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Optimum Thread Rolling Process That Improves SCC Resistance

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ABSTRACT

Accelerated testing in environments aggressive for the specific material have shown that fastener threads that are rolled after strengthening heat treatments have improved resistance to SCC initiation. For example, intergranular SCC was produced in one day when machined (cut) threads of high strength steel (ASTM A193 B-7 and A354 Grade 8) were exposed to an aggressive aqueous environment containing 8 weight % boiling ammonium nitrate and stressed to about 40 % of the steel's yield strength (120 ksi, 827 MPa). In similar testing conditions, fasteners that had threads rolled before heat-treatment (quench and temper) had similar susceptibility to SCC. However, threads rolled after strengthening, exhibited no SCC after a week of exposure, even when stressed to 100 % of the B-7 alloy yield strength. Similarly, intergranular SCC was produced in less than one day when machined (cut) threads of nickel-base alloys (X-750 and aged 625) were exposed to an aggressive 750°F doped steam environment (containing 100 ppm of chloride, fluoride, sulfate, nitrate and a controlled hydrogen overpressure) and stressed to about 80% of the alloy yield strength (117 ksi, 807 MPa). In similar testing conditions, threads rolled after strengthening exhibited no SCC after 50 days of exposure. This beneficial effect of the optimum thread rolling process (i.e., threads rolled after strengthening) is due to the retention of large residual compressive stresses in the thread roots (notches) which mitigate the applied notch tensile stresses resulting from joint design pre-loads. Use of these material specific aggressive environments can provide an accelerated test to verify that threads were produced by the optimum thread rolling process. These tests could support fastener acceptance criteria or failure analysis of fasteners with unknown or uncertain manufacturing processes. The optimum process effects may not always be detected by more conventional methods (e.g., metallography or hardness testing).

BACKGROUND

The capacity of the rolled thread process to provide improved fatigue life performance has been recognized for a considerable period of time and is the basis for aerospace threaded fastener process controls. This property improvement occurs only when the threads are rolled after the material strengthening heat treatment is performed. In contrast to the availability of improved fatigue performance data, only limited data exist to assess the performance improvements to stress corrosion cracking (SCC) of fasteners of specific materials in a variety of susceptible environments. Most of the test environments are mildly SCC sensitive; e.g. 3.5% NaCl solutions for steel. A few test environments are aggressive; e.g., magnesium chloride for austenitic (300 series) stainless steel. These limited experiences show improved resistance of rolled threads to susceptible environments when rolled after final heat treatment. However, demonstration of the rolling process improvements is lacking for environments that are extremely aggressive to specific materials.

Although fatigue test acceptance criteria has been the backbone of aerospace rolled thread fastener quality, similar acceptance testing for corrosion resistance to hostile environments has not been standardized. Thus, it remains possible that cost incentives may dictate the selection of the rolling process rather than use of controlled rolling processes that provide maximum resistance to stress corrosion cracking. Currently, the commercial (non-aerospace) fastener industry tends to prefer rolling of threads before a strengthening heat treatment so that the rolling die life is maximized and costs are minimized. Also, rolling of fully hardened fastener materials result in more frequent die replacements on rolling machines, reducing production rates and increasing costs. Although lower production costs may be paramount, without process quality attention, SCC performance may be impacted in fastener applications where environmental compatibility is a concern.

EXPERIMENTAL AND EVALUATION BASIS

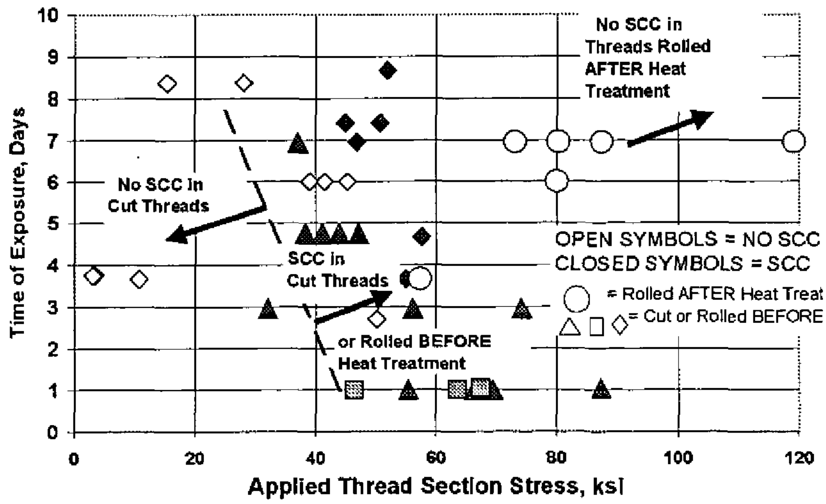
By comparing the minimum applied stress at which SCC occurs in machined threads, (i.e., as a baseline condition) or in stress relieved threads that were heat treated after rolling, to the maximum applied stress at which no SCC occurs in rolled threads, a process improvement factor can be defined numerically. Thus, the measure of the process induced SCC improvement will be stated in terms of resistance to applied stress.

LOW ALLOY HIGH STRENGTH QUENCHED AND TEMPERED STEEL

Low alloy, high strength steel fasteners were tested in an aggressive environment of 8 weight percent boiling (210°F, or 99°C) ammonium nitrate (BAN) solution. Significant effects of this environment on SCC of steel are cited in Ref (a). Mechanical properties of the test bar lot of A193 B-7 quenched and tempered (Q&T) steel are 120 ksi (827 MPa) yield strength, 139 ksi (958 MPa) ultimate tensile strength with a hardness of 30 Rockwell C (HRC). The hardness of the A354 Grade 8 Q&T steel bolts is 36 HRC. Threads were 0.75 inch in diameter with a Unified National coarse thread pitch of 0.10 inch (2.5 mm).

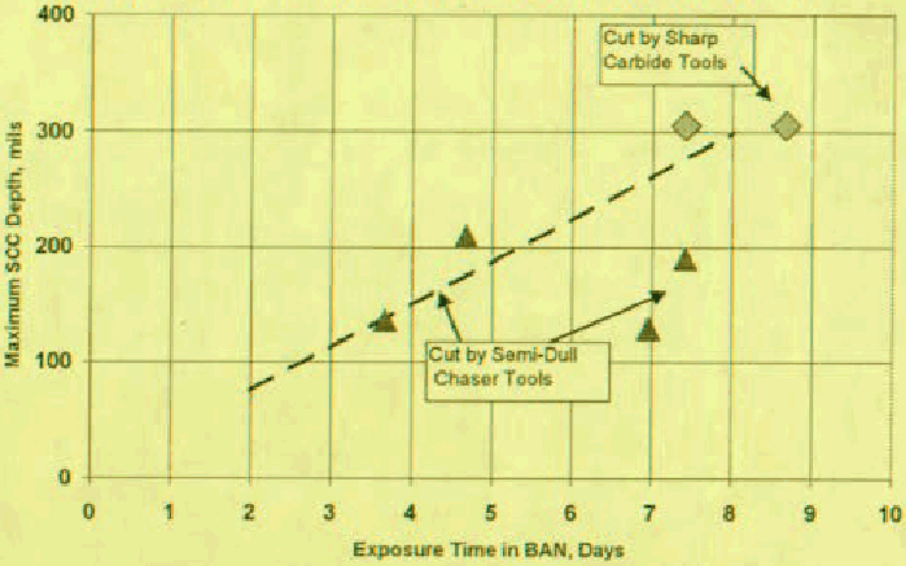
Rapid occurrence of intergranular (IG) SCC in machined (cut) threads of B-7 and Grade 8 steel bolts is shown in Figure 1 for applied thread section stresses over 30 ksi (207 MPa) and exposure times at little as one day. A similar SCC occurrence trend was found in threads rolled before the Q&T heat treatment. Metallographic evaluation of threads heat treated after rolling showed complete recrystallization and fine equiaxed grains which would be devoid of any beneficial residual compressive stresses induced by the previous thread rolling stage.

FIGURE 1. - SCC OF Low Alloy High Strength Steel Fasteners In Boiling Ammonium Nitrate



However, threads rolled after the Q&T heat treatment had retained residual compressive stresses in the thread roots and remained free of SCC for exposure times of 7 days and applied stresses up to 119 ksi (820 MPa) as noted in Figure 1. Absence of SCC was determined by destructive fractography evaluation. This contrast in results reveals at least a 3-fold increase in applied stress resistance to SCC associated with the optimum thread rolling process of rolling after Q&T heat treatment.

FIGURE 2 – IGSCC Depth in Machined (Cut) Threads of A193 B-7 Steel As a Function of Exposure Time in Boiling Ammonium Nitrate



The extent of IGSCC, in terms of depth determined by fractography of machined threads stressed to about 50 Ksi (345 MPa), is shown in Figure 2. Extrapolation of the average depth trend implies that SCC initiates in less than one day, possibly at or near time zero. From Figure 2 the apparent crack growth rate is about 30 to 40 mils per day (0.01 x 10^{-6} meters/second). Typical IGSCC shapes in both machined threads and threads heat treated after rolling are shown in Figures 3 and 4, respectively, after one day exposure to BAN at a thread section stress of 60 and 77 ksi (414 and 531 MPa), respectively. Typical IGSCC paths observed in both ASTM A354 Grade 8 and A193 B-7 Q&T steel exposed to BAN are shown in Figure 5, for B-7 steel.

FIGURE 3 – IGSCC Site Shape and Depth in Machined (Cut) Threads of Grade 8 Steel Tensile Pulled for Fractographic Evaluation After SCC Testing

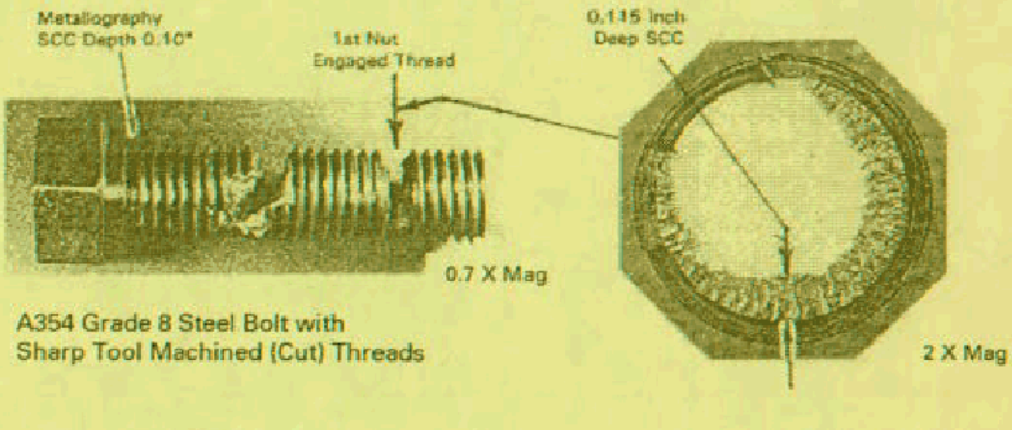


FIGURE 4 - IGSCC Depth in Grade 8 Steel Bolts Heat Treated AFTER Thread Rolling

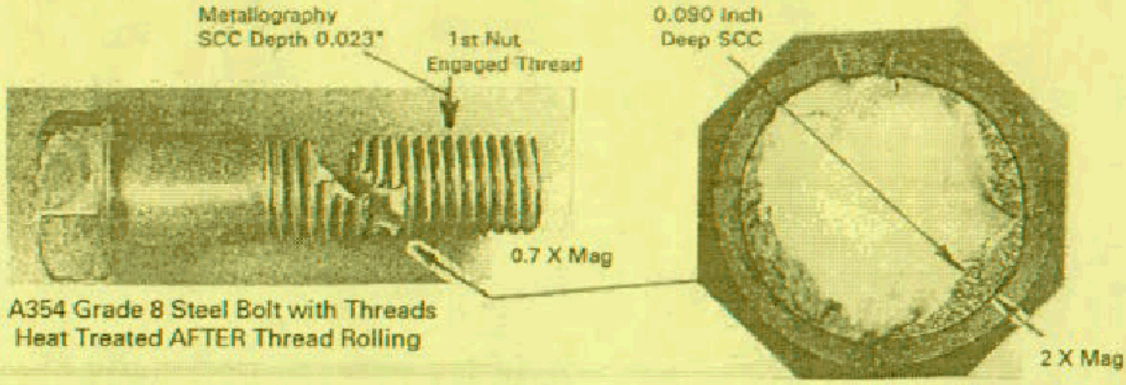
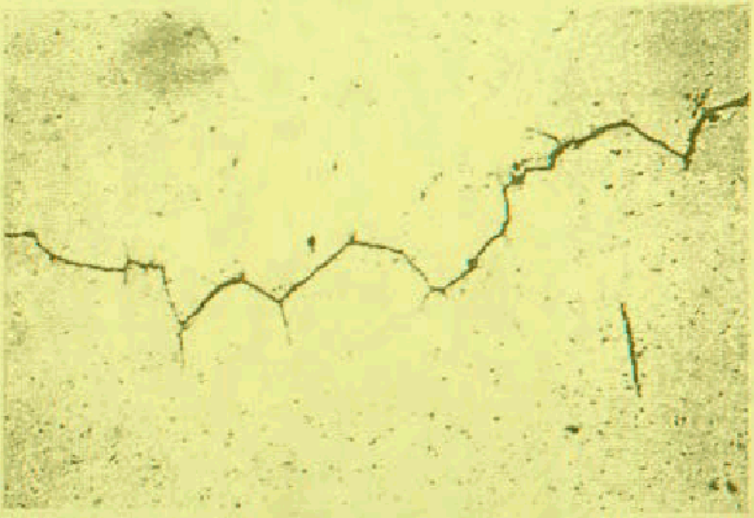


FIGURE 5 – IGSCC Crack Paths in Grade 8 Steel Exposed to Boiling Ammonium Nitrate



As-Polished 850 X Mag

HIGH STRENGTH NICKEL-BASE ALLOYS

Testing to demonstrate rolled thread process improvements to SCC resistance of high strength nickel-base fastener alloys of X-750 and aged 625 was conducted by exposure to high temperature steam containing known corrosive elements. For this study the aggressive environment was 750°F (399°C) steam containing 100 parts per million (ppm) of chloride, fluoride, sulfate and nitrate, in addition to a hydrogen overpressure of 11 psia. This doped steam (DS) environment has been shown to produce rapid IGSCC in nickel-base alloys, Ref. (b). Determination of the rolling process effects was limited to a comparison of machined threads with rolled threads. All threads were rolled after the precipitation hardening heat treatment, thus the process-induced residual compressive stresses were maintained.

Mechanical properties of the test bar lot of gamma prime precipitation hardened Alloy X-750 HTH were 117 ksi (807 MPa) yield strength, 175 ksi (1207 MPa) ultimate tensile strength with a hardness of 35 Rockwell C (HRC). Mechanical properties of the gamma double-prime precipitation hardened Alloy 625 were 134 ksi (924 MPa) yield strength, 176 ksi (1214 MPa) ultimate tensile strength with a hardness of 39 Rockwell C (HRC). Threads were 0.625 inch in diameter with a Unified National coarse thread pitch of 0.091 inch (2.8 mm).

Doped steam testing of all machined (cut) threads showed IGSCC in short exposure times (as little as one day); whereas controlled process rolled threads showed no IGSCC as determined by destructive fractographic evaluation for exposures of up to 75 days. As shown in Figure 6 the minimum applied stress that revealed IGSCC in machined threads was as low as 44 ksi (303 MPa); whereas, rolled threads survived with no IGSCC at applied stresses as high as 89 ksi (614 MPa), representing at least a two-fold increase in SCC resistance to applied stress. Typical IGSCC initiation and growth sites in cut threads are shown in Figure 7 for both alloys studied. Fractographically determined IGSCC depths from machined threads exposed from 0.4 to 12 days in doped steam at an applied section stress of about 75 ksi (517 MPa) show that SCC begins at near zero time with crack growth rates of about 12 mils per day (0.003×10^{-6} meters/second), Figure 8.

FIGURE 6. - SCC Resistance of Machined vs. Rolled Threads of High Strength Nickel-Base Alloys in 750 F Doped Steam

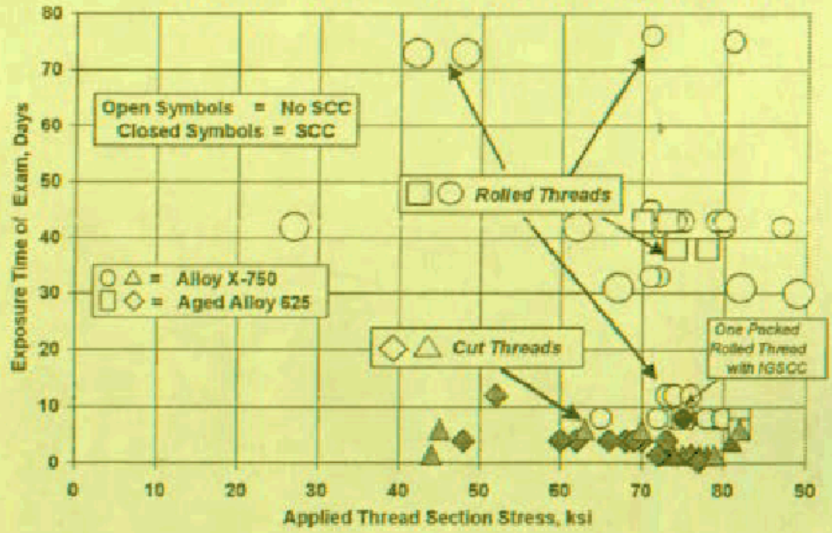


FIGURE 7 – Typical IGSCC Doped Steam Site Shapes in Alloy X-750 and Aged 625 Cut Threads

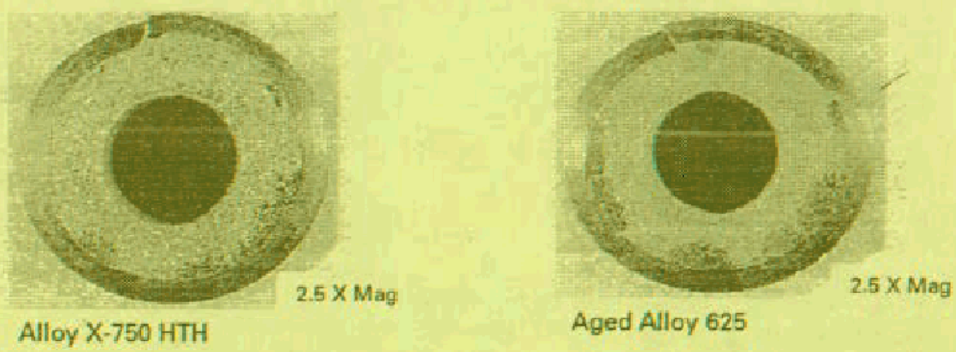
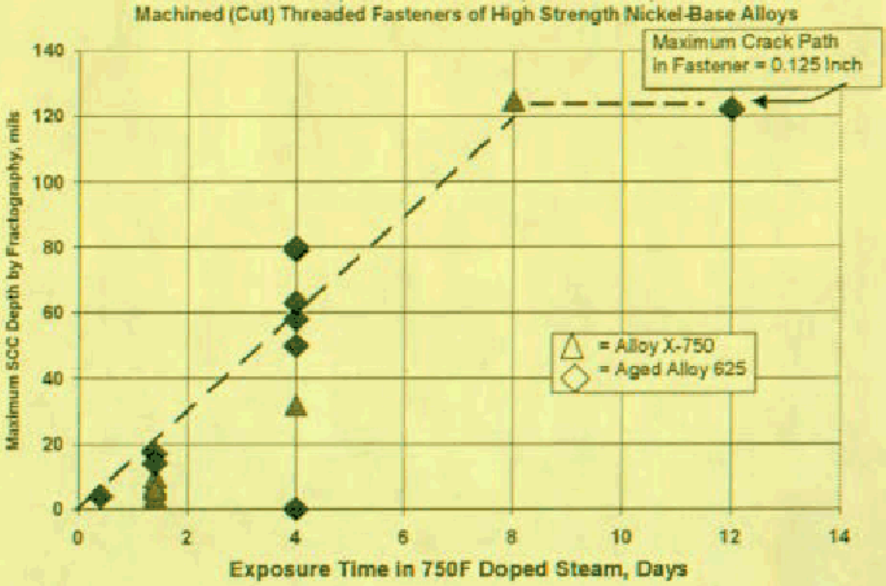


FIGURE 8. - Depth of IGSCC for Doped Steam Exposure of Machined (Cut) Threaded Fasteners of High Strength Nickel-Base Alloys



Inclusion of thread rolling process deviations in the test matrix did reveal one thread rolled alloy X-750 HTH test stud with IGSCC after 8 days exposure at an applied test stress of 75 Ksi (517 MPa) or 70% of the yield stress, (Figure 6). This process deviation resulted from a full forming of the thread into the rolling die shape so that the total thread volume was bound by the die (packed) and further die penetration into the thread blank was prevented. During this packing stage the rolling machine rotation and die contact continues and may degrade the process induced residual stresses. Because some separately conducted fatigue tests of packed rolled threads has shown lifetimes no better than machined threads, packed threads may have reduced or minimal compressive residual stresses without any significant process benefits. Accordingly, packed threads should be prohibited from production rolling where optimum fatigue and SCC performance are required. Use of the aggressive doped steam test that revealed IGSCC shows an ability to detect an unacceptable process deviation that affects stress corrosion cracking resistance.

LIMITATIONS

While tests using aggressive chemical cracking environments have successfully shown the effects of manufacturing process on SCC resistance, they cannot be used to rank the relative SCC resistance of different materials in other application environments. Chemical and electrochemical factors, which differ for specific materials and specific environments, control the materials' SCC susceptibility.

CONCLUSIONS

1) Aggressive environmental testing is practical to show the benefits of thread forming process improvements relative to fastener survival times in SCC susceptible environments.

2) Aggressive environmental testing is practical to identify preferred process options to achieve maximum SCC resistance.

3) Aggressive environmental testing may identify process limitations that could degrade the optimum benefits of rolled threads to SCC resistance.

4) Aggressive environmental testing may provide a means of acceptance testing of production lots to assure that a minimum standard of SCC resistance quality is present.

REFERENCES

a) SW Ciaraldi, "SCC of Carbon and Low-Alloy Steels", Chapter 2, Stress-Corrosion Cracking, Materials Performance and Evaluation, RH Jones, Ed, ASM International, 1992.

b) R Jacko, et. al. "Qualification of Alloy 718 for Fuel Assembly Fastener Application", Paper #86, 10th International Conference on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, August 2001,

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