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Corrosion Fatigue of High Strength Fastener Materials in Seawater

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Prepared for
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SUMMARY

Environmental effects can significantly reduce the fatigue life of metals. As such, corrosion fatigue is a major concern in the engineering application of high strength materials in marine environments. One critical use of high strength materials in marine environments is for fasteners which may be subjected to cyclic stresses superimposed over relatively high static axial stresses. This results in rather high ratios of minimum to maximum stress. High stress ratios are generally considered detrimental to corrosion fatigue strength but the data base is not extensive for engineering materials.

The failure of an AISI 41L40 high strength steel blade-to-hub attachment bolt at the MOD-0A 200 KW wind turbine generator in Oahu, Hawaii prompted the current test program. The cause of this failure was determined to be corrosion fatigue due to the combined action of normal fatigue loads at high stress ratios and the corrosive marine atmosphere.

Tests were undertaken to confirm the dramatic reduction of fatigue strength of AISI 41L40 in marine environments and to obtain similar corrosion fatigue data for candidate replacement materials. AISI 41L40, AISI 4140, PH 13-8Mo stainless steel, alloy 718 and alloy MP-35N were tested in axial fatigue at a frequency of 20 Hz in dry air and natural seawater. The fatigue data were fitted by regression equations to allow determination of fatigue strength for a given number of cycles to failure.

Results of the tests demonstrated a 77% reduction in fatigue strength (versus fatigue in air) for 41L40, a 72% reduction for 4140, a 51% reduction for PH 13-8 Mo, a 15% reduction for MP-35N, and a 4% reduction for alloy 718. The 4140 and 41L40 failed at stresses well below the normal operating stresses in a relatively few number of cycles. Pitting corrosion was observed to accompany corrosion fatigue failure of PH 13-8 Mo. Relatively little environmental effect was observed for alloy 718 and MP-35N.

INTRODUCTION

The U.S. Federal Wind Energy Program was established to enable research and development on various applications of wind energy systems. The program was originally administered by the National Science Foundation, and is currently directed and funded by the U.S. Department of Energy. One phase of the program involves the design, fabrication and experimental operation of large horizontal axis wind turbine generators. This part of the program is managed by the Lewis Research Center of the National Aeronautics and Space Administration. The first wind turbine generators to be placed into utility operation under this program were four 200 kW horizontal axis machines designated MOD-0A. Figure 1 shows a schematic drawing of the structure.

The purpose of the MOD-0A experimental installation was to obtain early operation and performance data while gaining experience in the operation of a large wind turbine in various utility environments. These wind turbines were built and installed at Clayton, New Mexico in 1978; at Culebra, Puerto Rico in 1979; at Block Island, Rhode Island in 1979; and at Kahuku Point, Oahu, Hawaii in 1980 (Ref. 1).

Around November 11, 1981, a failure occurred on the MOD-0A wind turbine generator at Kahuku Point, Oahu, Hawaii. The failure was one of the 24 AISI 41L40 high strength steel blade-to-hub attachment studs. Figure 2 shows the location and design details of the studs. The cause of the cracking was determined to be corrosion fatigue due to the combined action of fatigue loads and the corrosive marine atmosphere (Ref. 2).

A study was undertaken at the LaQue Center for Corrosion Technology, Inc. (LCCT) for two reasons. The first was to confirm corrosion fatigue as a plausible cause of failure of 41L40 fasteners in a marine environment. The second goal was to obtain corrosion fatigue data for three candidate replacement alloys.

EXPERIMENTAL

Materials

AISI 41L40 high strength steel was evaluated to characterize the corrosion fatigue strength of the material of construction of the failed stud. AISI 4140 was included for comparison. 41L40 is essentially a compositional variation of 4140 with Pb added for improved machinability.

Three candidate replacement alloys were included in the study on the basis of their anticipated higher corrosion fatigue strength. These alloys included PH 13-8 Mo stainless steel, alloy 718, and Mutiphase MP-35N^{TM}. All materials for test specimens were obtained as commerically produced ½ inch diameter rod stock products. Table I gives the sources, heat treatments and relevant specifications. Table II gives the compositions of the five materials. All compositions and heat treatments represent typical commercial production and primary manufacturers recommendations for high fatigue strength.

Mechanical properties were determined according to ASTM Standard Method E8 on "Tension Testing of Metallic Materials," from specimens selected from the stock of fatigue specimens. The mechanical properties are given in Table III.

Specimen Production

All specimens were machined to threaded end, reduced gauge section geometry as shown in Figure 3. Final heat treatments were performed after machining to avoid any residual stress effects from the machining operation. The specimen gauge section was ground to 320 grit just prior to testing. The grinding paper was rotated on a ¼ inch shaft perpendicular to the specimen axis while the specimen was rotated. As a result, all grinding marks on the specimen gauge section were in a longitudinal direction and not in the circumferential direction, where stress concentration could result during axial fatigue loading producing early failure and increased data scatter.

Apparatus and Test Parameters

All fatigue tests were performed in accordance with ASTM Recommended Practice E466 on "Constant Amplitude Axial Fatigue Tests of Metallic Materials," using an MTS^{TM} closed-loop servo-hydraulic fatigue testing system, as shown schematically in Figure 4.

The machine was operated in load control. The fatigue parameters were taken from the NASA stress analyses of the blade studs on the MOD-0A wind turbine operating under extreme conditions at high wind loads and rotating speeds. The fatigue wave form was a 20 Hz sine wave. All tests were conducted at a constant load ratio of minimum stress divided by maximum stress, R = 0.6. Figure 5 shows diagrammatically the stress cycle used.

All tests were conducted until failure or 10 million cycles occurred.

Environments

Two environments were utilized, air and natural seawater. Air was included as a comparative standard to determine the magnitude of the loss in fatigue strength due to the corrosive environment. Design fatigue data is typically generated in air, but little data is available for stress ratios near 0.6 and/or in marine environments.

The field failure at Kahuku Point was in a marine atmospheric environment with high levels of airborne chlorides available and high dew point conditions. The studs are partially covered by the hub fairing, eliminating washing of deposited chlorides by rainfall. The field environment was conservatively approximated by a drip feed of natural seawater which was temperature controlled to 30°C and applied to the horizontally configured specimen. Due to dryout conditions, the gauge section of the specimen was exposed to saturated marine salts on the edges of the gauge section and a thin layer of seawater at the center. Rubber washers were installed on the ends of the specimen during test to avoid galvanic effects of seawater contact on the threaded alloy 625 grips.

RESULTS AND DISCUSSION

Table IV summarizes the fatigue data obtained. The data are plotted as mean stress versus log cycles to failure (S-N) curves in Figures 6-10. As indicated, several specimens failed outside the test section in the machined threads - owing to the high stresses involved (with respect to the yield stress) and the notch acuity in the threads. Data from the specimens that failed in the threads was not included in the analysis.

The data were analyzed by non-linear regression analysis in which the data were fitted to equations of the form:

$$\log (S-Se) = m * \log (N) + b$$

were S is mean stress in ksi, N is cycles to failure, Se is a constant akin to an endurance limit, and m and b are regression constants. The resultant regression equations are given below along with the correlation coefficient, C (unity indicates perfect correlation):

41L40:	air	$\log (S-172) = -1.473 \log (N) + 8.310$ $C = 0.990$
	seawater	$\log (S-40) = -3.297 \log (N) + 22.216$ $C = 0.999$

4140: air $\log(S-150) = -2.119 \log(N) + 12.673$
$C = 0.902$

seawater $\log(S-0) = -0.2813 \log(N) + 3.598$
$C = 0.942$

PH 13-8 Mo: air $\log(S-0) = -0.02163 \log(N) + 2.288$
$C = 0.999$

seawater $\log(S-67) = -1.7491 \log(N) + 11.922$
$C = 0.999$

alloy 718: air $\log(S-0) = -0.01564 \log(N) + 2.242$
$C = 0.936$

seawater $\log(S-130) = -1.862 \log(N) + 11.182$
$C = 0.924$

MP-35N: air $\log(S-0) = -0.03169 \log(N) + 2.388$
$C = 0.998$

seawater $\log(S-120) = -0.7226 \log(N) + 5.668$
$C = 0.949$

Figures 6-10 show the above regression equations plotted in addition to the raw data. Good correlation was obtained, as indicated by both the correlation coefficient and the graphical S-N curve plots. The corrosion fatigue strength was estimated from the above equations by computing the mean stress for 10 million cycles life. These fatigue strength estimates are summarized in Table V for the five alloys in air and seawater.

41L40 shows the highest fatigue strength in air, but the lowest in seawater. The performance of 4140 is very nearly equal to that of the 41L40. Both alloys lose over 70% of their air fatigue strength in seawater. These results are consistent with other corrosion fatigue data reported for AISI 4130 steel in which the corrosion fatigue strength at R=-1 was 68% less than the air fatigue strength (Ref. 3).

PH 13-8 Mo has the next highest fatigue strength in seawater, but it still represents a greater than 50% reduction from the air fatigue strength. One cause for concern in the use of PH 13-8 Mo in critical corrosion fatigue application in seawater is its tendency toward pitting corrosion which can serve to concentrate stresses and provide early initiation of fatigue failure. Indeed, one test specimen experienced pitting corrosion and probable initiation of the corrosion fatigue fracture from the pit as shown in the SEM micrograph in Figure 11.

Alloy MP-35N showed significantly higher corrosion fatigue strength - almost double that of PH 13-8 Mo and triple that of 41L40. The fatigue strength in seawater was only 15% less than the air fatigue strength. With its highly alloyed composition (9% Mo), MP-35N is not considered susceptible to pitting corrrosion in seawater (Ref. 4). High resistance to crevice corrosion in seawater has also been reported (Ref. 5).

Alloy 718 had the highest corrosion fatigue strength of all five alloys. The corrosion fatigue strength was only 4% less than the air fatigue strength. Although some sensitivity to crevice corrosion has been reported, alloy 718 is not considered susceptible to pitting corrosion in typical seawater environments (Ref. 4, 6).

CONCLUSIONS

AISI 41L40 and AISI 4140 high strength steels are extremely susceptible to corrosion fatigue failure in marine environments. Fatigue strength can suffer losses of over 70% as compared to dry air.

PH 13-8 Mo can offer improved (versus 41L40 or 4140) corrosion fatigue performance in seawater but seawater can still reduce fatigue strength by over 50%. The observed susceptibility to pitting corrosion suggests extreme caution for critical corrrosion fatigue application in seawater.

Alloy 718 and Multiphase alloy MP-35N offer very good resistance to corrosion fatigue in seawater. Seawater corrosion fatigue properties of alloy 718 are very nearly equal to those in air.

When high strength alloys are required for critical fastener applications in marine applications, including marine atmospheres, careful attention must be paid to corrosion fatigue. All the advantage of high strength steel can be lost by reductions of up to 70% and more in fatigue strength by the marine environment.

As expected, high stress ratios further reduce corrosion fatigue strength. Engineering fatigue design for service in corrosive environments should include fatigue data generated in the corrosive environment.

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TABLE I

Sources and Heat Treatments of Alloys Tested

	Source	Heat No.	Heat Treatment	Specification
AISI 41L40	SKF Steels Charlotte, NC	8198055	1550°F/20 min oil quench + 825°F/2 hr air cool	ASTM A-304
AISI 4140	Aero Met, Inc. Englewood, NJ	6068769	1550°F/20 min oil quench + 825°F/2 hr air cool	MILS 5626
PH 13-8 Mo	Aero Met, Inc. Englewood, NJ	4X1924	1100°F/4 hr, air cool	--
alloy 718	Aero Met, Inc. Englewood, NJ	6L5792K14	1200°F/4 hr, air cool	AMS 5662D
MP-35N	Latrobe Steel Latrobe, PA	E3000	Cold drawn + 1100°F/ 4 hr, air cool	AMS 5844A

TABLE II

Composition of Alloys Tested

	C	Si	Mn	S	P	Cr	Ni	Mo	Co	Al	Ti	Fe	Other
AISI 41L40	0.41	0.23	0.84	0.032	0.008	0.97	--	0.17	--	--	--	Bal	0.15-0.35P
AISI 4140	0.40	0.22	0.88	0.018	0.008	0.97	0.10	0.20	--	--	--	Bal	
PH 13-8 Mo	0.030	0.01	0.01	0.004	0.002	12.61	8.25	2.21	--	1.10	--	Bal	
alloy 718	0.044	0.09	0.11	0.002	0.007	18.25	51.69	3.06	0.51	0.56	1.01	19.37	5.10 Cb+T 0.0041 B
MP-35N	0.009	0.03	0.02	0.003	0.003	20.94	35.38	9.39	Bal	--	0.79	0.16	

TABLE III

Mechanical Properties of Alloys Tested

Alloy	0.2% Yield Stress (ksi)	Ultimate Stress (ksi)	Percent Reduction in Area
AISI 41L40 steel	207	216	48.0
AISI 4140 steel	230	236	54.6
PH 13-8 Mo stainless steel	212	219	31.2
alloy 718	210	238	41.8
alloy MP-35N	288	303	15.7

TABLE IV

Summary of Corrosion Fatigue Data

Specimen Number	Material	Environment	Mean Stress* (ksi)	Cycles to Fail (megacycles)
G03AA1	41L40 Steel	Seawater	60	2.1297
G03AA4	41L40 Steel	Seawater	50	2.7100
G03AA5	41L40 Steel	Seawater	40	7.2208
G03AA6	41L40 Steel	Seawater	38	10.3498 NF
G03AA7	41L40 Steel	Seawater	65	2.1014
G03AA8	41L40 Steel	Air	155	2.1237 FT
G03AA9	41L40 Steel	Air	155	11.1548 NF
G03AA10	41L40 Steel	Air	160	10.0000 NF
G03AA11	41L40 Steel	Air	170	10.0000 NF
G03AA13	41L40 Steel	Air	180	0.1496
G03AA14	41L40 Steel	Air	175	0.1484
G03AA15	41L40 Steel	Air	172	10.0000 NF
G03AA16	41L40 Steel	Air	174	1.6292 FT
G02AA1	4140 Steel	Seawater	50	7.8861
G02AA2	4140 Steel	Seawater	45	5.6425
G02AA3	4140 Steel	Seawater	40	10.4342 NF
G02AA6	4140 Steel	Air	110	1.1399 FT
G02AA7	4140 Steel	Air	110	1.8247 FT
G02AA11	4140 Steel	Air	160	0.8098
G02AA12	4140 Steel	Air	140	10.0000 NF
G02AA13	4140 Steel	Air	150	5.7780
G02AA14	4140 Steel	Air	155	10.3585 NF
G02AA15	4140 Steel	Seawater	60	2.7135
G02AA16	4140 Steel	Air	158	0.2082
G02AA17	4140 Steel	Air	150	10.0000 NF
G02AA18	4140 Steel	Seawater	80	1.1786
S05AA1	PH 13-8 Mo	Seawater	70	3.3306
S05AA2	PH 13-8 Mo	Seawater	65	10.0000 NF
S05AA3	PH 13-8 Mo	Seawater	67.5	10.0000 NF
S05AA4	PH 13-8 Mo	Air	140	3.4383
S05AA5	PH 13-8 Mo	Seawater	80	10.0000 NF
S05AA6	PH 13-8 Mo	Air	120	10.0000 NF
S05AA7	PH 13-8 Mo	Air	150	0.1436
S05AA8	PH 13-8 Mo	Air	145	10.0000 NF
S05AA9	PH 13-8 Mo	Air	148	10.2160 NF
S05AA10	PH 13-8 Mo	Seawater	90	11.0980 NF
S05AA11	PH 13-8 Mo	Seawater	100	0.9077
S05AA12	PH 13-8 Mo	Air	145	0.7397

TABLE IV (continued)

Summary of Corrosion Fatigue Data

Specimen Number	Material	Environment	Mean Stress* (ksi)	Cycles to Fail (megacycles)
N01AA3	alloy 718	Seawater	120	10.1710 NF
N01AA4	alloy 718	Air	130	4.3370 FT
N01AA5	alloy 718	Seawater	140	0.2922
N01AA6	alloy 718	Seawater	150	0.5801
N01AA8	alloy 718	Seawater	130	9.7968
N01AA9	alloy 718	Air	140	1.3255
N01AA10	alloy 718	Air	135	10.2210 NF
N01AA11	alloy 718	Air	137.5	7.0742
N01AA12	alloy 718	Seawater	132.5	0.4633
N01AA13	alloy 718	Air	145	10.0000 NF
N01AA14	alloy 718	Seawater	135	0.2408
M01AA1	MP-35N	Seawater	200	0.2214
M01AA2	MP-35N	Seawater	160	0.4907
M01AA3	MP-35N	Seawater	180	0.1654
M01AA4	MP-35N	Seawater	140	1.5515
M01AA5	MP-35N	Seawater	130	1.9234
M01AA6	MP-35N	Seawater	120	10.0000 NF
M01AA7	MP-35N	Air	135	10.0000 NF
M01AA8	MP-35N	Air	150	5.3951
M01AA9	MP-35N	Air	147.5	7.9713
M01AA14	MP-35N	Air	160	0.6419

NOTES:

* All tests were performed at R = min. stress/max. stress = 0.6, wave form, and 20 Hz frequency

NF - Removed from test; did not fail

FT - Failed in threads at notch

TABLE V

Summary of Fatigue Strength

Material	Fatigue Strength (mean stress) @ 10^7 cycles, ksi		% Reduction
	Air	Natural Seawater	
AISI 41L40	172.0	39.7	76.9
AISI 4140	150.0	42.5	71.7
PH 13-8 Mo Stainless Steel	136.9	67.5	50.7
alloy 718	135.8	130.0	4.3
alloy MP-35N	146.7	124.1	15.4

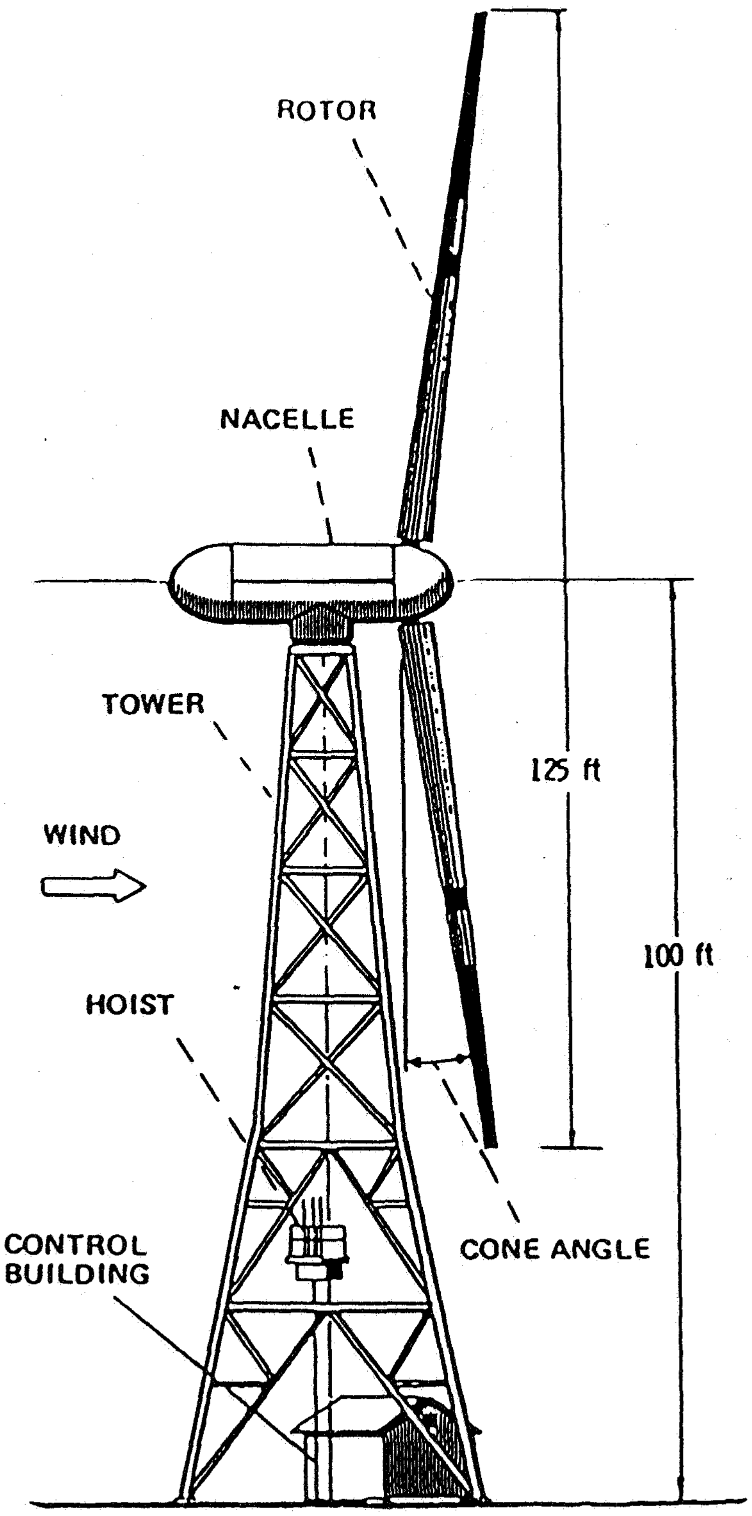


Figure 1. MOD-OA wind turbine.

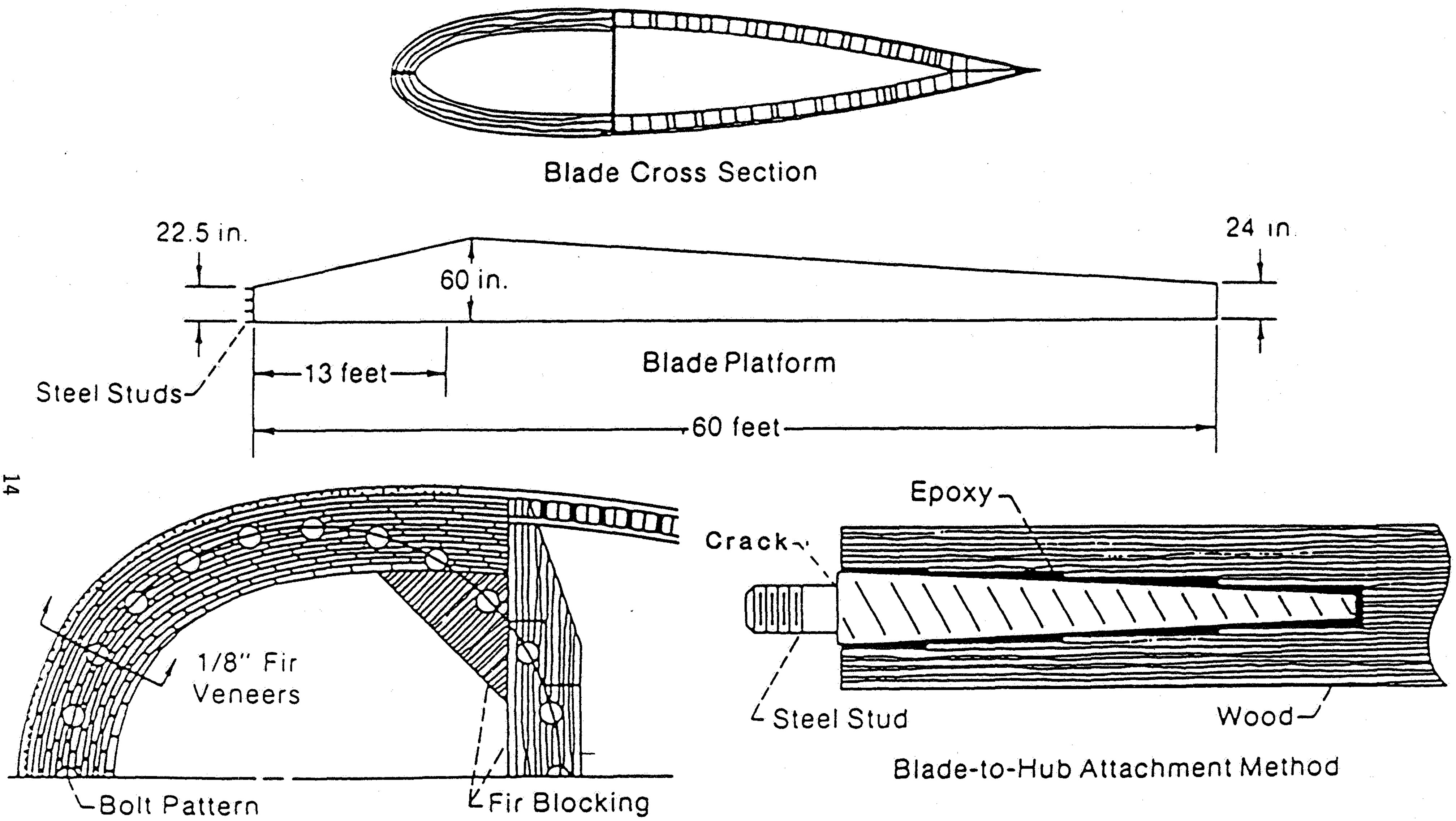
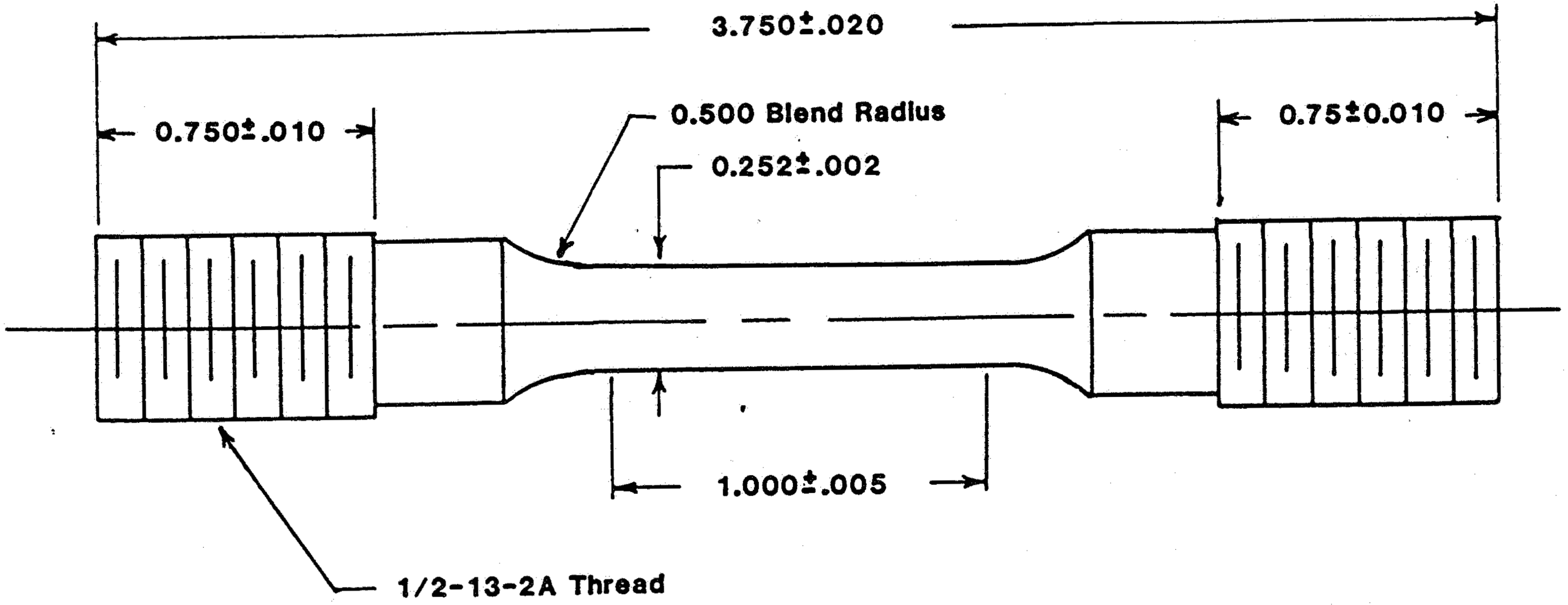


Figure 2. Blade-to-hub attachment stud configuration.



All dimensions in inches
No undercutting in gage section
No machine marks visible at 20X

Figure 3. Specimen geometry.

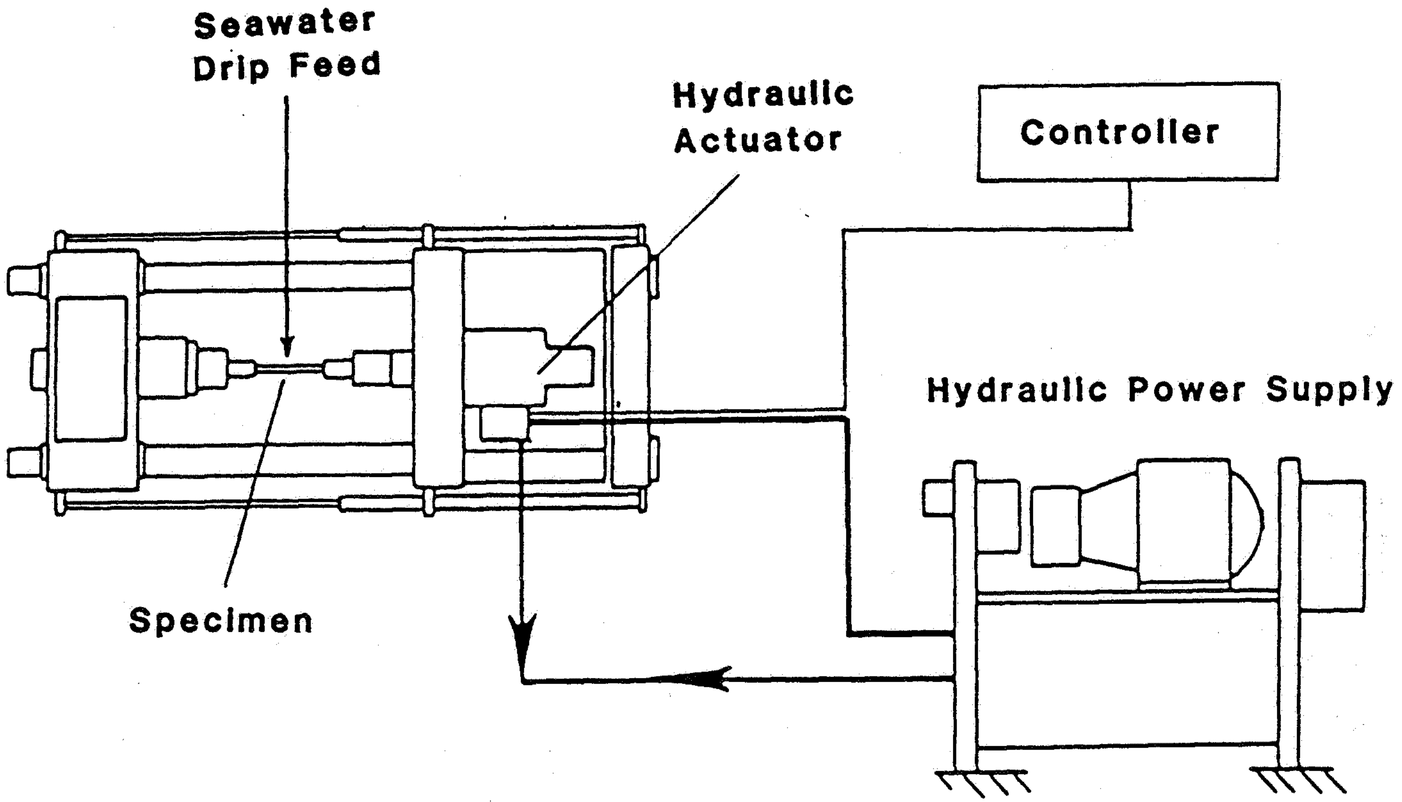


Figure 4. Schematic of fatigue test apparatus.

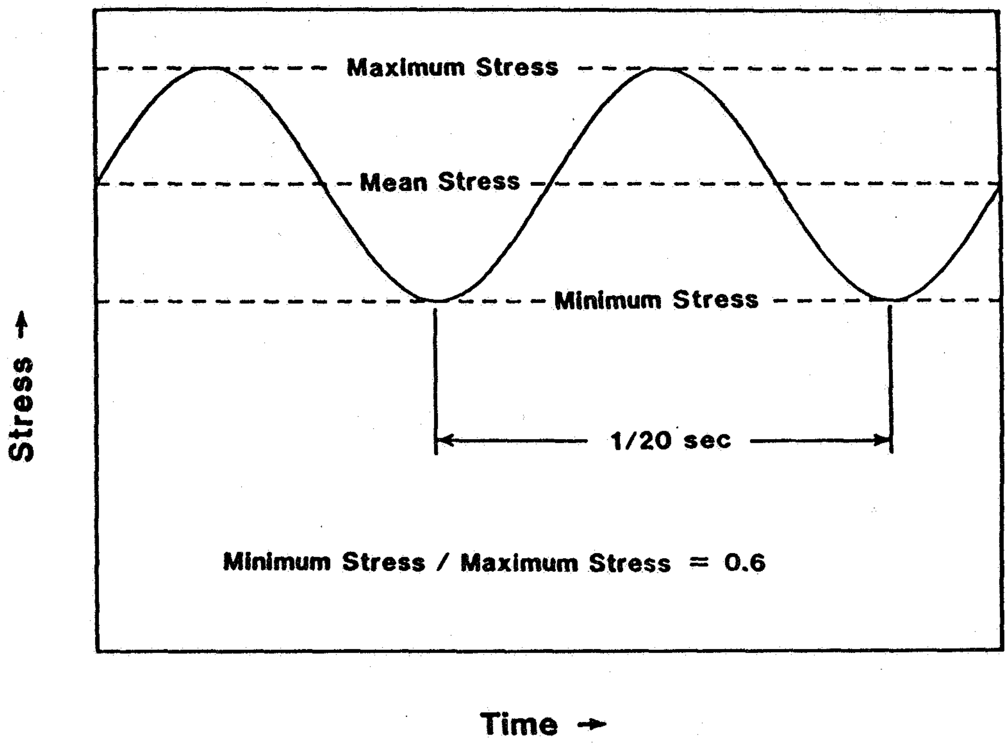


Figure 5. Diagram of fatigue cycle.

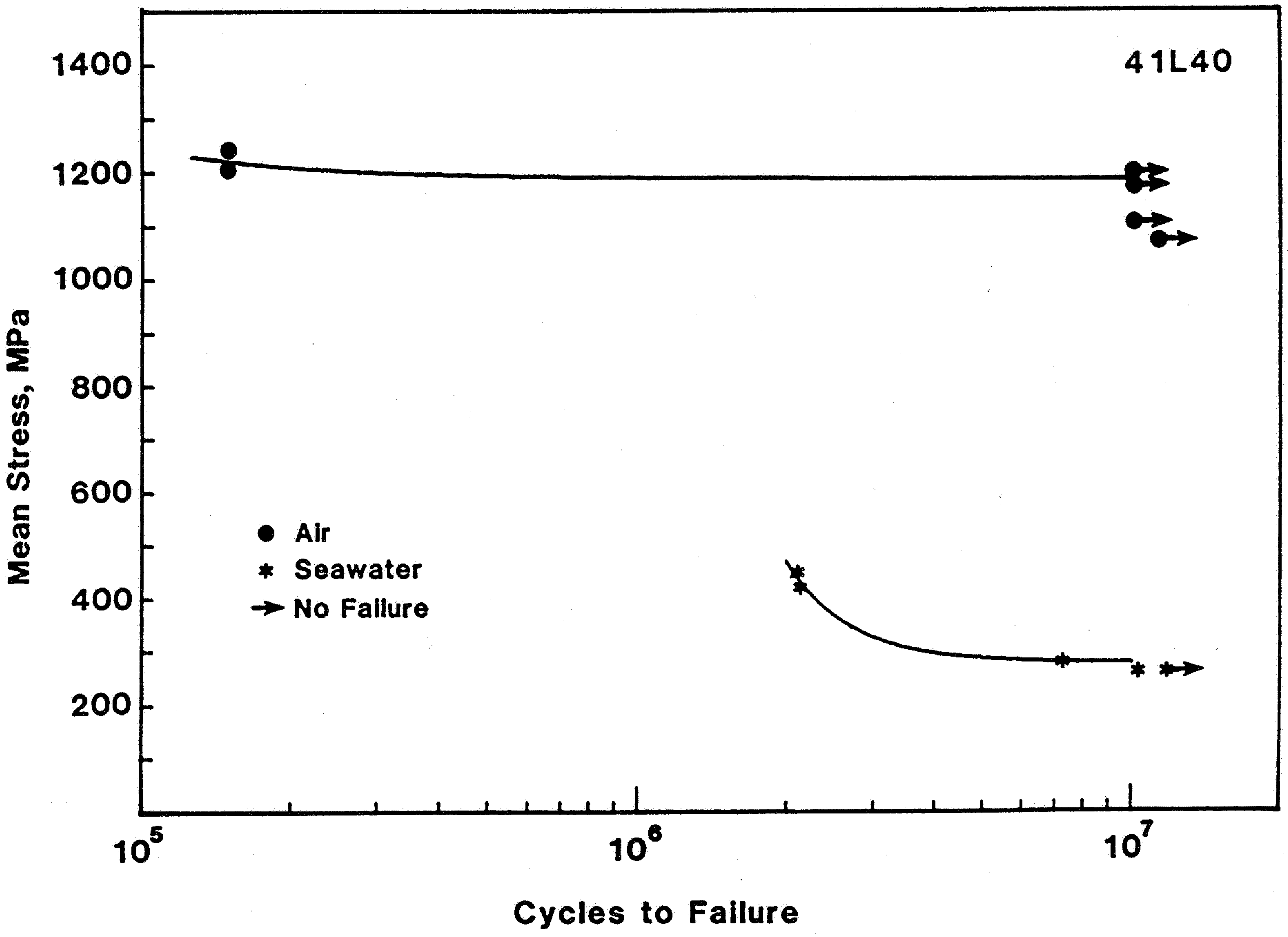


Figure 6. Corrosion fatigue behavior of AISI 41L40 steel in natural seawater.

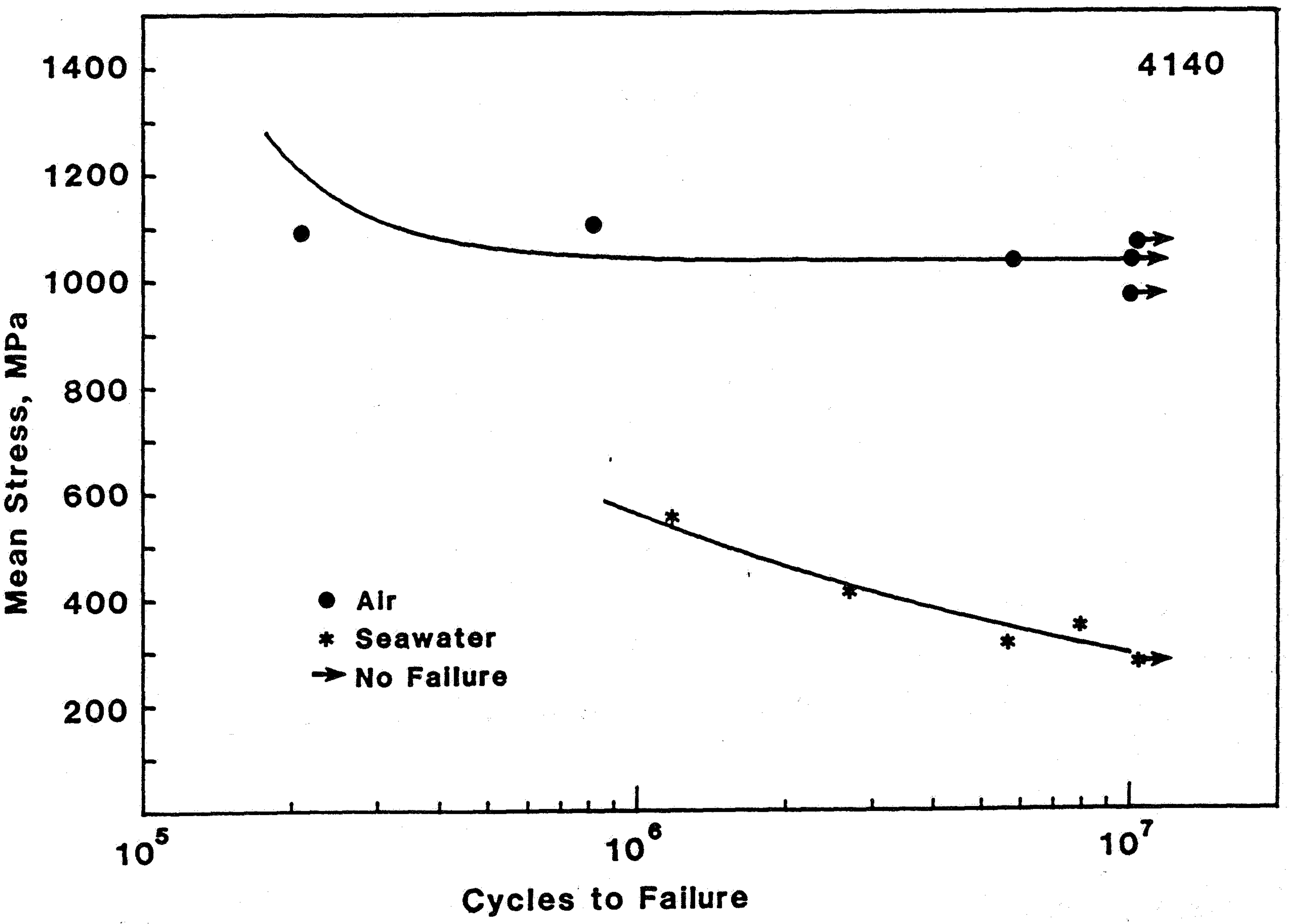


Figure 7. Corrosion fatigue behavior of AISI 4140 steel in natural seawater.

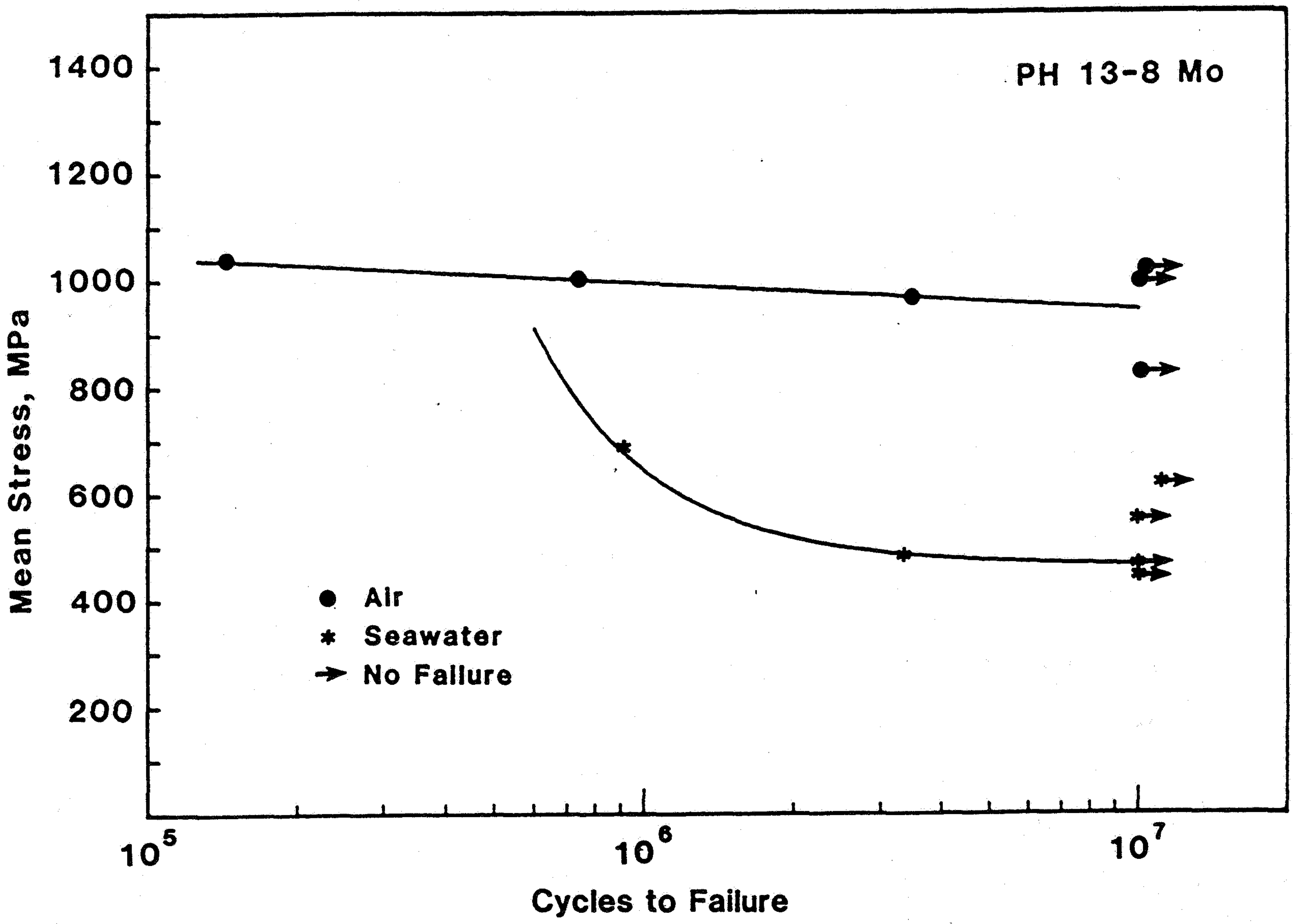


Figure 8. Corrosion fatigue behavior of PH 13-8 Mo stainless steel in natural seawater.

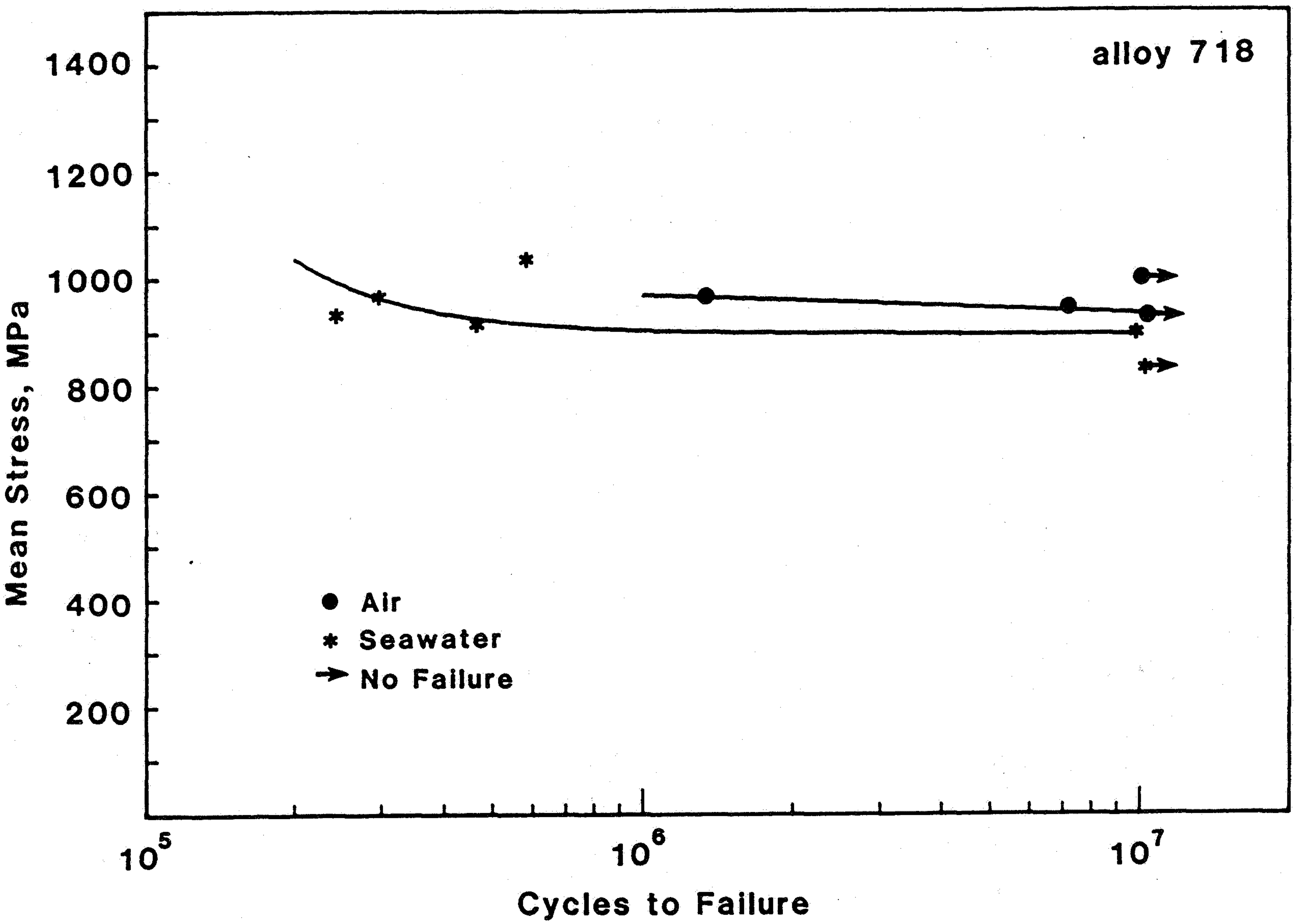


Figure 9. Corrosion fatigue behavior of alloy 718 in natural seawater.

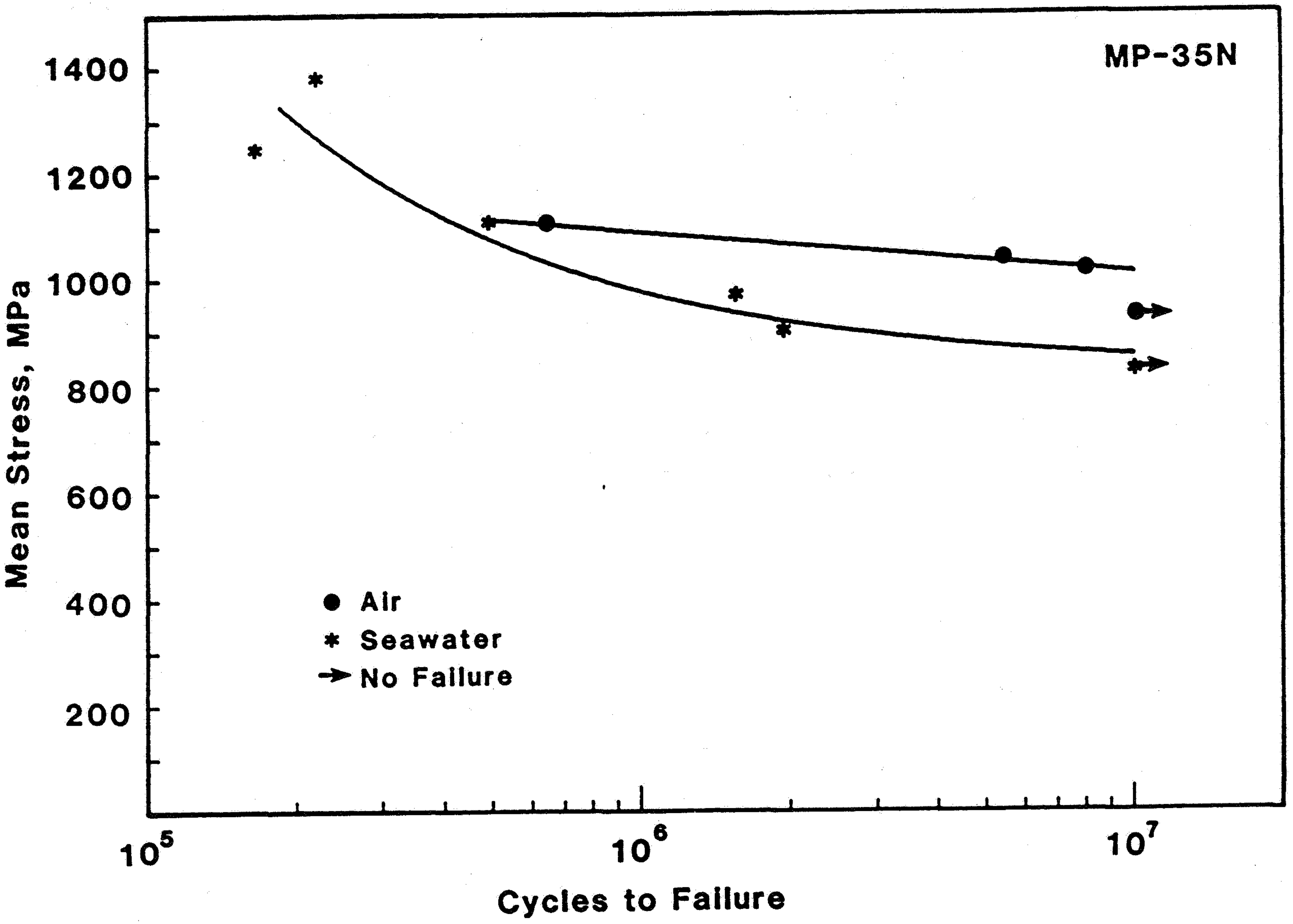
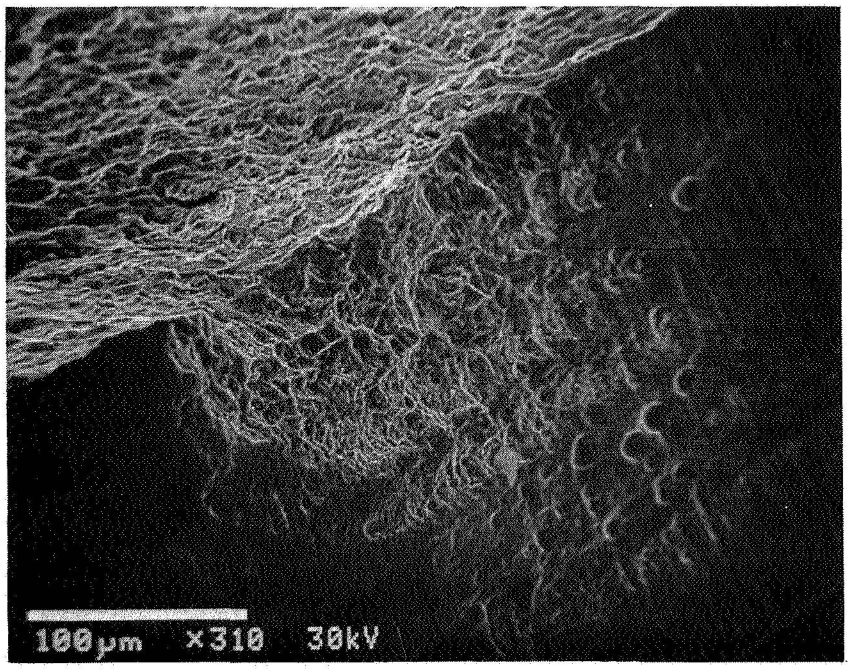


Figure 10. Corrosion fatigue behavior of alloy MP-35N in natural seawater.



SEM 277

Figure 11. Fractograph of corrosion fatigue specimen of PH 13-8Mo in seawater. Top left is fracture surface. Lower right is circumferential surface of fatigue specimen. Note pitting corrosion at fracture interface.

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16. Abstract
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