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FAILURE ANALYSIS OF THE MAIN ROTOR RETENTION NUT FROM THE AH-64 HELICOPTER

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ABSTRACT

A comprehensive analysis of the failed main rotor hub retention nuts of the Apache helicopter was carried out at the U.S. Army Materials Technology Laboratory (MTL). An inspection of the entire fleet of Apache helicopters revealed that eight nuts contained cracks. The goals in this investigation were to determine the failure mode and cause, to establish the mechanical and corrosion properties of the nut material, to verify that cadmium and nickel coatings were applied in accordance with the specification requirements and to make appropriate recommendations to prevent further problems. Additional nuts from both the inventory and field were characterized and tested for comparison. The following analyses and tests were performed: visual examination; light and electron microscopy of the retention nuts and fracture surfaces; metallographic analysis of both failed and intact nuts; chemical analysis of the 18 Ni maraging steel C-250 grade steel; mechanical property, stress corrosion, and electrochemical tests. The chemical composition of the steel was well within the contractors specification and met the industry standards for maraging C-250 grade steel. Mechanical properties were also within specified requirements. Hydrogen-assisted cracking was the cause of all cracks found in the retention nuts. To eliminate this problem two routes should be pursued: replace the retention nuts with new ones made from a material with greater resistance to hydrogen-assisted cracking (lower hardness C-200 grade maraging steel), and remove the hydrogen source from the nut by replacing the nickel plated bolts in contact with the cadmium plated bolt holes of the retention nut with cadmium plated bolts. Keeping the region dry and free of water vapor by the application of appropriate sealants and water displacing components would also stop the electrochemical processes and reduce hydrogen absorption.

CONTENTS

INTRODUCTION

A one-time inspection during 1989 of the entire fleet of Apache helicopters by magnetic-particle examination revealed that eight main rotor hub retention nuts (PN 7-3114111102) contained cracks. Failure of these critical parts during flight could result in the loss of aircraft and aircrew. As a consequence, the Apache fleet was temporarily grounded and the U.S. Army Materials Technology Laboratory (MTL) was requested by AVSCOM to perform a metallurgical investigation.

MTL's goals in this investigation were to determine the failure mode and cause, to establish the mechanical and corrosion properties of the nut material, to verify that the cadmium and nickel coatings were applied in accordance with the specification requirements, and to make appropriate recommendations to prevent further problems. Therefore, a series of interrelated studies were performed including visual examination, light and electron microscopy of the retention nut and fracture surfaces, metallographic analysis of both failed and intact nuts, chemical analysis of the steel, mechanical property testing, stress-corrosion testing, and electrochemical testing. Recommendations were made after a thorough review of all available test results.

It should be noted that during this investigation additional relevant background information became available. After preliminary MTL analyses it was necessary that additional critical experiments had to be carried out to resolve the problem; thus, the investigation extended beyond the period originally anticipated.

BACKGROUND

The main rotor retention nut is a flight-critical component that secures the main rotor hub and blade assemblies to the static mast. A schematic cross section is shown in Figure 1a. Figure lb is a top view of the retention nut showing the 12 threaded bolt holes in the nut and the threaded internal diameter of the nut. The nut, which is made out of 18 Ni maraging steel C-250 grade per HMS 6-1080, is installed by screwing it down hand tight onto the static mast. The upper retainer is placed on top of the nut and 12 electroless-nickel plated (QQ-N-290) 8740 steel (MIL-S-6047) bolts are inserted and torqued according to a numbered sequence to a final level of 225 in-lbs., in order to generate compressive residual stress in the nut.

In the fall of 1989, upon inspection, one nut was found cracked, as shown in Figure 2a and 2b, (nut 0223). Subsequently, a Safety of Flight message was issued and a fleetwide inspection was carried out. A total of 10 nuts were reported as cracked, of which eight were confirmed. Two of these 10 nuts were found to be defect free upon re-examination in the laboratory. All the cracked nuts belonged to a *discrepant batch* heat 6644-A, Serial Nos. 0212 through 0226. These nuts were supplied to McDonnell-Douglas Helicopter Co. (MDHC) by FENN Manufacturing. The discrepant batch was forged by Teledyne Vasco. The drawing calls for a ring rolled microstructure. However, Teledyne Vasco reports indicated that ring rolling was not performed. The forged nuts were machined by McMellon Bros. Inc., and vacuum cadmium plated by Vacuum Deposited Coatings, Inc. per HP4-22. During the manufacture of the discrepant batch, hardness measurements (required for flight critical parts) were inadvertently omitted. Since this discovery was made after the cadmium plating operation, these nuts were sent to Westfield Electroplating for stripping of the cadmium by an ammonium-nitrate process. The cadmium stripping process renders the nuts prone to corrosion. The bare nuts were supposed to be protected with a corrosion prevention compound until they were replated. However, this operation was inadvertently left out for a few nuts, and verbal reports of isolated corrosion have been noted during the hardness measurements.

FENN then sent the nuts to McMellon Bros. to grind out the hardness indentations. Upon their return, the nuts were sent to Vacuum Deposited Coatings for recoating and, subsequently, sent out to the field. (It is not known whether the nuts were properly remachined to dimension and surface finish and recoated since there is no inspection documentation.)

One of the cracked nuts (5TH-0223) was examined by MDHC and preliminary findings indicated the cause of failure to be hydrogen-assisted cracking as shown in Figure 3. The source of hydrogen was believed to be the result of a corrosion reaction in the field. MTL received the unused portion of this nut to perform a thorough failure analysis. During the course of investigation it became clear that additional factors were involved and efforts were directed towards determining if the problem was generic or isolated to a single batch. To that end, five additional nuts were received by MTL for examination and tests. Nuts 0223, 0257, and 0250 were from the discrepant batch. Nuts 0845, 0338, and 1202 were from other lots and showed no cracking.

RESULTS

Visual Examination

The retention nuts shipped to MTL were examined for irregularities and the presence of cracking. Nuts examined by MTL from heat 6644-A showed radial cracks emanating from one or more bolt holes. Figure 4 shows a schematic of nut 0257 and the locations of the radial cracks; additional typical cracks are shown in Figure 5. The radial direction of crack growth demonstrates that hoop stresses were the primary crack driving force. One nut examined, 0223, had experienced a complete fracture from the growth of one radial crack which, upon closer examination, showed the crack originated from the base of a thread root.

Microscopic Examination of Cracks

Optical and scanning electron microscopy (SEM) were utilized to examine the fracture surfaces of the radial cracks. Where necessary, samples were sectioned from the retention nuts and loaded in a three-point bend fixture to separate the crack faces for observation. Figure 6 shows an optical photograph of a typical crack from nut 0257 opened with the three-point bend apparatus.

At higher magnification in the SEM two distinct regions of crack growth can be observed; near the origin the crack has a faceted, intergranular appearance signifying hydrogen embrittlement or hydrogen-assisted stress corrosion cracking, while farther away from the origin the final failure produced a dimpled appearance typical of ductile tensile failure though some cleavage areas were present. Small transition regions exists between these areas where the fracture appearance is mixed. The fracture appearance is the same as reported by McDonnell-Douglas in their analysis[1]. The smaller, incomplete cracks (Figures 6 and 7) all showed intergranular fracture regions. The ductile dimple topology was due to the fast fracture subsequently induced by the three-point bending apparatus.

Microscopic Examination of Exposed Surfaces

The exterior finish and surface condition of the retention nuts varied considerably. In most cases, including the discrepant batch, the cadmium coating had corroded or worn off the

1. HAWKINS, J. *Analysis of Cracks in Hub Nut S/N 0223.* McDonnell-Douglas Helicopter Company, Report LR 89M0128, Mesa, AZ, January 1990, p. 22.

surface of the nut. This is not unexpected since cadmium is anodic and prone to atmospheric corrosion; however, these corrosion products should not seize and interfere with disassembly. Pitting corrosion observed on some retention nuts, as shown in Figure 8, attests to the long term exposure to a corrosive environment.

Chemical Analysis

The chemical composition of nut 0223 was determined using standard chemical techniques and a LECO (carbon and sulfur) analyzer. The composition is well within the contractors specification (Hughes Materials Specification HMS6-1080), as shown in Table 1. Additionally, the contractor specification meets the industry standards for the chemical composition for maraging C-250 grade steel.

Table 1. COMPOSITIONS WEIGHT PERCENT

Source	Ni	Co	Mo	Ti	Al	Cr	Cu	Mn	Si	C	P	S	Zr	B
Nut 0223	18.45	8.16	4.93	0.45	0.12	0.16	0.07	0.01	0.03	0.007	0.004	0.002	0.013	0.002
HMS 6-1080	17-19	7-8.5	4.6-5.2	0.30-0.50	0.05-0.15	0.50 maz	0.50 max	0.10 max	0.10 max	0.03 max	0.010 max	0.010 max	-	-
Industry Standard*	17-19	7-8.5	4.6-5.2	0.30-0.50	0.05-0.15	0.50 maz	0.50 max	0.10 max	0.10 max	0.03 max	0.010 max	0.010 max	-	-

*Aerospace Metals Handbook

Metallographic Analysis

The microstructure of the C-250 steel used in the retention nuts is martensitic, as shown in Figure 9. The presence of *banding* was noted in several cases. Banding is caused by segregation of alloying elements, usually Ti and Mo in maraging steels, in the original ingot and is usually present to some extent in most commercial steels. Upon further working of the ingot the areas of segregation are deformed or compressed into thin bands. Etching reveals this microsegregation as alternate *bands* of light and dark areas. Figure 10 shows the micro-structure from nut 0250; appreciable banding can be seen. Banding was also detected to a lesser degree in nuts 1202 and 0845. These bands can produce variations in local mechanical properties most often detected by reduced values of elongation at tensile failure. The cadmium coating was also examined using standard metallographic techniques.

The cadmium coating on the recoated nut 0250 was 0.04 mm thick (see Figure 11), twice the specified maximum of 0.02 mm (HP-4-22).

Mechanical Testing

A number of mechanical tests were performed on specimens machined from the material from the nuts as well as other C-250 steel obtained by MTL from an independent source for comparison. Tables 2 and 3 list the test results obtained for the respective nuts along with contractor specifications. Yield and ultimate tensile strength values were consistent and within specified requirements; however, percent reduction in area and elongation were not consistent for the different heats though all fell within specified limits per HMS 6-1080. Nuts 0257 and 0223 exhibited appreciably lower values than nut 1202 and the MTL independently supplied material. Fracture toughness and Charpy impact tests demonstrated no significant difference between all the specimens tested. All nuts were within the specified hardness range.

Table 2. TENSILE VALUES

Specimen	Y.S. KPSI	U.T.S KPSI	Elong. (%)	Red. Area (%)	Modulus MPSI
MDHC. Spec.	250 Min.	255 Min.	6.0 Min.	45.0 Min.	-
*0257-A1	260	265	6.4	37.8	29.2
*0257-A1B	264	270	-	44.0	27.9
*0223-B1A	260	265	8.8	47.2	25.0
*0223-B1B	270	270	6.8	46.7	28.4
†1202-G2	263	269	13.3	56.8	24.9
†1202-G4	245	261	15.5	54.4	26.7
†1202-G5	249	264	11.1	50.0	24.5
‡MTL-2	273	275	16.0	60.0	29.2
‡MTL-3	262	262	-	58.8	32.1
‡MTL-4	238	247	14.0	51.0	32.1
‡MTL-5	224	233	14.0	50.0	28.8
**0338-VT1	265	269	8.2	54.5	26.2
**0338-VT2	265	269	11.0	51.5	27.7
**0338-VT3	263	269	10.0	53.0	25.9

*Discrepant Nut
†Reference Nut
‡Reference Material Via MTL
**IVD Aluminum-Coated Nut

Table 3. MECHANICAL PROPERTIES

Specimen	Charpy Impact (ft-lb)	K_{Ic} (ksi $\sqrt{in.}$)	Hardness Rockwell C
MDHC. Spec.	-	-	48-53
*0257-A1	9.0	-	51.7
*0223-B1	17.0	-	49.9
*0250-FT1	-	73.1	-
*0250-FT2	-	78.9	-
*0250-FT3	-	84.4	-
*0250-CV3	6.5	-	-
†1202-C	-	-	50.8
†0845-ZF1	-	73.2	-
†0845-ZF2	-	71.3	-
†0845-ZF3	-	74.6	-
†0845-Z1	11.5	-	-
‡MTL-C1	16.6	-	50.9
‡MTL-C2	17.0	-	50.2
**0338-VT1	-	105.1	-
**0338-VT2	-	104.6	-
**0338-VT3	-	107.9	-

*Discrepant Nut
†Reference Nut
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**IVD Aluminum-Coated Nut

Stress Corrosion Testing

The interface between the cadmium on the hub retention nut and the electroless nickel on the twelve torque bolts created both crevice corrosion conditions and a galvanic couple, the nickel being cathodic to the cadmium. The actual mixed potential measured for the electroless nickel/cadmium couple was -0.75 V versus SCE. At this potential, significant hydrogen could be produced under the acidic condition present within a crevice. Recent testing of steels indicated the electrochemical condition in a crevice in steel is comparable to cathodic charging at -1.0 V versus SCE[2]; additionally, Pickering[3] has shown the presence of hydrogen gas bubbles within crevices in iron. The combination of the galvanic couple, moisture, and the crevice would therefore be expected to create atomic hydrogen which diffuses into the steel and causes hydrogen embrittlement. Constant potential rising-step load single-edge bend tests[4] were conducted, as illustrated in Figure 12, to determine the stress-intensity threshold for hydrogen-assisted cracking (K_{Iscc}). The specimens were machined and then notched and precracked so that the crack growth was in the radial direction of the nut. The samples were tested in 3.5% NaCl at potentials of -1.2 V versus SCE and -0.8 V versus SCE to simulate the worst case scenario and the nickel/cadmium mixed potential, respectively. Specimen 0845-23 was electroless nickel plated and coupled with cadmium to simulate inservice conditions. Specimen 0845-22 was tested in 1.25N $NH_4(NO_3)$ solution at -0.6 V versus SCE to examine the effect of the cadmium stripping process. The results are listed in Table 4.

Table 4. STRESS-CORROSION CRACKING STRESS INTENSITY VALUES (K_{Iscc})

Specimen	K_{Ic} (ksi $\sqrt{\text{in.}}$)	Solution	Potential V versus SCE
*0257-A1	15.3	3.5% NaCl	-1.2
*0223-B2	15.9	3.5% NaCl	-1.2
†1202-C	14.0	3.5% NaCl	-1.2
†1202-E	14.8	3.5% NaCl	-1.2
‡MTL-C4	22.8	3.5% NaCl	-1.2
*0250-CV2	34.0	3.5% NaCl	-0.8
†0845-Z4	28.6	3.5% NaCl	-0.8
**0338-V3	32.4	3.5% NaCl	-0.8
†0845-Z3	34.9	3.5% NaCl	W/Ni and Cd
†0845-Z2	>30.0	$NH_4(NO_3)$	-0.6

*Discrepant Nut
†Reference Nut
‡Reference Material Via MTL
**IVD Aluminum-Coated Nut

The samples taken from nut 0250 showed equal K_{Iscc} values to samples from nut 0845 and other independently obtained material at both -0.8V and -1.2V. Additionally, all the samples tested at -1.2 V versus SCE showed intergranular fracture. However, samples tested at -0.8 V versus SCE showed a difference in fracture mode. The discrepant batch material showed a greater tendency towards hydrogen-assisted intergranular cracking than did samples

2. BUCKLEY, P., PLACZANKIS, B., LOWDER, L., and BROWN, I. G. *Noble Metal Implantation to Reduce Hydrogen Embrittlement in Steels.* April 1990, In press, p. 6.
3. PICKERING, H. W. *On the Roles of Corrosion Products in Local Cell Processes.* Corrosion, v. 42, no. 3, March 1986, p. 125-140.
4. RAYMOND, L. *Effect of Thread Radius, Plating Potential, Stress Relief, and Crevice Corrosion of the HEM Susceptibility of ESR 4340 Steel Bolts.* L. Raymond Associates, Newport Beach, CA, Contract DAA629-85-C-0006, Final Report, MTL TR 88-8, April 1988.

from the other nut. Figures 13 and 14 show fractographs from samples tested at -0.8 V that were made from nut 0250 (heat 6644-A) and nut 0845, respectively. Sample 0845-24 showed transgranular crack growth while sample 0250-CU2 from heat 6644-A showed a combination of intergranular crack growth and ductile crack growth. The intergranular regions occur in long *bands* in the direction of crack growth, alternating with ductile regions. The size and orientation of the intergranular/ductile regions matches the banding found metallographically. An attempt was made to determine the degree of alloy segregation in the bands using energy dispersive X-ray analysis in a SEM, but no measurable difference was apparent.

A transition from intergranular to transgranular fracture mode as the charging potential was changed from -1.2 V to -0.8 V has been reported elsewhere for a similar T250 steel[5]. As the potential becomes less electronegative (more anodic) the rate of hydrogen generation is reduced and less hydrogen becomes available at the crack tip to diffuse into the steel. The grain boundary decohesion effect due to hydrogen in this martensitic steel is thereby reduced and the stress required for crack propagation in an intergranular mode increases as shown in Table 4, by the increase in K_{Iccc} at more anodic or noble potentials (from 15 ksi $\sqrt{in.}$ to 30 ksi $\sqrt{in.}$). Accordingly, the cohesive grain boundary strength increases to a point where the advancing crack tip no longer sees the grain boundary as a plane of weakness and fracture occurs in a transgranular rather than intergranular mode.

Electrochemical Testing

The short duration of the rising-step load test eliminated the possibility of long initiation periods necessary for crack initiation from surface pits. Therefore, cyclic-potentiodynamic polarization tests were conducted to determine if the failed nuts were more susceptible to pitting; no discernable difference was found. Potential decay measurements were made to determine if the failed nuts showed a difference in the potential decay over time, a faster decay rate indicating greater susceptibility to hydrogen embrittlement; again, no difference was found.

Hydrogen may exist in a component in either trapped or mobile form. Most methods of hydrogen analysis measure total hydrogen; the bulk of this hydrogen is in its trapped molecular form which is considered to be nondiffusible and innocuous in the embrittling mechanism. The level of mobile (atomic) hydrogen is of most importance because it is the primary embrittling species leading to the delayed failure of high-strength steels. Since the development of the Barnacle Electrode Method,[6] it is possible to measure diffusible (embrittling) hydrogen. This technique is based upon the electrochemical permeation method. If hydrogen is present in a part which is made the anode in an electrochemical cell, the hydrogen is oxidized as it diffuses to the surface. The oxidation current can then be related to the relative hydrogen content of the part and, therefore, the degree of hydrogen embrittlement.

This hydrogen can enter the steel by various means such as chemical cleaning, pickling, and electroplating; if there is a coating on the steel it must be removed by a method which neither damages the steel nor introduces hydrogen. Since a 1.25 N ammonium nitrate solution was used to remove the cadmium plate in order to make hardness measurements it was deemed necessary to determine whether or not this operation introduced hydrogen into the maraging steel. Table 5 contains hydrogen contents measured as current density and

5. TYLER, P. S., LEVY, M., and RAYMOND, L. *Investigation of the Conditions for Crack Propagation and Arrest Under Cathodic Polarization by Rising Step Load Bend Testing.* Corrosion, v. 37, no. 2, February 1991, p. 82-87.
6. ARGAWALA, V. S., BERMAN, D. A. *The Electrochemical Measurement of Diffusable Hydrogen In Steels (Barnacle Electrodes).* ASTM Designation F1113-88.

converted to parts-per-million employing the Barnacle Electrode technique and under the conditions described therein. These data show that the ammonium-nitrate stripping operation introduced neglible hydrogen into the maraging steel and the concentration in both discrepant and other nuts was comparable. However, in the case of those nuts that were IVD aluminum plated as an alternative to cadmium and chemically stripped with sodium hydroxide, the stripping operation introduced a substantial amount of hydrogen. It should be noted that MDHC does not specify baking for hydrogen removal after the ammonium nitrate stripping of cadmium plate, but does require the baking treatment after IVD aluminum stripping with sodium hydroxide.

Table 5. BARNACLE ELECTRODE VALUES

Material	Mechanically Stripped	Chemically Stripped	Barnacle μA	After 24 Hours	Δ μA	After 672 Hours	After 168 Hours Stripped
*Nut 0250		x	0.429	0.385	0.044	0.317	
		x	0.477	0.403	0.074	0.353	
		x	0.450	0.339	0.111		
*Average			0.452	0.376		0.335	
			0.092 ppm	0.078 ppm		0.070 ppm	
†Nut 0845	x		0.492				
	x		0.439				
	x		0.441				
	x		0.433				
†Average			0.455				
			0.095 ppm				
‡MTL C-250			0.250				0.231
			0.360				0.283
			0.278				0.309
							0.273
‡Average			0.296				0.274
			0.062 ppm				0.059 ppm
**Nut 0338	x		0.446	0.299	0.147	0.273	
	x		0.297			0.245	
**Average			0.3715	0.299		0.259	
			0.076 ppm	0.064 ppm		0.055 ppm	
**Nut 0338		x	0.857	0.399	0.458	0.443	
		x	0.715	0.374	0.341	0.378	
**Average			0.786	0.3865		0.4105	
			0.160 ppm	0.081 ppm		0.084 ppm	
				after 4 weeks			

*Discrepant Nut
†Reference Nut
‡Reference Material Via MTL
**IVD Aluminum-Coated Nut

DISCUSSION

Hydrogen-assisted stress corrosion cracking was the cause of all cracks found in the retention nuts. Given this, it is necessary to determine whether or not the material used in the discrepant batch has an inherent deficiency that increases its susceptibility to this type of failure. The examination of the processing history and the mechanical and electrochemical tests did reveal several differences or irregularities between the discrepant batch and other nuts. The major differences and their importance follows:

- The discrepant nuts experienced a cadmium stripping/recoating operation. This was thought to have two possible consequences: (1) the introduction of hydrogen to the nut material, and/or (2) rusty areas after stripping could create local flaws in the cadmium coating causing pitting and early crack formation. However, no increases in the hydrogen levels were found using the barnacle electrode, nor were changes in K_{Iscc} values detected. Further, the soft cadmium coating cannot be expected to maintain complete integrity so the rusty areas cannot be considered critical or unusual flaws.
- The discrepant nuts showed lower values of elongation to failure and reduction in area during tensile testing than the reference nuts. Still all the values measured fell within specifications so the material cannot be considered substandard.
- Banding was observed qualitatively to be more severe in the discrepant nuts and it correlated with a change in fracture appearance between the discrepant nut and the other nuts. The banded structure produced by segregation of elements clearly affects the chemical reactivity of the material as indicated by the differential etching behavior. Prolonged exposure can reveal the deleterious effects of slight differences in chemical reactivity and mechanical properties. The presence of greater degrees of banding in combination with environmental exposure in the field may have been responsible for early failures of the nuts from the discrepant batch. Though this may indicate a deficiency in the discrepant material, banding is extremely difficult to quantify and requirements based upon banding are seldom used. Severe banding is normally precluded through elongation specifications and the material in the discrepant nuts meets all mechanical property requirements. Therefore, no clear definable and measurable difference due to banding can be made.

The irregularities noted above probably played a role in the early failure of the retention nuts from the discrepant lot and, therefore, none of the retention nuts from this heat (6644-A) should remain in service. However, of these differences, none can be conclusively proven to be the chief fault that led to the failure of the nuts and, therefore, it must be assumed that other heats could suffer similar cracks in the future. In effect, the problem cannot be considered merely a batch problem since the material from the questionable nuts meets all applicable standards. However, an improvement in the quality of the steel and subsequent performance of the nut might be achieved by increasing the minimum percent elongation requirement specified in HMS 6-1080 from 6% to 10%.

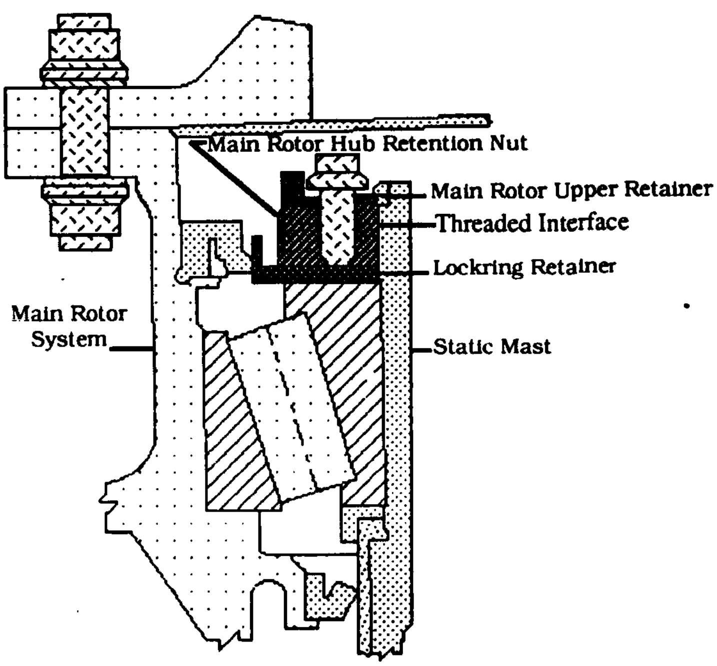
The hydrogen-assisted stress corrosion cracking must be treated as a systemic problem. To eliminate or reduce this risk two routes should be pursued: (1) replace the retention nuts with new ones made from a material with greater resistance to hydrogen assisted stress corrosion cracking, and (2) remove the hydrogen source from the nut. The first part is straightforward but the second approach requires knowledge of the hydrogen source. The presence of a crevice environment within the bolt holes combined with the Ni-Cd electrochemical cell (nickel plated bolts in contact with the retention nut) creates a ready source of hydrogen.

Thus, removing the Ni portion of the cell by using Cd-plated bolts would decrease the availability of hydrogen. Keeping the region dry and free of water vapor would also stop the electrochemical processes and reduce hydrogen absorption.

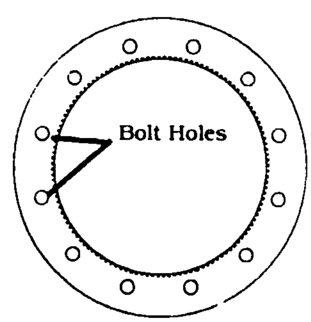
The retention nuts could be replaced using a lower hardness maraging steel if it meets all other design criteria, such as a C-200 grade maraging steel. This would increase the components resistance to hydrogen embrittlement. This must be done in conjunction with a detailed stress analysis that considers the critical flaw size for K_{Iscc} from a bolt hole in a hydrogen-rich environment.

RECOMMENDATIONS

- The cracking should not be treated as a batch problem.
- All the retention nuts in heat 6644-A should remain out of service.
- The nickel plated bolts should be replaced with cadmium plated bolts.
- Replacement of nuts with a lower strength steel (C-200) should be considered.
- A frequent inspection interval should be utilized until the retention nuts can be upgraded.
- Eliminate moisture entry and entrapment by the application of appropriate sealants and water-displacing compounds within the entire main rotor hub assembly.



(a)



(b)

Figure 1. (a) Cross-sectional view of main rotor system, (b) Top view of main rotor hub retention nut with 12 bolt holes shown. Central hole is threaded to fit onto the threaded external diameter of the static mast.

(a)

Figure 2. (a) Top view of main rotor retention nut 0223 showing crack transversing the thickness of the nut at a bolt hole. Note corrosion and wear evidence by the discolored regions.

(b)

Figure 2. (b) Bottom view of main rotor retention nut 0223 showing crack transversing the thickness of the nut at a bolt hole. Note corrosion and wear evidence by the discolored regions.

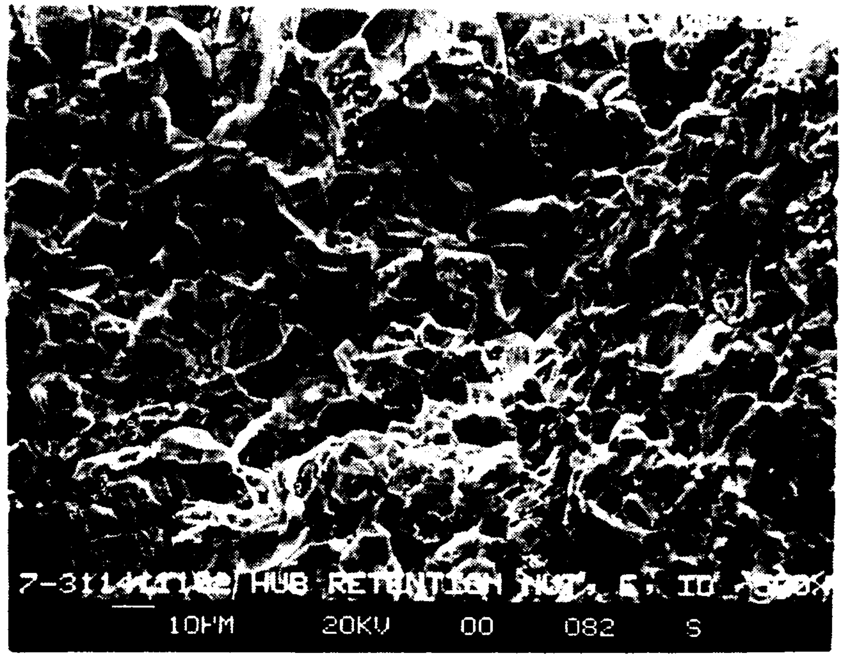


Figure 3. McDonnell-Douglas SEM examination of fracture surface of nut 0223 indicating hydrogen-assisted cracking by the appearance of an intergranular crack path.

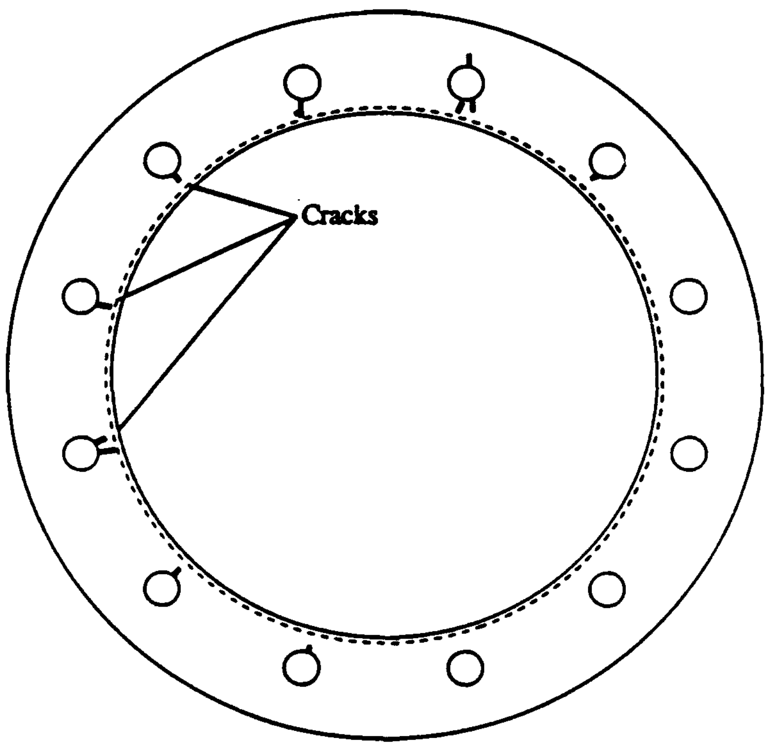
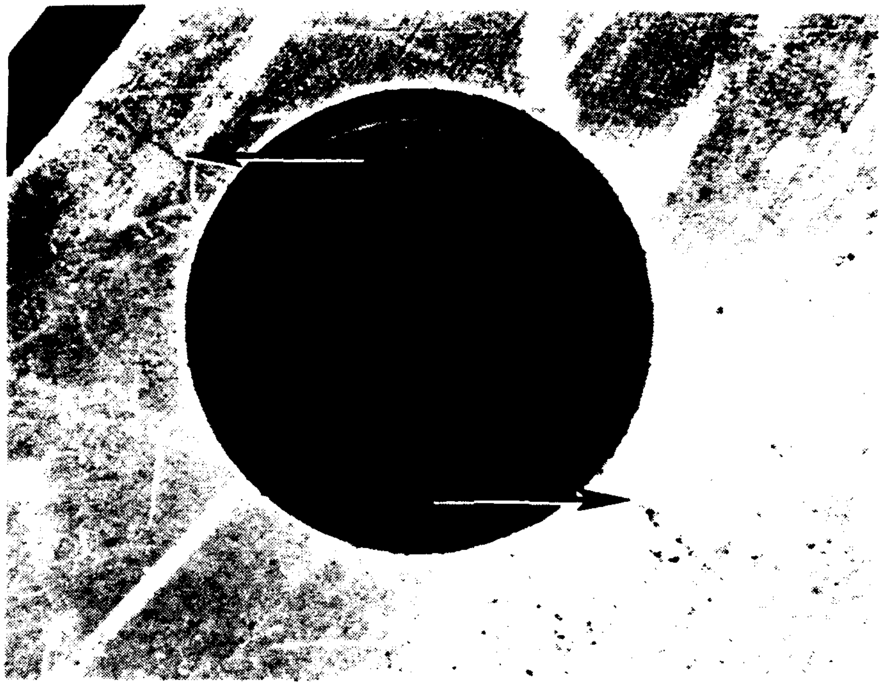
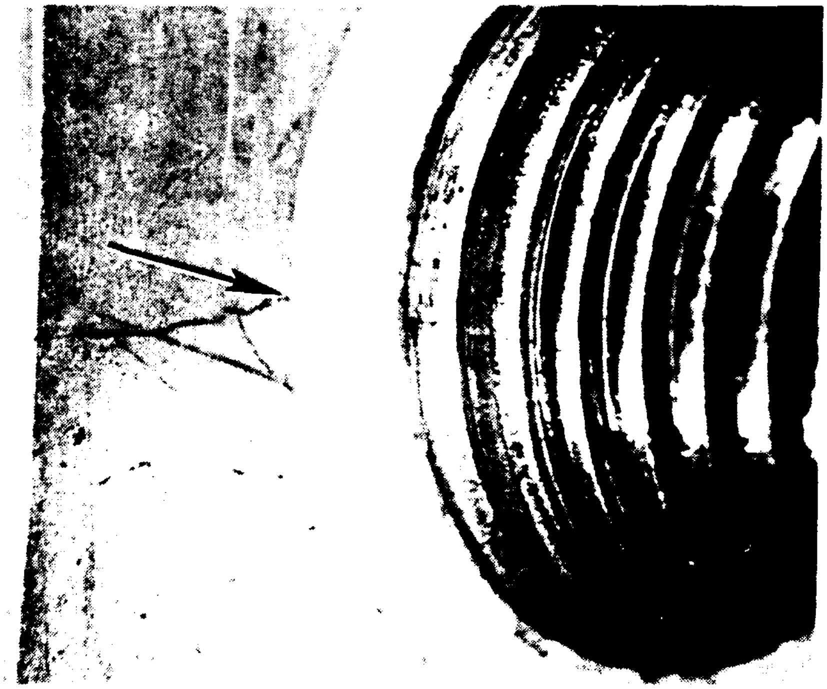


Figure 4. Schematic of main rotor hub retention nut 0257 with position of radial cracks emanating from bolt holes shown.



(a)



(b)

Figure 5. Optical micrographs of typical cracks emanating from bolt holes. Arrows denote location of cracks. (a) Mag. 7.5X., (b) Mag. 15X.

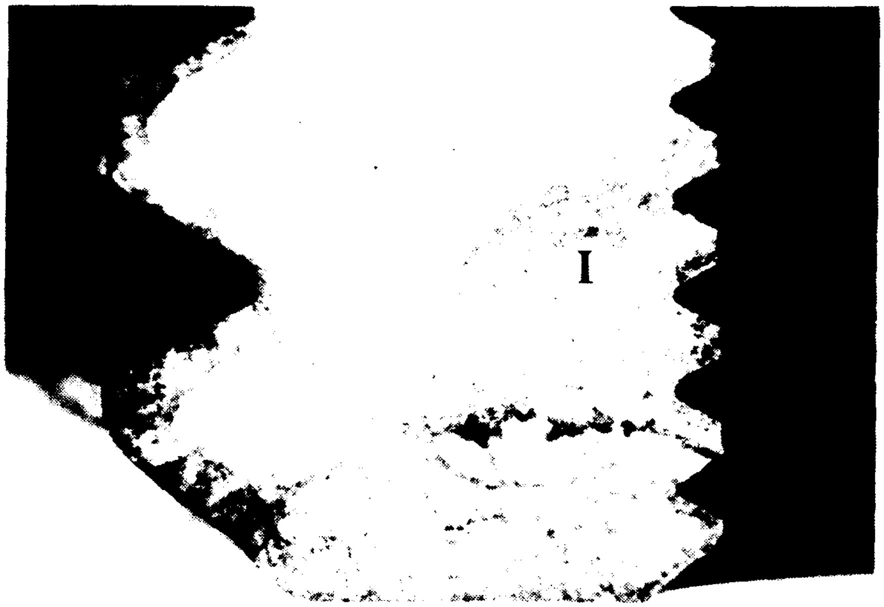
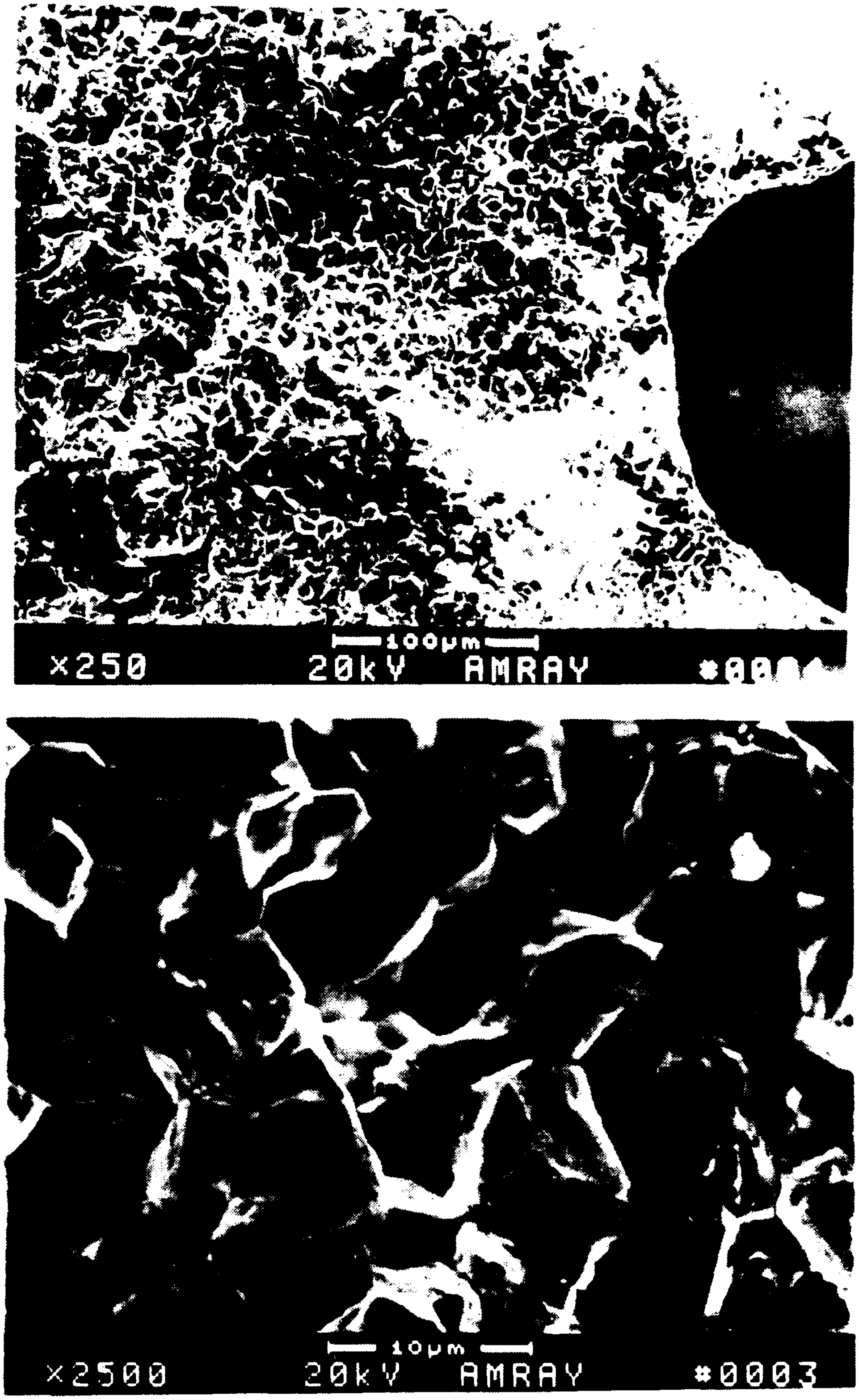


Figure 6. Optical photograph of crack from nut 0257. The region marked "I" shows intergranular fracture. The rest of the fracture was subsequently formed by opening the crack with the three-point bend apparatus. Mag. 15X.



(a)

(b)

Figure 7. SEM micrographs showing origin of crack from Figure 4. (a) Origin near thread root at Mag. 250X. (b) Close-up view of origin of crack depicting the intergranular nature of the crack.

Figure 8. Optical micrographs showing typical pitting effects on the retention nuts. Mag. 30X.

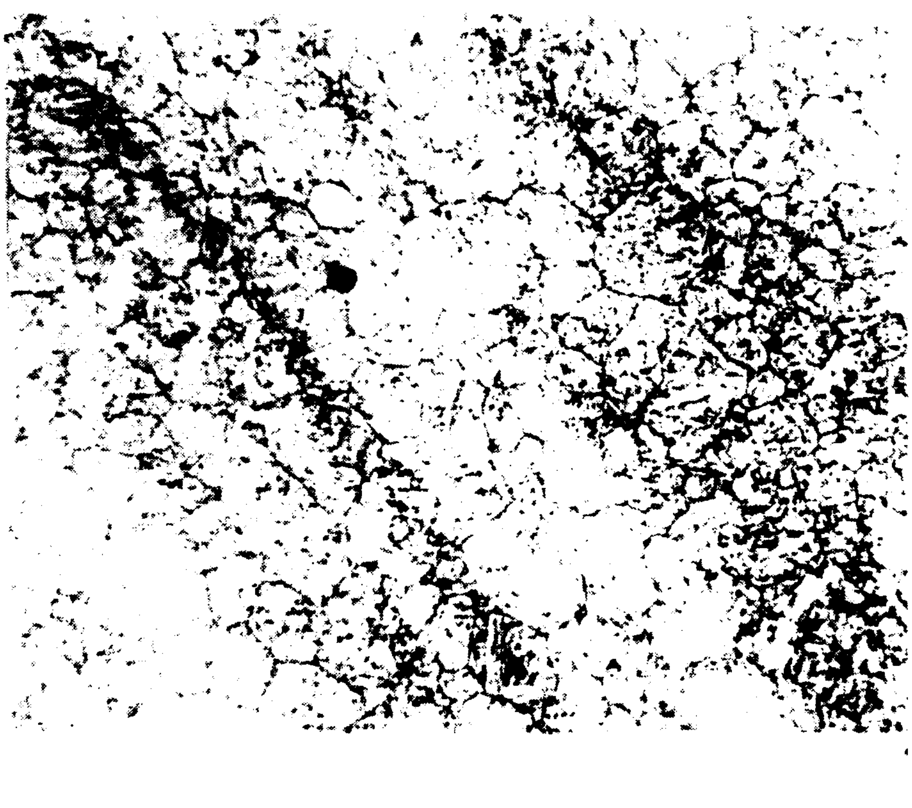


Figure 9. Micrograph showing the typical microstructure for the C-250. The structure consists of aged martensite, banding is apparent. Nital etch. Mag. 50X.

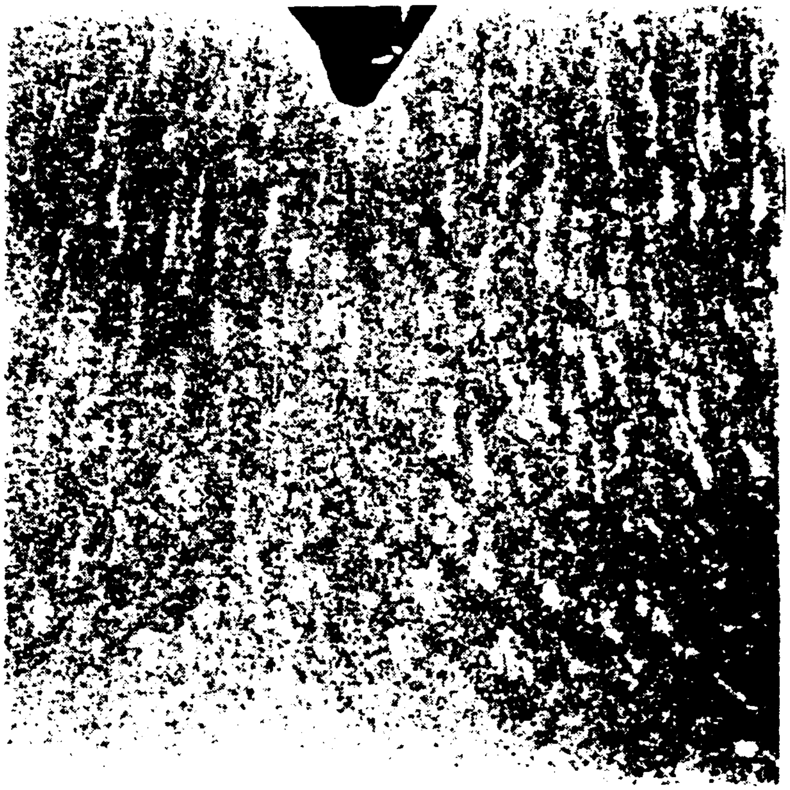


Figure 10. Micrograph showing banding in nut 0250. Maraging etch. Mag. 10X.

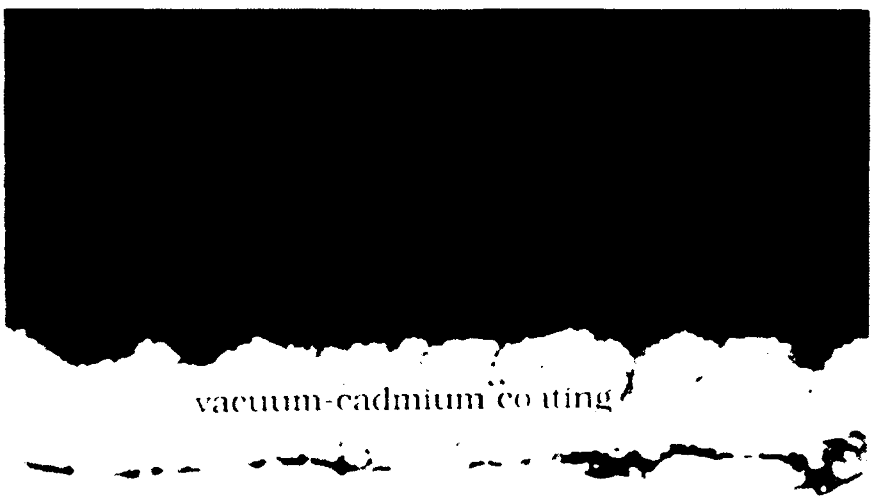


Figure 11. Micrograph depicting vacuum-cadmium coating from nut 0250. Mag. 500X.

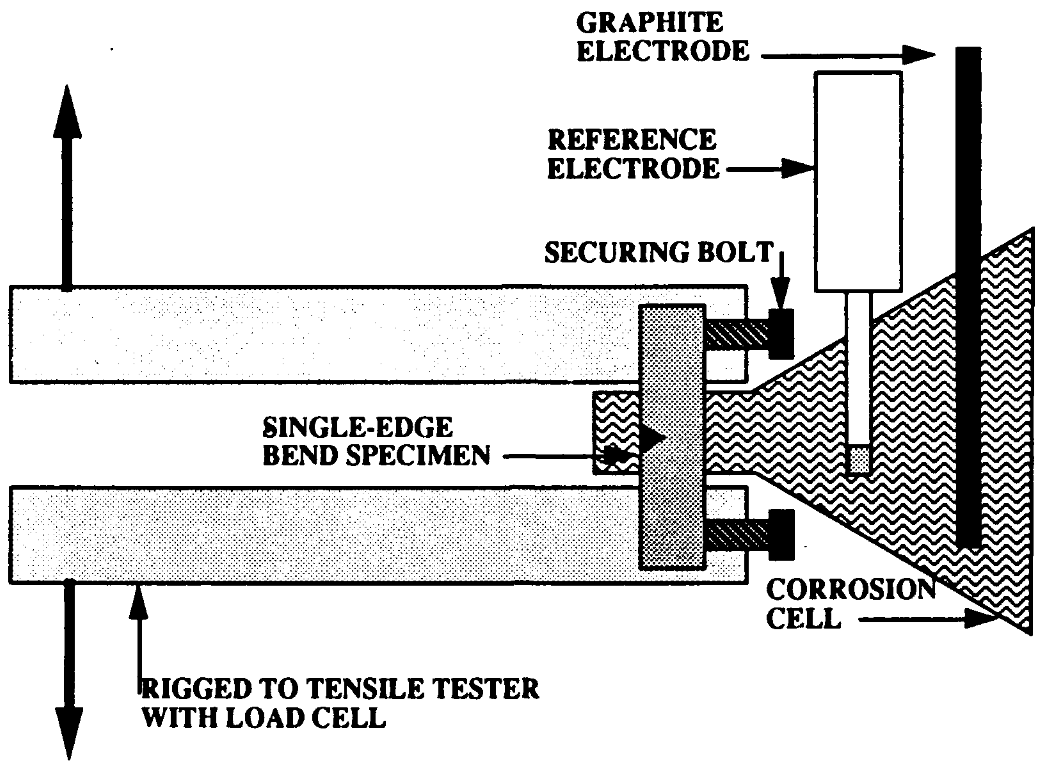
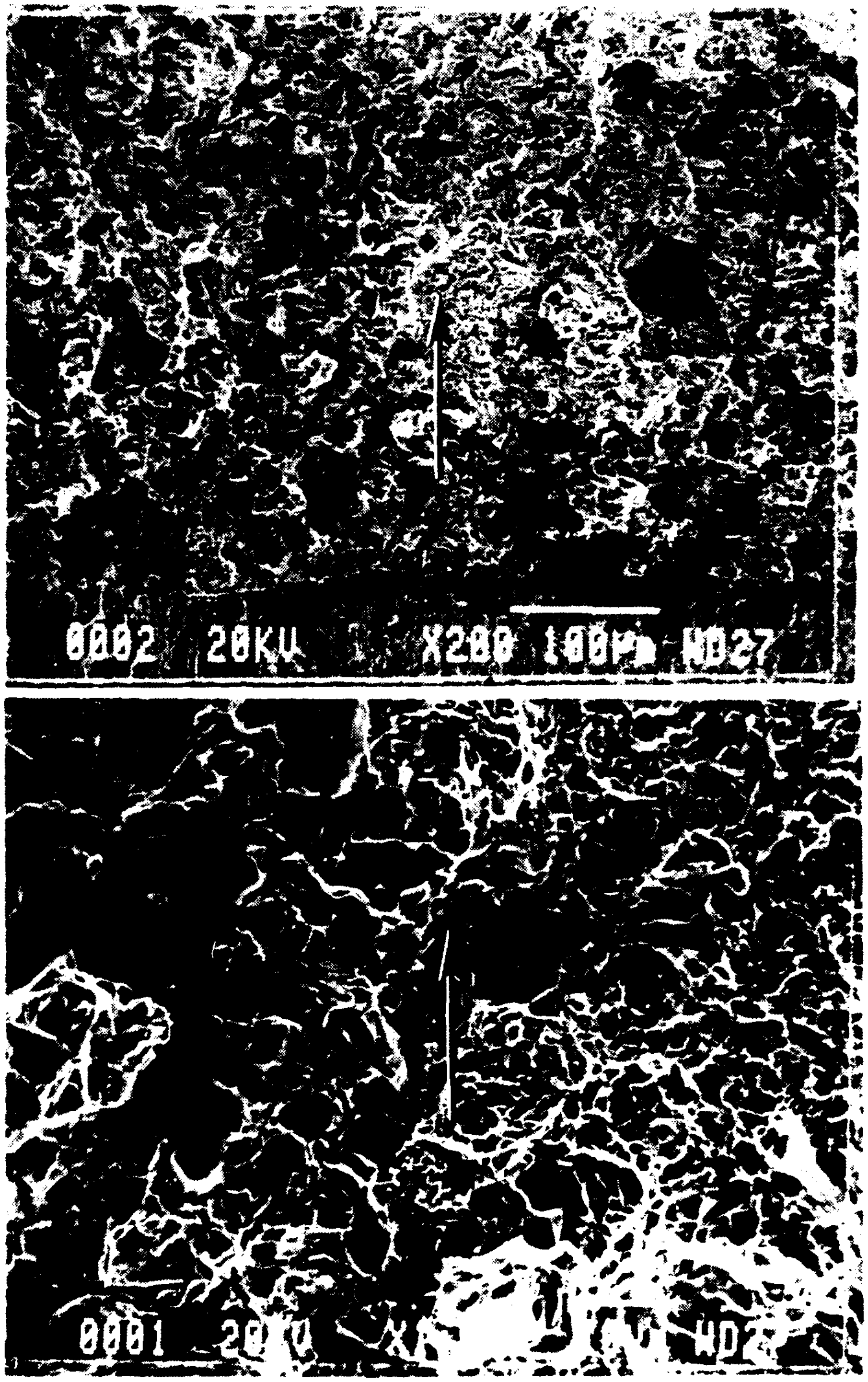


Figure 12. Constant-potential rising-step load single-edge bend test used to determine mining K_{ISCC} values.



(a)

(b)

Figure 13. SEM micrographs of the fracture surface of K_{ISCC} specimen taken from nut 0250 and tested at -0.8 V versus SCE. Crack growth direction is noted. Alternating regions of intergranular and ductile crack growth can be seen. These regions match the size and orientation of the bands depicted in Figure 8. (a) Low Mag. (b) High Mag.

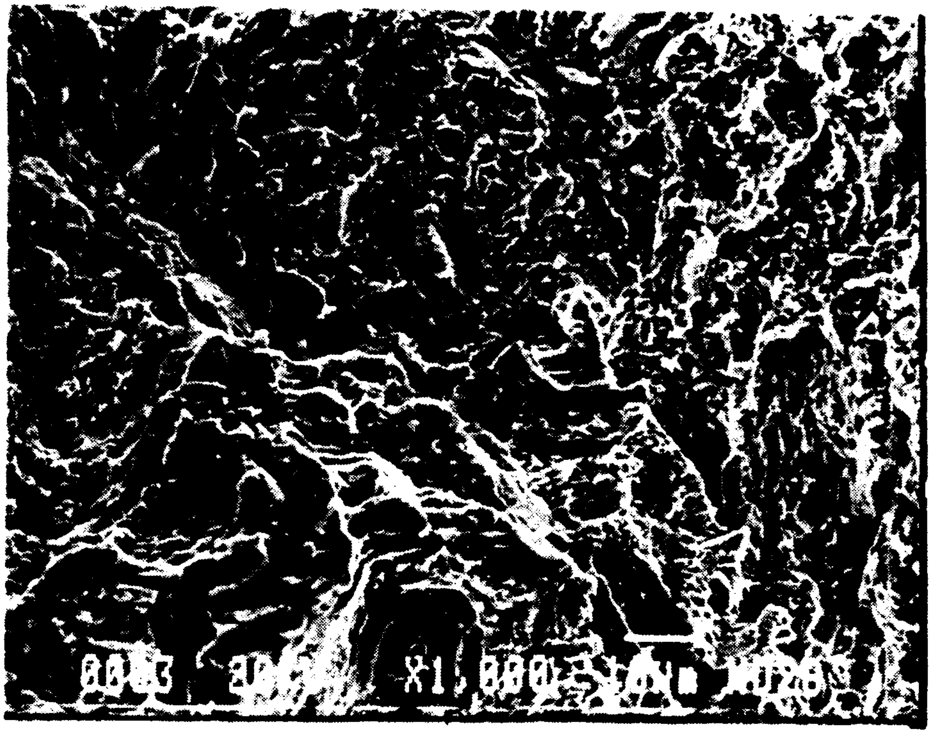


Figure 14. SEM micrographs of the fracture suface of K_{ISCC} specimen taken from nut 0845 and tested at -0.8 V versus SCE. Note transgranular crack growth.

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A comprehensive analysis of the failed main rotor hub retention nuts of the Apache helicopter was carried out at the U.S. Army Materials Technology Laboratory (MTL). An inspection of the entire fleet of Apache helicopters revealed that eight nuts contained cracks. The goals in this investigation were to determine the failure mode and cause to establish the mechanical and corrosion properties of the nut material, to verify that cadmium and nickel coatings were applied in accordance with the specification requirements and to make appropriate recommendations to prevent further problems. Additional nuts from both the inventory and field were characterized and tested for comparison. The following analyses and tests were performed: visual examination; light and electron microscopy of the retention nuts and fracture surfaces; metallographic analysis of both failed and intact nuts; chemical analysis of the 18 Ni maraging steel C-250 grade steel; mechanical property, stress corrosion, and electrochemical tests. The chemical composition of the steel was well within the contractors specification and met the industry standards for maraging C-250 grade steel. Mechanical properties were also within specified requirements. Hydrogen-assisted cracking was the cause of all cracks found in the retention nuts. To eliminate this problem two routes should be pursued: replace the retention nuts with new ones made from a material with greater resistance to hydrogen-assisted cracking (lower hardness C-200 grade maraging steel), and remove the hydrogen source from the nut by replacing the nickel plated bolts in contact with the cadmium plated bolt holes of the retention nut with cadmium plated bolts. Keeping the region dry and free of water vapor by the application of appropriate sealants and water displacing components would also stop the electrochemical processes and reduce hydrogen absorption.

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