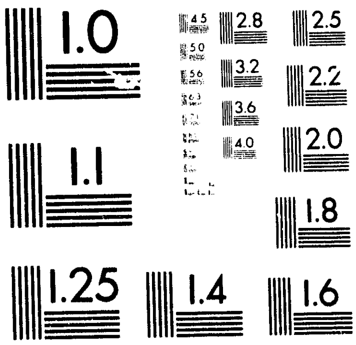
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# BENEFITS OF THREAD ROLLING PROCESS TO THE STRESS CORROSION CRACKING AND FATIGUE RESISTANCE OF HIGH STRENGTH FASTENERS

by

Alan R. Kephart and Steven Z. Hayden

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Schenectady, New York

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# CONTENTS

Page

ABSTRACT....1

INTRODUCTION....1

THREAD ROLLING PROCESS DESCRIPTION....1

TEST PROGRAM DESCRIPTION AND SCOPE....2

TEST RESULTS - SCC AUTOCLAVE PHASE....5

ROLLED THREAD PROCESS SENSITIVITY TO SCC....6

CORROSION AND AIR FATIGUE CRACK INITIATION....7

DISCUSSION OF CAUSES OF PROCESS BENEFITS....7

CONCLUSIONS....8

ACKNOWLEDGEMENTS....8

REFERENCES....8

## TABLES

1 Rolled Thread Test Program Scope....2

2 Test Material Description....3

3 Test Environment Description....4

## ILLUSTRATIONS


Figure No. Page

1 Illustration of Roll Forming of a Metal Bank by the In-Feed Process........1

2 Cylindrical Die-Work Piece Configuration for 3 Die Action in In-Feed Rolling Process........1

3a First and Following Stages of Metal Flow During Die Indentation Producing Thread Crest Laps........2

3b First and Following Stages of Metal Flow During Die Indentation Producing Minimal Crest Laps........2

4 Typical Metal Flow in Threads Produced by the Roll Forming Alloy X-750........3

5 Microhardness Profiles of Rolled Thread Roots of Alloy X-750, Condition HTH........3

6 Grain Flow Resulting from Thread Forming of Alloy X-750, Condition HTH........4

7 Illustration of Highly Deformed Microstructure in Rolled Thread Roots of Alloy X-750, Condition HTH........4

8 Distribution of Very High Cold Worked Regions of Alloy X-750........4

9 Stress Corrosion Cracking in Small Cut Threads of Alloy X-750, AH........5

10 Stress Corrosion Cracking in Large Cut Threads of Alloy X-750, AH........5

11 Typical Intergranular Stress Corrosion Cracking Thumbnail Sites in Cut Threads of Alloy X-750, AH........5

12 Stress Corrosion Cracking Depth in Cut Threads of Alloy X-750........6

## ILLUSTRATIONS (Cont'd)


Figure No — Page

13 Stress Corrosion Cracking Initiation of Life for Cut Threads of Alloy X-750 .......... 6

14 Illustration of IGSCC Response of Rolled vs. Cut Threads of Alloy X-750 .......... 6

15 Thread Rolling Process Induced Thread Crest Laps or Folds in Alloy X-750 .......... 6

16 Lack of Crest Laps Growth and IGSCC Occurance in Alloy X-750 .......... 6

17 Illustration of Improved Fatigue Initiation Resistance of Rolled Threads over Cut Threads of Alloy X-750 in 24 C Air .......... 7

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## ABSTRACT

The stress corrosion cracking (SCC) behavior of cut (machined) vice thread rolled Alloy X-750 and Alloy 625 fasteners in a simulated high temperature primary water environment has been evaluated. SCC testing at 360°C and 338°C included 157 small and 40 large 60° Vee thread studs. Most of the test studs had rolled threads (128) while the remainder (69) had cut threads to provide a baseline for a comparison of SCC initiation resistance. Thread rolled fasteners exhibited improved resistance relative to cut fasteners of the same material condition in terms of both SCC initiation life and applied stress.

Tests of fatigue resistance in air at room temperature and both air and primary water at 315°C were conducted on the smaller studs with both cut and rolled threads. Results have shown rolled threads can have significantly improved fatigue lives over those of cut threads in both air and primary water.

Fasteners produced by two different production thread rolling methods, in-feed (radial) and through-feed (axial), revealed similar SCC initiation test results. Testing of thread rolled fasteners revealed no significant SCC or fatigue growth of rolling induced thread crest laps typical of the thread rolling process. While fatigue resistance differed significantly between the two rolled thread supplier's studs, neither of the suppliers studs showed any SCC initiation at exposure times significantly beyond that of cut threads with SCC. In contrast to benefits afforded by rolling at room temperature, warm rolled (427°C) threads showed no improvement over cut threads in terms of fatigue resistance.

The observed improved SCC and fatigue performance of rolled threads is postulated to be due to several interactive factors, including the presence of beneficial residual stresses in the critically stressed thread root region, reduction of plastic strains during loading and the formation of a favorable microstructure.

## INTRODUCTION

Over the last two decades, several of the conventional high strength nickel and iron-based threaded fasteners materials have revealed intergranular stress corrosion cracking (IGSCC) in primary pressurized water reactor (PWR) environments. [1, 2, 3] While improvements in resistance to SCC have been achieved by using modified heat treatments, susceptibility to pressurized water SCC (PWSCC) remains for commercial alloys. [4, 5]

In addition to emphasizing the search for more SCC resistant high strength fastener materials, the benefits of manufacturing process and surface technology opportunities merit evaluation. Whereas both nickel base alloys and stainless steels have experienced premature IGSCC initiation when subjected to adverse fabrication induced residual (tensile) stresses and surface conditions, [6, 7] the benefits of the thread rolling process to fatigue and SCC resistance has led to widespread applications in aircraft, aerospace, chemical, transportation, power generation, and petroleum industries. [8, 9]

Currently, the potential for manufacturing process enhansed reliability of threaded fasteners for PWR applications has not been exploited. To evaluate IGSCC benefits, thread rolling has been applied to the high strength nickel-base alloy X-750 in its most SCC susceptible condition (AH, two step aged). Also, the more SCC resistant condition of Alloy X-750 (HTH) and direct aged Alloy 625 were included to evaluate fabricability and SCC behavior.

## THREAD ROLLING PROCESS DESCRIPTION

Thread rolling is a process in which hardened steel shaped dies cold roll a cylindrical blank to form the full thread shape. The dies are indented into the metal to form the thread roots and the displaced metal moves radially outward to form the crests of the threads. No metal cutting or removal occurs in this process.

Since the early use of thread rolling dies of the flat reciprocating type, the size, dimensional control and production rate of threads was limited until cylindrical die machines were developed in 1950's. Since the early 1960's, rolled threads have become the standard for industrial applications of high reliability fasteners. Safety-critical fastener needs mandate use of rolled threads, particularly in aircraft applications. References 10 and 11 provide background information for the thread rolling process.

An illustration of the cold form rolling setup for external threads is shown in Figure 1. Thread rolling of high strength materials is usually accomplished by the use of three driven cylindrical dies (Figure 2) which close inward (radially) to form the threads, hence the process term of in-feed. Another variant of the thread rolling process employs fixed radially spaced dies where the material to be threaded is fed axially through the dies, hence the process term through-feed.

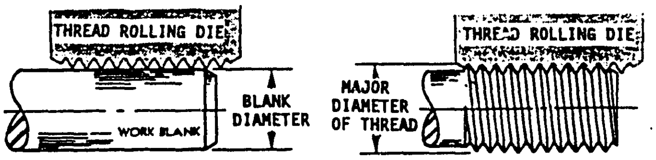


**Figure 1.** Illustration of Roll Forming of a Metal Blank by the In-Feed Process, Courtesy of Reed Rolled Thread Die Co.

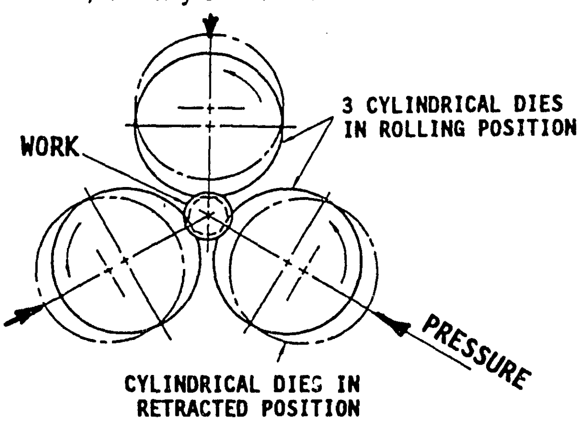


**Figure 2.** Cylindrical Die-Work Piece Configuration for 3 Die Action in In-Feed Rolling Process, Courtesy of Reed Die Co.

Two of the most obvious features of rolled threads are the roughness and laps (folds) in the thread crests resulting from the outward displacement of metal during roll forming. Depending on the flow resistance of the metal, grain size, die-rolled metal friction and the rates of metal displacement, the extent of the crest folds and roughness can vary significantly. Figures 3a and 3b illustrate the several stages of die penetration and crest fold formation for fold-prone and minimal fold results, respectively.[11]

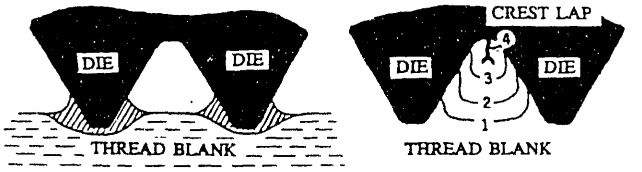


**Figure 3a.** First and Following Stages of Metal Flow During Die Indentation Producing Thread Crest Laps, Courtesy of Reed Co.

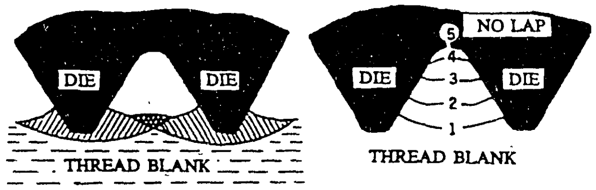


**Figure 3b.** First and Following Stages of Metal Flow During Die Indentation Producing Minimal Crest Laps, Courtesy of Reed Co.

While the appearance of the rough crests and the presence of limited crest laps have been viewed with suspicion, no significance to SCC or fatigue crack growth has been reported. On the other hand, attempts to control the appearance (laps and roughness) by changing process parameters, particularly using high deformation rates and more hydrostatic forces, may lead to loss of rolling process benefits.

The basis for the improved reliability of cold formed threads is traditionally associated with work hardening of the threads and preventing the typical microstructural and chemical non-uniformities, present in wrought metal bars, from intersecting critical stressed thread roots and flanks. Combination of cold work hardening and favorable microstructure of rolled threads provide increased tensile and shear strength of rolled threads over cut threads.

The observed improvement of rolled threads to fatigue crack initiation has been attributed to cold work, beneficial flow lines and residual compressive stresses in the thread roots.[12] Also, the smoother and burnished surface finish of rolled threads is considered beneficial to fatigue life and provides an engaged joint less likely to loosen during service.

## TEST PROGRAM DESCRIPTION AND SCOPE

While rolled threads have been found to be superior to cut threads in some material-environment conditions (alloy steel in salt water), [13] there is insufficient evidence to support significantly improved SCC initiation life for fastener materials in PWR environments. Potential benefits of rolling induced residual compressive stresses, reduced plasticity and grain deformation have not been integrated into any fundamental SCC behavior model. Thus, empirical testing was required to develop a comprehensive test database before the process benefits could be accepted for PWR applications.

Some potentially negative features of rolled threads prompted special testing, i.e., the effect of rolled thread crest laps on SCC growth. Also, from an electrochemical potential viewpoint, the negative experience with SCC of cold worked austenitic stainless steel in BWR piping [14] required specific testing to resolve its relevance to IGSCC of nickel-base alloys in PWR environments.

### OVERALL TEST SCOPE

Table 1 describes the scope of the test program. The test program was based on comparative evaluations of cut and rolled threads for IGSCC, corrosion fatigue behavior and other potentially influencing factors. SCC fastener testing employed static displacement fixturing which simulates typical fastener loading conditions. Measuring load-induced length changes before and after testing revealed no significant load relaxation occurring during hot water testing. Evaluation of the extent of IGSCC was done by destructive means.

**TABLE 1. ROLLED THREAD TEST PROGRAM SCOPE**

| TEST CATEGORY | TEST PARAMETER | NUMBER OF UNITS |
|---|---|---|
| TYPES OF TESTS | Stress Corrosion<br>Fatigue<br>Corrosion Fatigue | 197 Studs<br>50 Studs<br>12 Studs |
| MATERIALS FOR FASTENER TESTS | Alloy X-750 AH<br>Alloy X-750 HTH<br>Aged Alloy 625 | 4 Heats<br>2 Heats<br>2 Heats |
| THREAD DESIGN FOR SCC TESTS | 0.625-11 UNR-2A<br>1.688- 8 UNR-2A | 157 Studs<br>40 Studs |
| APPLIED STRESS FOR SCC TEST OF ROLLED THREADS | 95% of Yield Strs<br>80% of Yield Strs<br>60% of Yield Strs | 29 Studs<br>80 Studs<br>19 Studs |
| METHODS OF THREAD MANUFACTURING | Rolling<br>Cutting | 172 Studs<br>83 Studs |
| SCC TEST ENVIRONMENT | 360°C<br>338°C<br>288°C | 74 Studs<br>102 Studs<br>21 Studs |

### TEST MATERIAL DESCRIPTION

Fastener alloy types and descriptions for this test program are listed in Table 2. Four of the Alloy X-750 heats were of the more SCC susceptible two-step aged (AH) condition so that a thread rolling process benefit can be quantified in a reasonable time period. This approach was preferred over use of doped accelerated testing environments (e.g., caustic solutions) to avoid uncertainties in relevant IGSCC mechanisms. The more SCC resistant alloys of X-750 HTH and aged Alloy 625 were included in the test to demonstrate no degraded compatibility of cold work and materials for SCC resistant service.

### TEST FASTENER DESIGN TYPES

Both large and small sized rolled fasteners were employed to cover the range of applications. The smaller test stud employed a 15.9 mm (0.625 inch) diameter unified national coarse, 11 threads per inch (TPI) 60° Vee thread, whereas, the large stud thread diameter was 42.9 mm (1.688 inches) with 8 TPI. Threads had controlled root radii consistent with unified national root radius controlled (UNR) thread forms where the 11 and 8 TPI threads have root radii of 0.28 mm and 0.38 mm, respectively. Both stud types had center holes for heater rod thermal expansion loading of the studs. The smaller stud had a shank diameter equal to the maximum thread diameter to enable use of the highest of applied membrane stresses without yielding of non-threaded regions. The large stud had a reduced shank diameter, more typical of flexible cut thread fasteners. Thread membrane stresses of the large stud were limited to 550 MPa because of onset of plasticity at 690 MPa in the smaller area shank (82% of the thread membrane area).

### TEST FASTENER FABRICATION DESCRIPTION

All threaded regions of the test studs were either machined (cut) or rolled from bar material described in Table 2. Two thread rolling suppliers provided the test studs, each employing different thread rolling equipment and process parameters. All thread rolling was performed after age-hardening to maximize the process benefits.

One supplier (A) applied the in-feed rolling process to both small and large test studs. The smaller studs were rolled on a three cylindrical die A-22 Reed Co. machine, whereas the large studs were rolled on an A-34 Reed Co. machine. Die contact forces were applied by motor driven gears and cams. Roll diameter for the small threads was 7.0 cm, whereas the large thread rolls were 11.4 cm in diameter.

The other supplier (B) employed a two cylindrical die machine.

## TABLE 2. TEST MATERIAL DESCRIPTION

| Heat ID → → | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| **ALLOY and PROCESS** | | | | | | | | |
| Type | X-750 | X-750 | X-750 | X-750 | X-750 | X-750 | 625 | 625 |
| Condition | AH | AH | AH | AH | HTH | HTH | H | H |
| Melt Process | VIM+ESR | Air | Air | Air | VAR | VAR | VAR | VAR |
| Bar Size (cm.) | 5.1 | 5.4 | 5.4 | 2.5 | 5.1 | 4.8 | 3.8 | 5.1 |
| Heat Treatment | AH | AH | AH | AH | HTH | HTH | Direct Age | Direct Age |
| Anneal °C, Hrs | 885, 24 | 885, 24 | 885, 24 | 885, 24 | 1093, 1 | 1093, 1 | none | none |
| Aging °C, Hrs | 704, 20 | 704, 20 | 704, 20 | 704, 20 | 704, 20 | 704, 20 | 663, 80 | 663, 80 |
| Hardening Phase | γ' | γ' | γ' | γ' | γ' | γ' | γ'' | γ'' |
| Grain Bound. Carbides | MC | MC | MC | MC | $M_{23}C_6$ | $M_{23}C_6$ | $M_{23}C_6$ | $M_{23}C_6$ |
| **PROPERTIES** | | | | | | | | |
| Yield Stress, MPa | 738 | 814 | 807 | 869 | 794 | 814 | 731 | 925 |
| Ultimate Stress, MPa | 1200 | 1242 | 1180 | 1256 | 1194 | 1194 | 1104 | 1221 |
| Hardness, $R_c$ | 33 | 34 | 35 | 36 | 31 | 31 | 30 | 37 |
| Reduct. Area, % | 37 | 32 | 36 | 36 | 37 | 35 | 42 | 51 |
| Elongation, % | 23 | 20 | 24 | 22 | 27 | 27 | 34 | 28 |
| Grain Size, $d_n$, (μm) | 22 | 16 | 16 | 11 | 105 | 125 | 45 to 125 | 16 |
| **CHEMICAL COMP. Wt%** | | | | | | | | |
| Ni | 72.6 | 70.8 | 72.4 | 70.8 | 71.4 | 71.7 | 62.5 | 62.0 |
| Cr | 15.4 | 16.3 | 16.0 | 15.1 | 15.6 | 15.1 | 21.8 | 20.7 |
| Fe | 7.4 | 7.8 | 7.0 | 8.22 | 7.9 | 7.9 | 2.3 | 4.1 |
| Al | 0.64 | 0.80 | 0.71 | 0.82 | 0.68 | 0.74 | 0.28 | 0.37 |
| Ti | 2.48 | 2.50 | 2.49 | 2.49 | 2.59 | 2.65 | 0.28 | 0.33 |
| Mo | - - | - - | - - | - - | 0.000 | 0.000 | 8.82 | 8.59 |
| Nb + Ta | 0.94 | 0.98 | 0.97 | 0.96 | 1.00 | 1.02 | 3.91 | 3.71 |
| Mn | 0.24 | 0.27 | 0.09 | 0.24 | 0.09 | 0.08 | 0.03 | 0.06 |
| Si | 0.14 | 0.31 | 0.19 | 0.33 | 0.01 | 0.03 | 0.05 | 0.02 |
| Cu | 0.03 | 0.26 | 0.08 | 0.28 | 0.01 | 0.01 | 0.02 | 0.04 |
| Co | 0.03 | 0.04 | 0.04 | 0.05 | 0.01 | 0.01 | 0.01 | 0.03 |
| C | 0.04 | 0.05 | 0.05 | 0.04 | 0.037 | 0.04 | 0.042 | 0.036 |
| P | 0.007 | - - | - - | - - | 0.001 | 0.001 | 0.003 | 0.006 |
| S | 0.001 | 0.004 | 0.007 | 0.004 | 0.002 | 0.001 | 0.001 | 0.001 |

AH - Equalization Annealed plus Age (precipitation strengthened), two-step aged
HTH - High Temperature Anneal plus Age (precipitation strengthened)
Direct Age - Hot Rolled plus Age (precipitation strengthened)

In-feed rolling was used on both stud threads, except for the long thread of the large diameter stud where through-feed rolling was used. Rolling forces for this equipment were applied by hydraulic means with large diameter (20 cm) rolls.

Acceptance testing by breaking strength and fatigue testing were in accordance with standard aircraft fastener requirements.[15] Subsequent to delivery of the rolled thread studs, heater holes were drilled and threads were thin, hard chromium plated to provide an anti-seizing surface treatment identical to the baseline cut thread test studs.

Evaluation of the rolled studs prior to testing provided a specific characterization of the response of Alloy X-750 to the rolling process. Figure 4 shows thread rolling induced metal flow of linear chemical segregation features typically present in Alloy X-750 bar material. Other process effects included microhardness (Figure 5), and grain deformation features, both macroscopic (Figure 6) and microscopic (Figure 7). The latter photograph shows the high degree of intragranular deformation by complex slip and cross-slip, in addition to severely stretched grain boundaries. The degree of local deformation is apparent from the grain shape change shown in Figure 6.

The depth and distribution of very high cold work regions can be revealed by a special heat treatment which causes the normally stable round precipitation hardening phase (gamma prime) in X-750 to transform to a platelet phase (eta). Figure 8 shows these highly cold work regions (estimated to be at least 50% equivalent reduction) delineated by the eta phase in both the thread flanks, crests and roots.

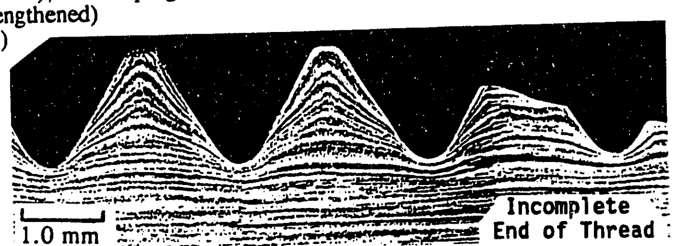


**Figure 4.** Typical Metal Flow in Threads Produced by the Roll Forming Alloy X-750

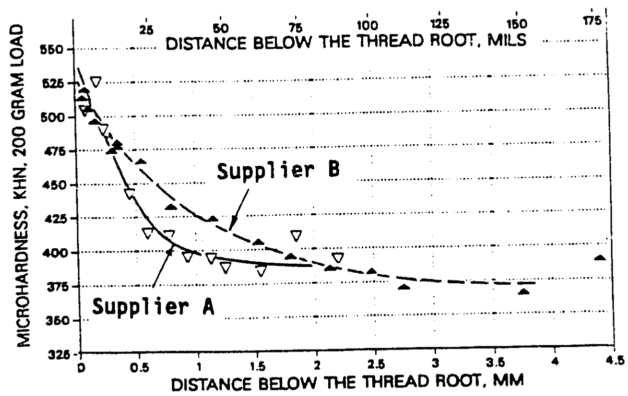


**Figure 5.** Microhardness Profiles of Rolled Thread Roots of Alloy X-750, Condition HTH, Rolled by Suppliers A and B.

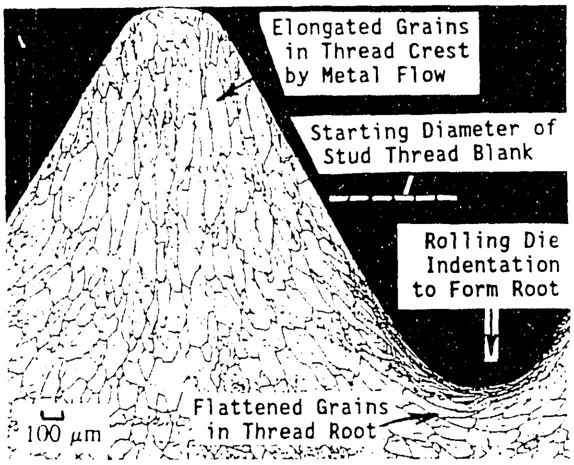


**Figure 6.** Grain Flow Resulting from Thread Forming of Alloy X-750, Condition HTH

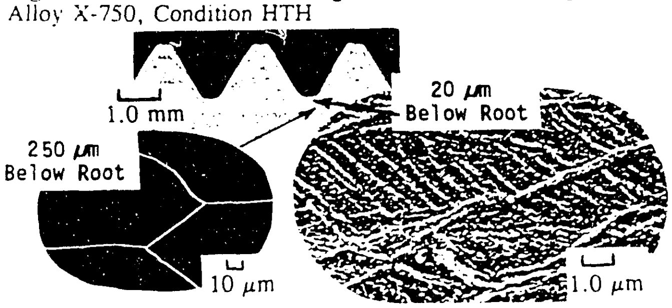


**Figure 7.** Illustration of Highly Deformed Microstructure in Rolled Thread Roots of Alloy X-750, Condition HTH

To provide a comparison baseline for the SCC initiation performance of the rolled threads, studs with cut threads were manufactured from the same alloys. The cutting process employed hard tungsten carbide tools and the depth of metal removal was limited to be consistent with good machining practices. Tool sharpness was maintained by limiting the tool wear land to 0.12 mm during the last thread cutting layer removal.

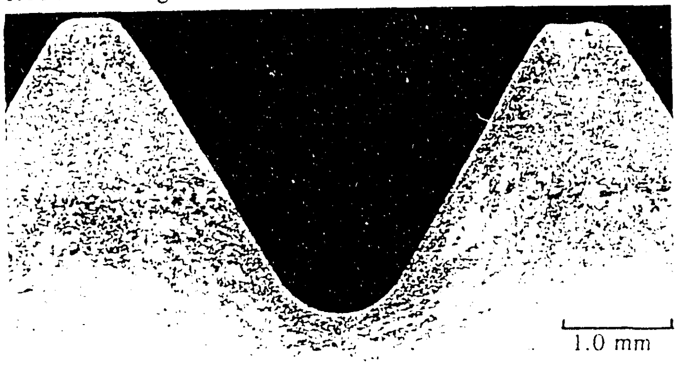


**Figure 8.** Distribution of Very High Cold Worked Regions of Alloy X-750 Resulting From Roll Forming of Threads and Revealed by a Special Eta Phase Transformation Heat Treatment

STRESS CORROSION CRACKING TEST DESCRIPTION

The test assemblies, including the compression sleeve and nuts, were made of the same alloy (X-750) as the test studs. Test loadings were achieved by use of a heater rod inserted in the center hole of the stud and turning the nut to give the desired length extension after cooling to room temperature. The test load was determined from the measured stud stiffness and stud elongation.

For both cut and rolled threads, the applied test stresses were about 95, 80 and 60% of the material yield strength at test temperature, typically about 700 MPa. For cut threads only applied membrane stresses of 40, 35 and 25% of the test temperature yield strength were used to establish a cut thread applied stress threshold and a process comparison baseline.

SCC initiation testing was conducted in controlled environment autoclaves of deaerated primary water (DPW) at temperatures of 360, 338 and 288°C. Controlled chemistry was maintained by recirculating autoclave systems. Typical purity characteristics of the test environment are listed in Table 3. After periodic exposures in autoclaves, the test studs were removed, without unloading, for inspection by ultrasonic testing (UT) to detect evidence of SCC initiation and growth. Most test studs were returned for further autoclave test exposure while some were removed for destructive evaluation (DE) of incipient SCC initiation. DE detection of SCC initiation by tensile pulling and fractography was capable of resolving SCC cracking of about 0.08 to 0.13 mm deep in fine and coarse grain alloys, respectively.

**TABLE 3. TEST ENVIRONMENT DESCRIPTION**

**CONDITIONS, Typical, Measured at Room Temperature**

| | |
|---|---|
| pH | 10.2 |
| Conductivity | 45 μS/cm |

**COMPOSITION - Typical**

| | | | |
|---|---|---|---|
| Oxygen | 3 ppb | $SO_4$ | 24 ppb |
| Hydrogen | 35 std. cc/Kg $H_2O$ | $PO_4$ | 14 ppb |
| Chloride | 4 ppb | Br | < 1 ppb |
| Fluoride | 10 ppb | $NO_3$ | < 1 ppb |
| Carbon, Total Organic | 350 ppb | ACETATE | < 1 ppb |
| Trace Metals (Al, Cd, Cu, Fe, Mg, Pb, Zn) | < 20 ppb each | FORMATE | < 1 ppb |
| | | Silicon | < 5 ppb |
| Sodium | 30 to 60 ppb | | |

CORROSION AND AIR FATIGUE TEST DESCRIPTION

While the principal effort was directed at SCC initiation testing, some corrosion fatigue testing was conducted to assure that no unexpected degradation occurred in the cold formed threads of Alloy X-750, condition HTH. A baseline of air fatigue data was developed to compare to the DPW corrosion fatigue test results. Another objective of the fatigue testing was the comparison of the rolled threads obtained from two different suppliers who used different rolling process parameters and equipment.

To protect the DPW corrosion fatigue facility from damage upon fatigue fracture of the tested studs, a special loading assembly was developed to detect small permanent displacement of the stud which would allow test termination prior to fracture. Two linear variable differential transformers (LVDT) attached between each thread and pull rod enabled fatigue initiation life to be expressed in terms of crack depths of less than 0.25 mm rather than stud fracture.

During initial air fatigue tests of rolled threads, the cut internal thread adapters made from high strength 17-4 PH stainless steel alloy, failed by both thread shear and adapter fracture. Like the external thread performance improvement, this equipment limitation was remedied by cold form tapping the adapter internal threads while using a lower strength Alloy 625 material. In contrast to the alloy 17-4 PH cut internal threads which failed during testing of only one rolled thread stud, the cold form tapped Alloy 625 adapters were reused to test 47 studs to fracture without any degradation of the internal threads or change in fatigue results. Thus, cold forming of the mating internal threads was essential to testing of improved fatigue resistant rolled external threads.

Fatigue tests were conducted on the smaller test stud in both the rolled and cut thread conditions. All tests were cycled at 10 Hz with a large stress range, R = 0.1, to maximize shakedown of rolling induced beneficial residual compressive stresses. The maximum membrane stress applied was 585 MPa, or about 50% of the ultimate tensile strength (UTS) of these alloys. This level of test stress is consistent with the acceptance testing requirements of aircraft quality fasteners of high strength cold rolled and aged Alloy 718.[16] Lower applied stresses were employed in some studs to establish a fatigue stress dependency. Similar corrosion fatigue tests were conducted in 315°C DPW at 0.017 Hz.

## TEST RESULTS - SCC AUTOCLAVE PHASE

DPW autoclave testing has currently accumulated a total exposure time of about one year. All cut thread studs of Alloy X-750, Condition AH, with a membrane stress above 250 MPa have initiated SCC in less than one month at both accelerated temperatures of 360°C and 338°C. No evidence of SCC initiation has been found in rolled threads of the same test heats tested at high applied stress (up to 650 MPa) for exposure times of up to one year. This absence of SCC has been confirmed by destructive evaluation means, both fractographic and metallographic. Comparison of cut and rolled thread test studs is presented in Figures 9 and 10, for small and large test studs, respectively.

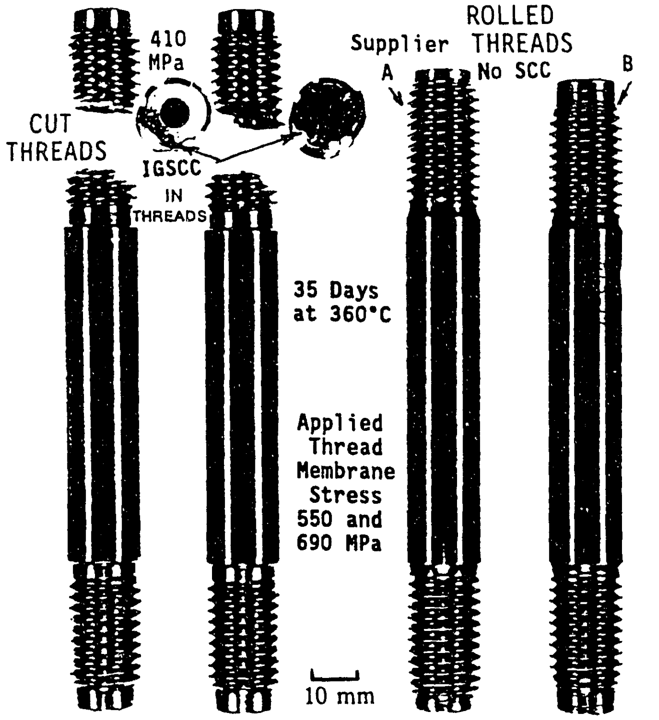


**Figure 9.** Stress Corrosion Cracking in Small Cut Threads of Alloy X-750, AH, Compared to No SCC in Rolled Threads.

Complete separation of the large cut thread occurred by hydrogen assisted low temperature fracture (LTF) and occurred during the cooldown of the test autoclave to room temperature.[16] Fracture occurred in cut threads where high temperature IGSCC initiation had occurred and the crack tip stress intensity factor was above the LTF threshold for Alloy X-750, Condition AH. In contrast, the rolled thread stud failed only in the shank fillet due to IGSCC initiation in the cut shank and fillet radius. This trend of shank fracture limited long term testing of the large rolled thread studs. Glass bead peening of the shanks was employed to mitigate early test stud shank failures of the very IGSCC prone Alloy X-750, Condition AH (two step aged).

Most of the rolled thread studs remain in test to provide a measure of the SCC initiation resistance improvement factor for rolled threads. Currently, the exposure time for rolled threads without SCC is about 100 times the exposure observed to form at least one shallow (10 mil deep) IGSCC site in cut thread studs.

Typical occurrence of IGSCC thumbnail sites emanating from the cut thread roots are shown in Figure 11 for Alloy X-750, Condition AH. Intergranular facets are also shown. Figure 12 shows the observed IGSCC depth in X-750 AH test studs as a function of applied stress and exposure time for 338°C DPW testing. Since the IGSCC growth rate for the more susceptible X-750 AH is about 0.03 to 0.04 mm per day at 338°C and crack tip stress intensity factor ($K_I$) greater than 15 MPa$\sqrt{m}$., the SCC extent observed in each stud after arbitrary exposure times can be normalized to a reference initiation life. Figure 13 shows the

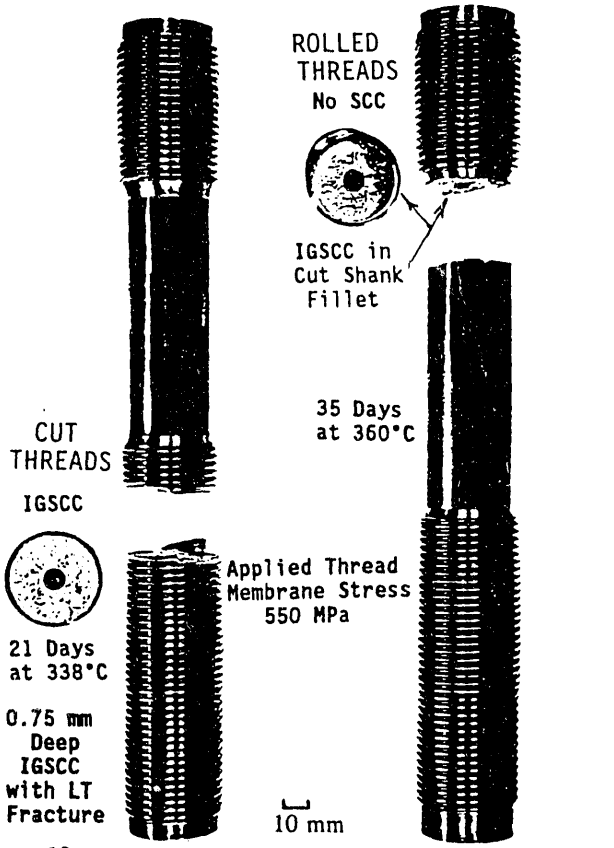


**Figure 10.** Stress Corrosion Cracking in Large Cut Threads of Alloy X-750, AH, Compared to No SCC in Rolled Threads.

results of this normalization where test studs would have an initiation life defined by the formation of small IGSCC sites 0.25 mm deep

While earlier SCC initiation was observed in tests at 360°C relative to 338°C, no SCC initiation has, as yet, been detected in the 288°C tests. Both the results at 360°C and 288°C are not inconsistent with the 338°C data, based on the temperature dependency reported for mill annealed steam generator tubing of Alloy 600[17, 18], of nearly identical composition as Alloy X-750. These data show an activation energy (Q) for Alloy 600 of about 45 to 50 Kcal/mol.

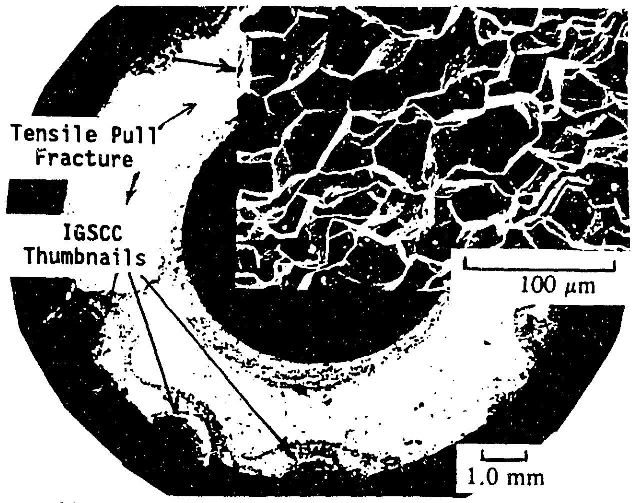


**Figure 11.** Typical Intergranular Stress Corrosion Cracking Thumbnail Sites in Cut Threads of Alloy X-750, Condition AH Exposed to High Temperature Deaerated Primary Water

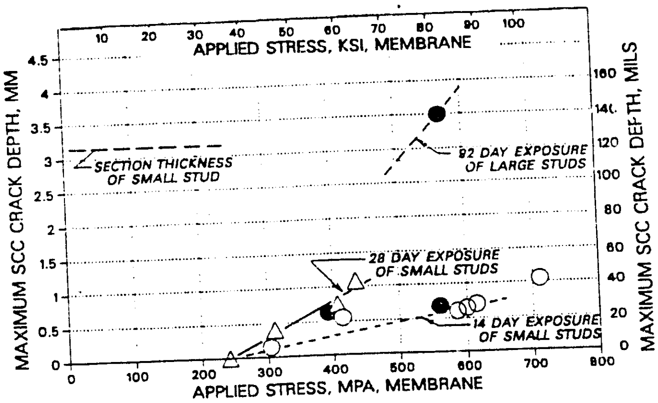


**Figure 12.** Stress Corrosion Cracking Depth in Cut Threads of Alloy X-750, Condition AH, After 338°C DPW Exposure

Figure 13 also illustrates the lack of any significant cracking when the applied membrane stress is below about 240 MPa for cut threads. Since the rolled threads do not exhibit any SCC in the same thread forms when stressed to approximately 580 MPa, or higher (650 MPa), the rolled thread improvement to IGSCC resistance, in terms of applied stress, is clearly significant. Figure 14 illustrates the metallographic evidence of IGSCC initiation and growth in the large stud cut threads contrasted to the lack of any SCC initiation in the rolled threads for the same test material, applied stress and autoclave test exposure.

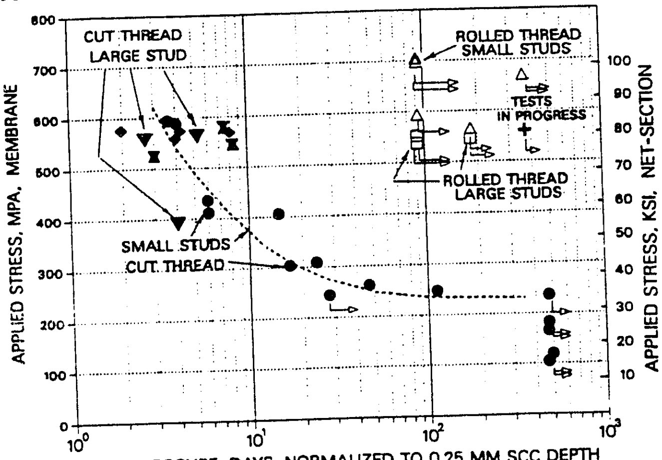


**Figure 13.** Stress Corrosion Cracking Initiation Life for Cut Threads of Alloy X-750, Condition AH, Compared to Rolled Threads After 338°C DPW Exposure

## ROLLED THREAD PROCESS SENSITIVITY TO SCC

In addition to the tests of nominal geometry rolled thread studs described above, several sensitivity tests were conducted to evaluate special process related concerns, including effects of crest laps and potential loss of the benefitial residual compressive stress.

### EFFECTS OF ROLLED THREAD CREST LAPS AND FOLDS

Since the occurrence of thread crest laps from the rolled thread process has been a persistent feature, its significance has remained an issue. Aerospace applications of both corrosion prone and corrosion resistant materials have not indicated any detrimental experience with crest laps for either fatigue or corrosion applications.

This rolled thread evaluation program employed two suppliers who provided thread crests with significantly different extents of laps. While Supplier A's threads revealed crest laps close to the acceptance limits for aerospace rolled threads[16], Supplier B, using different rolling equipment, produced a nearly lap-free thread crest, see Figure 15. Neither SCC nor fatigue testing of X-750

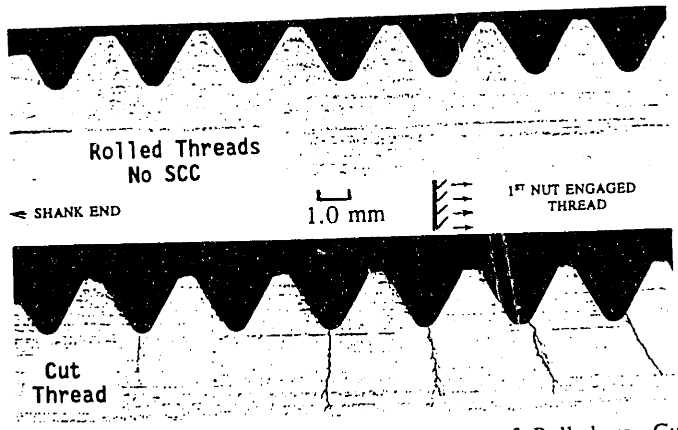


**Figure 14.** Illustration of IGSCC Response of Rolled vs. Cut Threads of Alloy X-750, AH, After 92 Day, 338°C Exposure

rolled threads showed any detrimental effects of the crest laps. In addition, a special over-test showed no effects with severe joint contact stresses, well beyond any application level. This special test employed a non-standard nut with a 35° half angle pressure flank, shown in Figure 16, contrasted to the 30.5° maximum allowance in standard 60°Vee threads. Severe local stresses in the thread crest regions provided an aggressive test to assure the stability of the laps in terms of IGSCC initiation or crack growth.

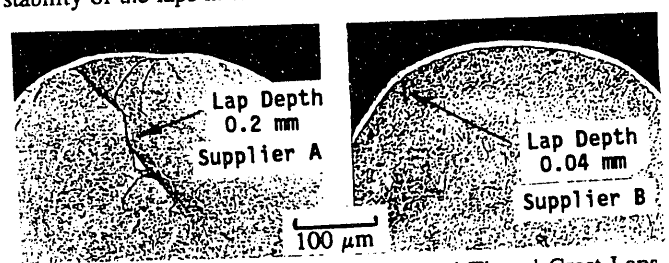


**Figure 15.** Thread Rolling Process Induced Thread Crest Laps or Folds in Alloy X-750, AH, from Rolling Suppliers A and B.

SCC testing was conducted with these 35° half angle nuts (asymmetric) for both large and small rolled studs from both suppliers, and included cut thread controls. Several studs remain in test without significant cracking at exposures well beyond the SCC initiation life for cut threads. However, a few studs, removed from test for destructive evaluation, showed no growth of the crest laps, but did exhibit SCC initiation in both cut and rolled thread flanks at the extreme pressure contact surface, shown in Figure 16. Nominal 60° Vee threads have stresses distributed over the engaging flanks without severe crest stresses. Thus, under both normal thread joint contact forces and unrealistically high local forces, there was no tendency of the crest laps to grow or be a source of SCC initiation.

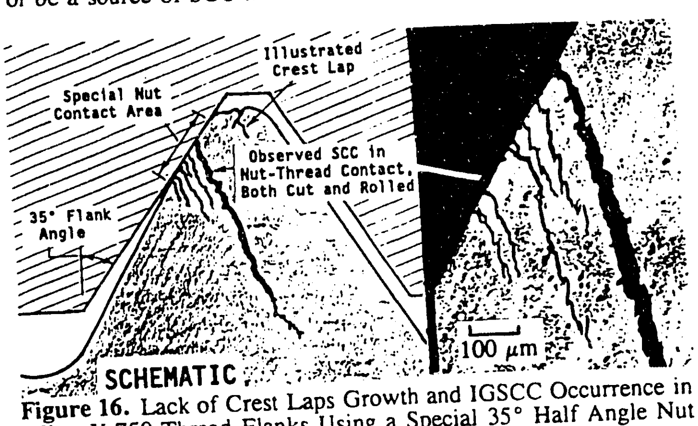


**Figure 16.** Lack of Crest Laps Growth and IGSCC Occurrence in Alloy X-750 Thread Flanks Using a Special 35° Half Angle Nut Overtest of Rolled Thread Process Induced Crest Laps

IRRADIATION ASSISTED SCC SENSITIVITY

Since some fasteners employed in DPW reactor environments are also exposed to irradiation, tests were performed to assure that the rolled thread process benefits were not significantly degraded by a neutron flux, i.e., neutron induced relaxation of residual compressive stresses. Limited tests of cut and rolled thread Alloy X-750 studs were performed in high temperature DPW environment at neutron exposure levels germane to light water reactors (LWR). Results, to date, for the most IGSCC susceptible form of Alloy X-750, two step aged AH, show IGSCC in cut threads as similar to that revealed by autoclave testing. No evidence of IGSCC was found in the neutron irradiated test of rolled threads, also consistent with the autoclave results. These results imply that for LWR neutron exposures, the benefits of the rolled thread process are retained.

COMBINED FATIGUE AND STATIC SCC STRESS

While the rolled threads exhibited a significant increase in fatigue resistance over cut threads implying moderate retention of residual compressive stresses, concerns were expressed for the potential early life shakedown of these beneficial stresses. This could possibly reduce process benefits to SCC resistance. Therefore, a special SCC test was conducted with rolled studs subjected to a severe fatigue duty cycle before subsequent SCC testing. The specific air fatigue exposure was 1000 cycles at a stress range from 45 MPa to 450 MPa in room temperature air. Cut threads were similarly treated to compare to the rolled thread behavior. SCC testing of the X-750 AH studs employed an applied membrane stress of 550 MPa. Results showed IGSCC occurrence (depth of 1.5 mm) in the cut threads after 49 days at 338°C, whereas the rolled threads showed no UT indications of SCC after much longer exposure times. Thus, the rolled threads retained satisfactory resistance IGSCC initiation even when subjected to severe fatigue precursor cycles.

EFFECT OF STRESS RELIEF ON SCC INITIATION

Since one of the principal factors explaining why the rolled thread process does increase fatigue, and perhaps SCC initiation, resistance, is the generation of residual compressive stresses, another test was conducted to assess this hypothesis. A few rolled thread studs were subjected to annealing at 885°C for 24 hours, then re-aged, after rolling. This exposure is sufficient for significant relaxation of process-induced residual stresses.

These studs showed no IGSCC initiation at exposure times well in excess of SCC occurring in cut threads. However, one stress relieved stud did exhibit severe SCC in the thread root after about 40 weeks of 640°F DPW exposure. Equivalent cut thread studs of the same material showed extensive SCC during a 2 to 4 week exposure. Therefore, the improved SCC behavior of stress relieved rolled threads over cut threads implies that factors other than residual stress are actively contributing to the rolling process benefits.

## CORROSION AND AIR FATIGUE CRACK INITIATION

Prior to performing corrosion fatigue testing of rolled and baseline cut thread studs, air fatigue testing was conducted at room temperature and 315°C. Results of the room temperature tests are shown in Figure 17 as a function of maximum membrane applied stress. Rolled thread studs from both suppliers were tested in addition to cut thread studs.

Fatigue lives for rolled threads were consistently longer than cut threads. Of significance was the fact that the fatigue life of Supplier A studs was significantly longer than that of Supplier B. Several of the rolled studs from Supplier B did not comply with the minimum acceptance requirements used for aircraft fasteners.[15] The cause of this difference has not been established but is believed due the higher hydrostatic rolling response of the larger roll diameter equipment and higher indentation rates from the hydraulically driven rolls, compared to the more conventional thread rolling equipment. The fact that the most fatigue resistant studs also contain the largest crest laps lends further support for negligible crest lap contribution to fatigue failures.

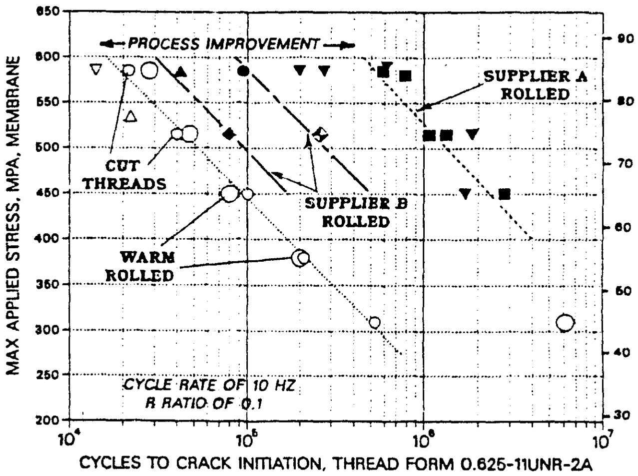


**Figure 17.** Illustration of Improved Fatigue Initiation Resistance of Rolled Threads Over Cut Threads of Alloy X-750 in 24°C Air

The minimal occurrence of laps in the more fatigue prone rolled thread studs can also be associated with the deeper metal working process behavior (high hydrostatic force) illustrated in Figure 3b. This result implies that thread rolling process variables have significant effects on the degree of process improvement over cut thread fatigue life. The sensitivity of fatigue test results makes this test a principal means of verifying the consistency of the process benefits. Therefore, fatigue testing remains the most practical and sensitive rolled thread process acceptance evaluation method.

Note that warm rolled (425°C) studs, from Supplier B, showed no fatigue life improvement over cut threads of Alloy X-750, Condition HTH. This observation would preclude the use of warm rolling of threads. In contrast to similar fatigue testing at room temperature, testing in 315°C air showed only slight decreases in fatigue initiation and fracture life for both rolled and cut threads.

A limited number of corrosion fatigue tests which have been completed show similar trends to the air fatigue test results. Fatigue tests in 315°C DPW were conducted under the same conditions as the air tests, however, the cycle frequency was reduced from 10 Hz to 0.017 Hz (1 cpm) to allow sufficient time for environmental effects to occur. Rolled threads have been shown to retain a superior fatigue initiation life to cut threads; however, Supplier A threads have superior life over those from Supplier B. Reduction in fatigue life of cut threads is about a factor of 10 for the specific test stress range in water, whereas the Supplier A rolled thread life is approaching the same fatigue life in 315°C DPW as in 315°C air. Also, the fatigue crack growth path in DPW remains the same as in air, i.e., transgranular. Again, as in other environmental tests, rolled threads have exhibited vastly superior resistance to cut threads in terms of crack initiation, albeit source dependent.

## DISCUSSION OF CAUSES OF PROCESS BENEFITS

Evidence supporting the fundamental causes of the rolling process benefits to crack initiation is almost non-existent. Also lacking are measurements of properties or conditions responsible for the improvements over cut threads. The acceptance of the rolled threads is generally based on years of evolving successful applications coupled with manufacturing cost benefits for large scale production.

The degree of improvement afforded by rolled thread process to Alloy X-750 AH is very profound since it overrides the high stress/strain concentrations in the thread roots without any IGSCC initiation. Conversely, the cut, smooth surface shank exhibited severe IGSCC when subjected to the same applied membrane stress.

Several factors may contribute to the benefits of rolled threads. These include:

**RESIDUAL COMPRESSIVE STRESS** - This is the commonly expressed basis for the improved resistance to crack initiation over cut threads, particularly for fatigue resistance, and also considered important to SCC resistance. Measurements of the residual stresses in actual rolled thread roots are restricted by limitations of conventional methods, e.g., X-ray diffraction, in terms of sharp thread root radii.

**WORK HARDENING** - The extensive metal deformation in both the rolled thread roots and thread flanks leads to work hardening, particularly for the high strain hardening fastener alloys used in nuclear applications. This reduces local plastic deformation that results from fastener loading during assembly. Enhanced resistance to plastic deformation is clearly a benefit to reduction of persistent slip band action which influences fatigue crack initiation and growth. Local plastic flow is also considered to be a principal factor in SCC initiation.

**MICROSTRUCTURE** - Thread rolling induces grain shape changes by flattening grains perpendicular to the applied tensile stresses, hence limiting the grain boundaries available for IGSCC growth by easy path means. In addition, this deformation stretches the grain boundary surface. The development of complex slip and cross-slip within the grains alters the normal deformation mode prevailing in equilibrium grain structures. Since planar (easy glide) slip has been associated with hydrogen assisted crack initiation, highly deformed grains would be less conducive to planar slip. High dislocation densities would also provide more trapping sites for hydrogen, thereby altering the potential role of hydrogen.

**GALVANIC OR ELECTRO-CHEMICAL POTENTIAL** - Since cold work increases the local electrochemical potential anodically, some benefits may be accrued for nickel-base alloys in DPW where PWSCC is favored by increasing cathodic potentials.[19]

Since all of these effects related to thread rolling are present in all of the heat treatment variations of Alloy X-750, the process benefits observed in the most IGSCC susceptible AH condition are considered beneficial to the more SCC resistant forms of X-750 (HTH) and other similar nickel-base alloys, i.e., aged Alloys 625 and 718.

## CONCLUSIONS

1. The rolled thread process applied to SCC susceptible Alloy X-750, Condition AH, provides significantly improved resistance to IGSCC initiation, in terms of lifetime, over cut threads of the same material when tested in a wide range of threaded fasteners in simulated PWR environments. A similar improvement can also be described in terms of a rolled thread increase in the IGSCC stress threshold over that shown for cut thread studs of the same material.
2. The presence of typical rolling induced thread crest laps, within acceptance limits, has no significant effect on IGSCC or fatigue crack initiation or growth, at applied stress levels beyond application needs.
3. Based on no observed degrading effects from neutron irradiation tests in a high temperature PWR environment for rolled threads of the most SCC susceptible X-750 condition, two-step aged AH, the rolling process benefits to IGSCC initiation resistance appear to be retained for irradiation levels characteristic of light water reactors.
4. Both in-feed (radial die closure) and through-feed (axial die action) thread rolling processes are acceptable manufacturing processes to improve resistance to IGSCC.
5. Significant variations in fatigue and corrosion fatigue performance of studs from two different suppliers are observed when different types of rolling equipment and different rates of metal deformation are employed. A symptom of the highest fatigue resistant threads is the presence of thread crest laps, whereas the absence of laps was associated with a much smaller improvement in fatigue resistance over cut threads.
6. Rolled threads exhibit significant improvement in corrosion fatigue resistance over cut threads when air fatigue testing complies with aerospace minimum requirements.
7. While this study shows significant rolled thread process improvements to IGSCC resistance and corrosion fatigue of susceptible nickel-base alloys exposed to PWR environments, this process benefit should be considered material-environment specific or situation dependent. Accordingly, specific empirical testing must be satisfactorily undertaken before this process is applied to other materials, designs and environment conditions.

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