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Failure Analysis of Lift Pad Studs for the Recovery of Objects from the Ocean

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ABSTRACT

This report describes the application of failure analysis to a Naval Problem regarding the recovery of underwater objects. A lifting pad is attached to the object to be recovered by four studs which are explosively driven through undersized pad eyes into the submerged structure. Experimental trials by the Naval Ordnance Laboratory using a shock resistant tool steel for the studs resulted in breaking stresses of the order of 30,000 psi, far short of the tensile strength of 290,000 psi. NRL was asked to examine the stud failures. K_{Ic} and K_{Iscc} measurements were made on several unfailed studs. Recommendations include the use of another more suitable, non-ferrous alloy or as a minimum requirement lowering the tensile strength of the steel now used.

PROBLEM STATUS

Consulting work for Deep Submergence Systems Project on one problem of concern is reported on here. Work for DSSP continues.

AUTHORIZATION

This research was supported by the Deep Submergence Systems Project with Mr. Harold Bernstein as Project Engineer under NRL Problem 84F01-17.

Failure Analysis of Lift Pad Studs for Recovery of Submerged Objects

BACKGROUND

As work with underwater capsules, habitants, etc. continues to expand the capability for recovery of such objects becomes an ever more firm requirement. As one part of the Navy's recovery program the Deep Submergence Special Project is sponsoring research at the Naval Ordnance Laboratory on the attachment of lifting pads to intended recovery items. The work reported on here involves the attachment of pads by steel studs explosively driven through undersized pad eyes into 2" thick plates of HY-80 steel. Work at NOL showed the studs to fail in salt water at stresses considerably below that of their tensile yield strength.

The studs are made of Venango steel which is a shock resistant tool steel, class S-2, hardened to approximately 57 R_c in the vicinity of the break. The studs are driven through undersized pad eye holes into HY-80 steel at about 1700 ft/sec making it necessary to harden the tips of the studs. Several sets of studs fractured on subsequent pad tests at an area in the shank near the surface of the HY-80 steel plate at stresses as low as one-tenth of the tensile strength of the stud material.

INITIAL CONFERENCE

An initial conference between NOL personnel and personnel from the Ocean Technology Division and the Metallurgy Division of NRL led to the tentative conclusion that stress corrosion cracking was responsible for the low failure stresses. (1) An examination of four fractured studs from one lifting pad failure showed that a very slight shear lip was present on each stud interrupted by a small arc segment without a shear lip on two of the studs. However, the studs were so corroded that little else could be concluded by microscopic examination. The shank portion of each stud was 0.6 inch in diameter. The average stress on the four studs reached a value of about 30,000 psi at fracture compared with a design stress of 110,000 psi. The estimated tensile strength of the steel in the studs was 290,000 psi. It was agreed to look at any additional failures and to measure the fracture toughness of the stud material both in air and in a salt water environment.

K_{Ic} and K_{Iscc} MEASUREMENTS

The failure of the steel far below design stress could have resulted from low resistance to cracks propagating from small flaws. Tests were made to evaluate the crack toughness parameter K_{Ic} of the steel in the vicinity of failure (2). The effect of stress corrosion was studied by comparing results in air and in salt water environments.

Five new studs were received from NOL for tests. A circumferentially notched round-bar test specimen, see Figure 1, was used in determining crack toughness. The notch location was near where failure had occurred in the studs during the pull test. The procedure for measuring K_{Ic} was adapted from an ASTM committee report (3). A fatigue precrack at the root of the notch was generated in a lathe used as a rotating beam fatigue machine. Two specimens were tested in air and three were tested with salt water surrounding the notch as shown in Figure 2.

The nominal analysis for an S-2 grade of steel is carbon 0.50, manganese 0.45, silicon 1.10, vanadium 0.20 and molybdenum 0.50 in per cent by weight. A check on the sulfur content gave the low value of 0.006 per cent, indicating a good steel melting-practice.

The test results are listed in Table 1. Unsymmetrical fatigue cracking probably was the cause of some eccentricity in loading as may be seen in Figure 3. Test No. 2 with a well-centered fracture gave 23,000 psi $\sqrt{in}$ as a probable value for K_{Ic} in air. In salt water, the stress-corrosion value of K_{Ic}, called K_{Iscc}, was estimated to be less than the quantity of 20,000 psi $\sqrt{in}$ obtained for fracture with a short time rising load and more than the 9,000 psi $\sqrt{in}$ stress intensity value which caused no fracture in 16 hours (test No. 4). It is believed that the salt water environment lowered fracture toughness to some extent but the effect was not large at this low level of K_{Ic}.

K values are used in estimating a critical flaw size which could cause catastrophic fracture. The formula for long cracks is $a_{cr} = (K_{Ic}^2 Q)/(1.2 \pi \sigma^2)$, (4). If a conservative value of 20,000 psi $\sqrt{in}$ is chosen for K_{Iscc}, critical crack depths (a_{cr}) related to stress levels of interest would be in the following order of size:

At the average failure stress (30,000 psi), $a_{cr} \approx 0.1$ inch.

At the design stress (110,000 psi), $a_{cr} \approx 0.01$ inch.

At the yield stress (290,000 psi), $a_{cr} \approx 0.001$ inch.

Because of unknown conditions, it was not feasible to estimate local stresses in the region where failure occurred during the NOL pull test. Under high local stress, a minute crack obviously could have initiated fracture. Although examination was difficult because of rusting in the sea water, crack origins were indicated by gaps in the shear lip surrounding the fracture.

METALLURGICAL EXAMINATION

Some additional metallurgical factors were examined. The typical microstructure of acicular martensite is illustrated in Figure 4A. A zephiran etch showed no indication of temper brittleness. The electron fractograph of a K_{Ic} test fracture in Figure 4B indicated a relatively ductile type of separation that might be expected of a steel with a high yield strength. Small corrosion pits were observed running perpendicular to the fracture surface in a failed stud supplied by NOL (Figure 5A). These pits apparently were developed in the sea water after the stud had fractured in the pull test. A similar pitting attack might have occurred at the surface of the stud during the pull test. Pitting at the surface is the usual start of stress-corrosion cracking of a smooth metallic part (6). Stringer inclusions (Figure 5B) extended in the same direction as the pits but the evidence was insufficient to establish a direct relation.

SECOND FAILURE STUDY

Studs in another lifting pad were embedded in fresh water by NOL and the whole pad immersed in salt water, first, for 18 hours under no load and then under a load of 80,000 pounds imposed for 3-1/2 hours. As the pad was being lifted out of the salt water the studs sheared off at 90,000 lbs load (80,000 psi stress). Of the three fractured studs examined by Dale Meyn of the NRL Metallurgy Division (5) one started from a small surface flaw and failed with an intergranular fracture typical of stress corrosion cracking. The fracture in the second stud started from an internal origin but was all dimple rupture with no intergranular fracture indicating a straight rupture with no assist from stress corrosion nor hydrogen embrittlement. The third stud failed by bending after the first two had snapped. The fourth stud was not recovered. This particular pad failure did not fall far short of the design stress of 110,000 psi when one realizes that bending stresses may have been superimposed and that loading may not have been uniformly distributed over the four studs. These examinations by Mr. Dale Meyn using the scanning electron microscope will be the subject of a separate report by Mr. Meyn.

CONCLUSIONS AND RECOMMENDATIONS

In summation, the tests indicated that fracture toughness (K_{Iscc}) in salt water probably was not much below K_{Ic} for air environment. The low K values ($\approx$ 20,000 psi $\sqrt{in}$) were about what might be expected in a quenched and tempered steel of high yield strength ($\approx$ 290,000 psi).

In salt water, the steel in the studs was subject to pitting from corrosive attack. A very small flaw combined with a high local stress could have initiated fracture at a low average stress level according to fracture toughness relations.

The application requires a high-strength metal resistant to sea water attack with properties suitable for ballistic penetration. The nickel-chromium base alloy Inconel 718 reportedly is under consideration. The nickel-cobalt-chromium-molybdenum alloy MP35 was suggested in (1). After working and aging, these alloys can be strengthened to about 260,000 psi. Both metals have good resistance to corrosion. Vacuum melting in steel manufacturing would also be beneficial due to a decreased number of inclusions. However, according to all available information no steel exists today which is safe for this application unless the tensile yield strength is 180,000 psi or less. MP35 specimens are on hand in the NRL Metallurgy Division and stress corrosion tests will be made on them in the near future.

ACKNOWLEDGMENT

Dr. Floyd Brown, Dr. Joseph Krafft and Mr. Miller Peterson of the NRL Metallurgy Division were present at this initial conference and made valuable contributions to the problem analysis.

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TABLE 1 - FRACTURE TOUGHNESS OF STEEL I.N STUDS USED FOR PULL TESTS UNDER SEA WATER. ENVIRONMENTAL TESTS IN AIR AND IN SYNTHETIC SEA WATER

[illegible] temperature [illegible]

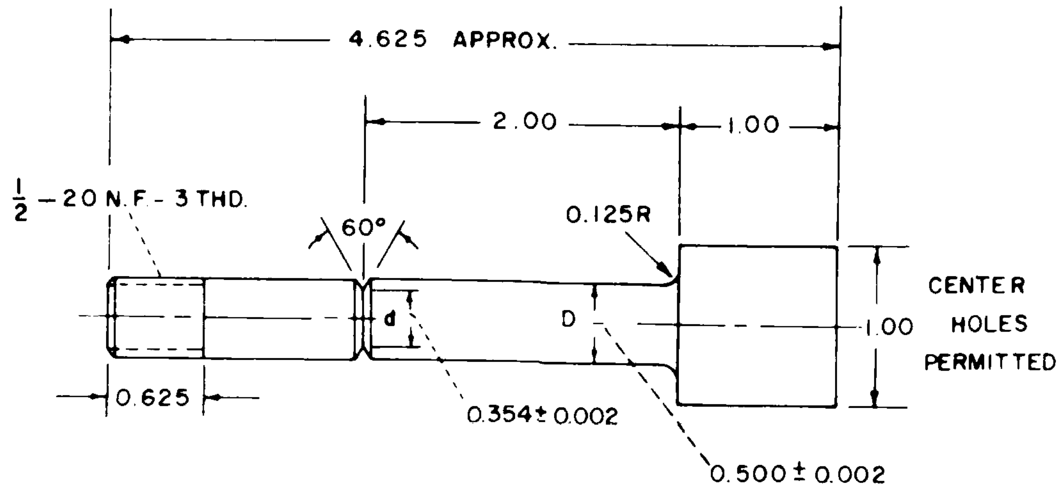
Test No.	Diameter [illegible]	Major Axis [illegible] Fracture	Minor Axis [illegible] Fast Fracture	Area [illegible] Fast Fracture	Diameter [illegible]	P Load [illegible] Mode	P Load at Fast Fracture	K_I (1) at Constant Load (ksi√in.)	K_I (1) at Fast Fracture (ksi√in.)	Net Section Stress at Constant Mode	Net Section Stress at Fast Fracture	Ratio [illegible]	Remarks [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	--	[illegible]		[illegible]	--	[illegible]	[illegible]	Air [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	--	[illegible]	--	[illegible]		[illegible]	[illegible]	Air [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	--	2,3[illegible]	--	[illegible]	[illegible]	[illegible]	[illegible]	Synthetic sea water, [illegible]
[illegible] (4)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	----	[illegible]	--	[illegible]		[illegible]	Synthetic sea water constant(4) [illegible] fracture.
[illegible]		(see above)				----	7,5[illegible]	--	[illegible]	--	[illegible]	[illegible]	Synthetic sea water, [illegible]
[illegible] fracture)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2,2[illegible]	2,2[illegible]	/	[illegible]	[illegible]	[illegible]	[illegible]	Synthetic sea water, constant load for [illegible] min. caused fracture.

NOTES: (1) K_I [illegible] where [illegible] 1.72(D/d)-1.27, reference ASTM STP 41[illegible], p.1[illegible].

(2) σ_{ys} was estimated to be [illegible] psi (reference (5)).

(3) The synthetic sea water was a 3-1/2 per cent solution of NaCl in distilled water. The [illegible] load was applied at the rate of [illegible] lb/min.

(4) History of [illegible] test No. 4: [illegible] hrs. at constant [illegible] lb load, load removed for [illegible] hrs., [illegible] hrs. at constant [illegible] lb, load removed for [illegible] hrs., [illegible] hrs. at constant [illegible] for a total of [illegible] hrs. at the [illegible] lb load level. The load then was raised at [illegible] until fracture occurred at 3,5[illegible] lb. The [illegible] was maintained constant by [illegible] control on an [illegible] hydraulic testing machine. The [illegible] was renewed at the start of each constant load period.



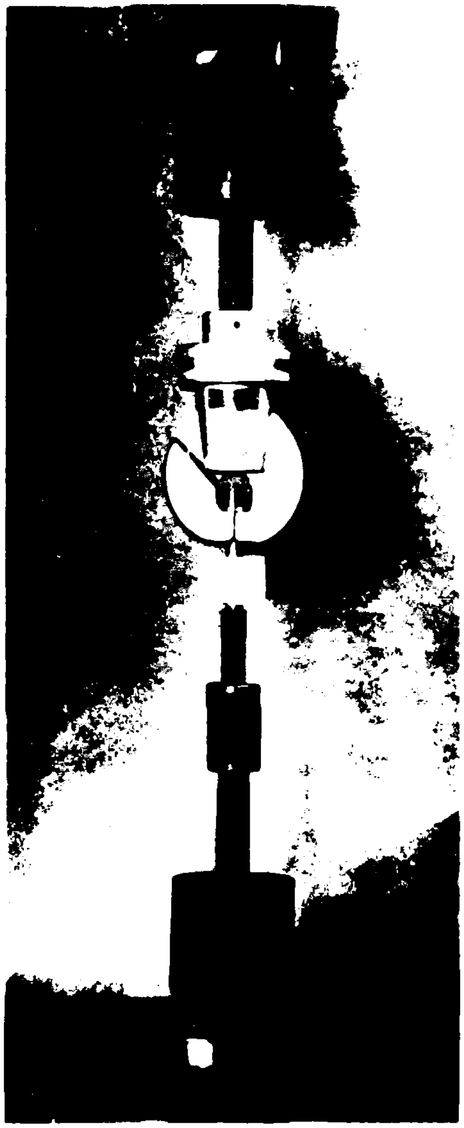
RADIUS AT NOTCH BOTTOM 0.001

DIMENSIONAL TOLERANCE TO BE ±0.005 EXCEPT WHERE NOTED

FIGURE 1

COMBINATION THREADED AND BUTTONHEAD CYLINDRICAL SHARP-NOTCH SPECIMEN

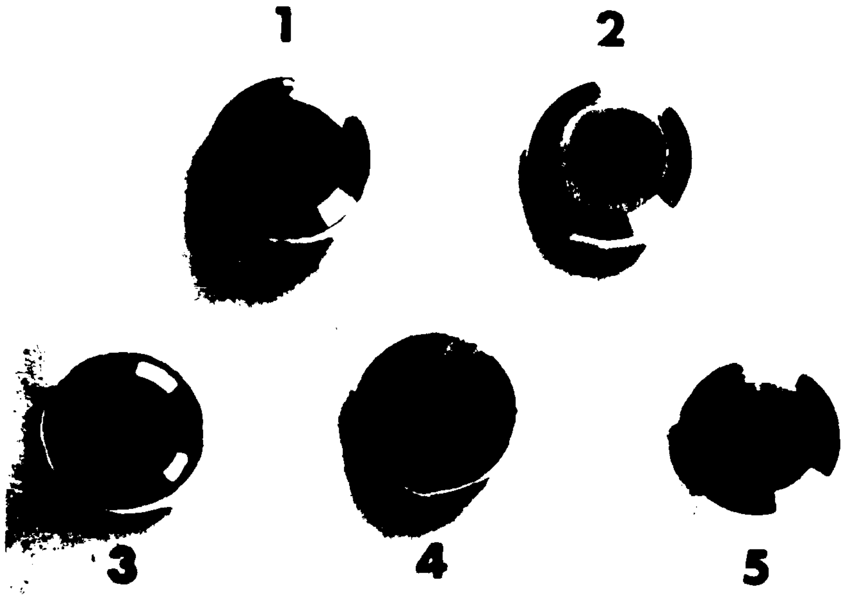
ALL DIMENSIONS IN INCHES



PHD-0991-6-68 **FIGURE 2**

SPECIMEN IN POSITION FOR STRESS CORROSION TEST

Synthetic sea water (3-1/2 percert NaCl in distilled water) was placed in the polyethylene cup surrounding the notch area. Constant load was maintained by closed loop control of the electro-hydraulic testing machine. The ball-and-socket fixtures at each end were hand-lapped and lubricated with molybdenum sulfide to promote alignment. A large plastic bag was fastened around the test section to contain splashing.

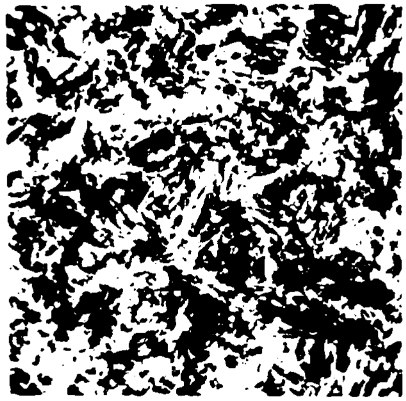


PHD-0992-6-68 FIGURE 3

PHOTOGRAPH OF FRACTURED TEST SPECIMENS

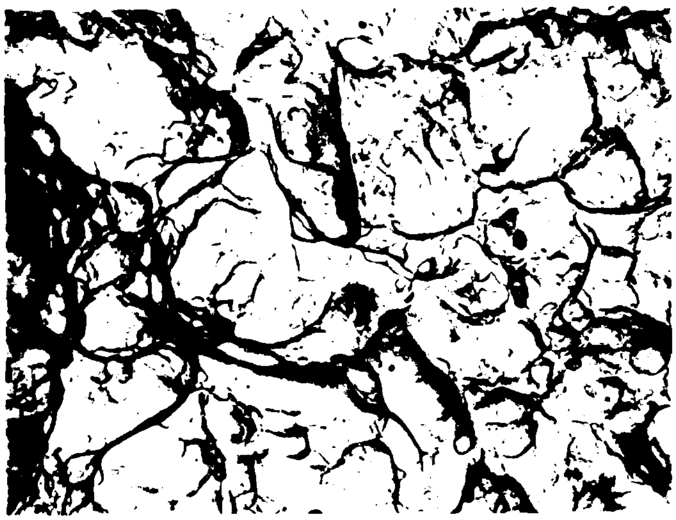
The numbers refer to tests in Table I. The inner most region with a freshly-separated appearance was assumed to be the area of fast fracture. The surrounding fatigue precrack was smoother and sometimes slightly stained. Only test No. 2 had a well-centered and a nearly circular area of fast fracture.

X2



A. TYPICAL MICROSTRUCTURE

Slighty tempered martensite.
Nital etch, X1000.

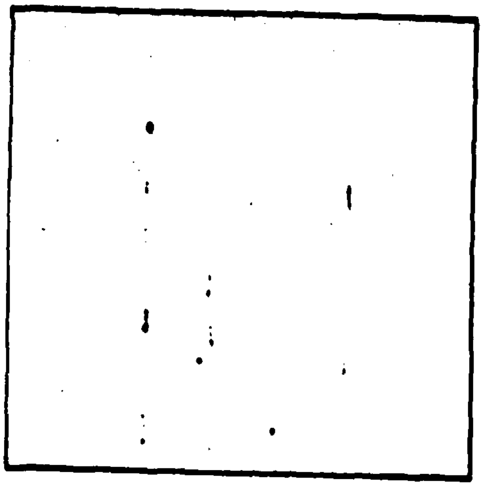


B. ELECTRON FRACTOGRAPH FROM FAST-FRACTURE AREA OF TEST NO. 2

The surface consisted largely of flat areas perpendicular to the stress field. There were indications of ductile dimpling but no clear evidence of brittle cleavage or intergranular fracture X7,000

PHD-0993-6-68 FIGURE 4

A. Cross section at the fracture surface illustrating corrosion pitting which developed after fracture in sea water at NOL.



B. Area in the body of the steel stud showing typical stringers of inclusions extending in the same direction as the corrosion pits.

PHD-0998-6-68 FIGURE 5

CORROSION PITTING AND STRINGER INCLUSIONS

Unetched, X100

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