NATIONAL BUREAU OF STANDARDS REPORT

9488

The Effect of Surface Reactions On Fatigue Failure

by

T. R. Shives and J. A. Bennett

U. S. DEPARTMENT OF COMMERCE
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National Aeronautics and
Space Administration
Contract No. R-14

Summary

The effects of oxygen and water vapor on the fatigue properties of titanium alloy Ti-4Al-4Mn and vacuum melted AISI 4340 steel were investigated by means of rotating beam tests of unnotched specimens in four environments; dry helium, dry air, moist helium and moist air. The fatigue strength of both alloys was lower in moist environments than in dry environments. Oxygen was detrimental to the fatigue strength of both alloys only in the absence of water vapor. A large number of the steel specimens failed due to fatigue cracks having origins below the specimen surface.

Introduction

This project was designed to determine the influence of water vapor and oxygen, both independently and together, on the fatigue properties of two engineering alloys. Previous work had shown that water vapor in the presence of air had deleterious effects on the fatigue properties of several alloys, two of which were selected for this investigation. Rotating beam fatigue tests were conducted on titanium alloy Ti-4Al-4Mn and on vacuum melted AISI 4340 steel

in both moist and dry air and in both moist and dry helium.

Materials and Testing Procedures

Analyses, conditions of materials, and tensile strengths of the materials used in this investigation are listed in Table I. The tensile strength value for the titanium alloy was obtained by G. W. Geil and N. L. Carwile for the same batch of material during another investigation (1).

The fatigue specimens were of the R. R. Moore type with smooth reduced sections. The titanium specimens had straight shanks (figure 1a) and the steel specimens had tapered shanks (figure 1b). In each case the diameter of the reduced section was nominally 0.200 in (0.508cm.).

The titanium specimens were finish machined with a lathe cutting tool and then wet polished longitudinally on abrasive paper, the final polish being obtained with No. 400 paper. The steel specimens were rough machined with a lathe cutting tool, heat treated, then ground to approximately the final diameter, the grinding wheel being parallel to the length of the specimen. Polishing was also done longitudinally, using emery tape without lubricant, the final polish being obtained with 000 grade paper. After polishing, all specimens were washed successively in two containers of high purity benzene. The diameters were then measured and the specimens were stored in a third container of benzene until tested.

Fatigue tests were conducted on R. R. Moore rotating beam machines which apply a uniform bending moment with a constant stress amplitude. Machine speeds were maintained at about 9000 rpm and tests were conducted at room temperature. During testing, there was a maximum temperature rise of about 20 C in specimens involved in long fatigue life tests. This was due to a large extent to heat, generated in the bearings of the bearing boxes, being transmitted to the specimen.

Specimens of both materials were tested under four atmospheric conditions as follows:

1. Dry air
2. Moist air
3. Dry helium
4. Moist helium

In order to obtain the dry atmospheres, the gases were passed through four drying towers containing silica gel and then through a cold trap containing a mixture of trichloroethylene and chloroform cooled with dry ice. This produced gases containing from 30 to 50 ppm water vapor. Moist atmospheres (above 85 percent relative humidity) were obtained by bubbling the gases through heated distilled water. In addition, the helium was passed through two titanium getters to remove oxygen (maximum oxygen 0.02 mole per cent).

Results and Discussion

a) Ti-4Al-4Mn

The fatigue results for the titanium alloy specimens are shown

in figure 2 and in Tables II and III. In the figure, each point in the finite life region of the curve is the median of five values. The staircase method (2) was used to determine the fatigue limits with sixteen specimens being used for each condition. Intervals were taken at one ksi.

In the finite life region specimens tested in dry helium had approximately double the life of those specimens tested in moist atmospheres. The slopes of the S-N curves are quite steep. The fatigue strength of the material tested in dry helium is approximately ten to thirteen percent greater than that for specimens tested in both moist air and moist helium in the finite life region. Specimens tested in dry air exhibited fatigue strengths intermediate to the strengths of those tested in dry helium and in both moist helium and moist air. There was essentially no difference between test results in moist air and moist helium in the finite life region.

In the fatigue limit region, there was only about a six percent difference between the highest and lowest values. Again, specimens tested in dry helium exhibited the best fatigue properties, while results from tests conducted in dry air were only slightly poorer. Moist helium atmosphere tests produced the lowest fatigue limit.

It would appear from the data presented here that the presence of water vapor is definitely detrimental to the fatigue properties of titanium alloy Ti-4Al-4Mn. The effects of oxygen are not so clearcut. In the presence of water vapor, oxygen had no discernible effect in the finite life region of testing, but

oxygen seemed to improve the fatigue limit in the presence of water vapor, although not greatly. The fatigue limit for specimens tested in moist air was about two to three percent greater than that for specimens tested in moist helium.

In the absence of water vapor, oxygen had a detrimental effect on the fatigue properties of this alloy over the entire range of testing, but again the effect was relatively small, especially in the fatigue limit area.

If the average results from both dry conditions are compared with the average results from both moist conditions, testing under dry conditions produced a four percent higher fatigue limit. While this difference is small, it indicates a definite adverse effect of water vapor on the fatigue limit of Ti-4Al-4Mn.

There is essentially no difference between the average fatigue limits for both series of tests in helium and both series in air indicating a negligible effect of oxygen in the fatigue limit area.

The effect of oxygen and water vapor together or separately on the fatigue properties of Ti-4Al-4Mn is quite small, and water vapor is more detrimental than oxygen. The effects of water vapor and oxygen are not additive.

b) Vacuum Melted AISI 4340 Steel

Fatigue tests were conducted on the steel in a relatively high strength condition ($52R_c$). The results for all of the specimens tested are given in Table IV.

Approximately three eights of the steel specimens failed due to a fatigue crack which originated below the surface at an inclusion (indicated by * in Table IV). The distance of these sources from the specimen surface ranged from 0.0007in (0.0018cm) to 0.010in (0.025cm) with the average being 0.0035in (0.0089cm). There is apparently no relationship between the distance of the crack source from the specimen surface and the specimen life. Obviously, the environment could not affect the initiation of the crack in these specimens, and would affect crack propagation only after the crack had broken through to the surface. As this portion of the life is relatively short, it is essentially correct to say that the life of specimens with sub-surface crack origins is unaffected by the environment. The values from these specimens therefore tend to cloud the effects that are being sought, as one can say that failure from a surface source would have required a larger number of cycles than were actually observed.

The data of Table IV are shown graphically in figure 3. Because of the large dispersion of the results, the only points plotted are the median values for groups of seven specimens tested at the same stress amplitude.

An arrow adjacent to a point indicates that the true median value is greater than that plotted because the median or some smaller value was observed on a specimen with a sub-surface origin. There does not appear to be any completely valid statistical method for obtaining an estimate of the true median for these sets of data, as each sample is distorted by members of a second population,

specimens with sub-surface origins. The characteristics of this population as far as fatigue failure from surface originating cracks are also unknown.

As the environment has essentially no effeot on the life of a specimen in which the crack initiates below the surface, data from such specimens for all environmental conditions can be considered together. It appears that the S-N curve for specimens with sub-surface crack origins is not far different from that for specimens tested in dry helium as one would expect from the large proportion of sub-surface origins in dry helium tests. If this conclusion is correct it means that this environment has eliminated all of the atmospheric constituents that have a significant deleterious effect on the fatigue strength of steel.

Conclusions

1. Water vapor in the absence of oxygen as well as in the presence of oxygen is detrimental to the fatigue properties of titanium alloy Ti-4Al-4Mn and vacuum melted 4340 steel, but not to a great extent.
2. Oxygen is detrimental, but to a lesser extent than water vapor, to the fatigue properties of both titanium alloy Ti-4Al-4Mn and 4340 steel in the absence of water vapor.
3. In the presence of water vapor, oxygen has little or no effect on the fatigue properties of either alloy.
4. Specimens with sub-surface fatigue crack origins have essentially the same fatigue strengths as those specimens tested in dry helium.

References

1. Geil, G. W., and Carwile, N. L.: Effect of Strain-Temperature History on the Tensile Behavior of Titanium and a Titanium Alloy. Journal of Research, National Bureau of Standards, Vol. 61, No. 3, September 1958, p. 173.

2. A Guide for Fatigue Testing and the Statistical Analysis of Fatigue Data; ASTM Special Technical Publication No. 91-A (Second Edition) 1963.

Table I. Materials

Material	Condition	Analysis(a)	Tensile Strength Ksi	Tensile Strength MN/m^2
Titanium Alloy Ti-4Al-4Mn	Hot rolled, annealed	Al 4.2% Mn 3.8 C < 0.1 H_2 0.006ppm N_2 0.02	149	1027
Vacuum Melted AISI 4340 Steel	Quenched in oil from 1500F Tempered 400F 75 minutes 52 R_c	C 0.38% Mn 0.59 P 0.004 S 0.001 Si 0.27 Ni 1.80 Cr 0.77 Mo 0.28 Cu 0.10 V < 0.01 H_2 4.4ppm N_2 53 O_2 6.3	298	2055

(a) Analysis by producer for titanium; analysis by NBS for steel.

Table II

Fatigue Test Tesults Ti-4Al-4Mn

S_A		Kilocycles to fracture			
Ksi	MN/m^2	Dry Helium	Moist Helium	Dry Air	Moist Air
117	807	38			
		41			
		42			
		51			
		64			
114	786			37	
				37	
				38	
				39	
				39	
112	772		22		20
			25		23
			26		24
			28		29
			31		40
109	752	69			
		72			
		80			
		119			
		148			
108	745			47	
				47	
				49	
				60	
				63	
100	689		33		59
			50		61
			60		71
			3837 →		14658 →

→ denotes runout (26×10^6 cycles without failing).

Table III

Fatigue Limit Data for Ti-4Al-4Mn

Stress Amplitude Ksi	MN/m^2	Condition	No. of spec.	% runouts
100	689	Dry Helium	4	0
99	683		8	50
98	676		4	100
96	662	Moist Helium	2	0
95	655		4	50
94	648		5	20
93	641		4	75
92	634		1	100
99	683	Dry Air	3	0
98	676		8	37.5
97	669		5	80
97	669	Moist Air	3	0
96	662		3	100
95	655		4	25
94	648		5	80
93	641		1	100

Table IVa

Fatigue Test Results Vacuum Melted
AISI 4340 Steel in Dry Atmospheres

S_A Ksi	S_A MN/m^2	Kilocycles to Fracture Dry Helium	Kilocycles to Fracture Dry Air
180	1241	20	
		26	
		28	
		29	
		32	
		34	
		36	
160	1103	157*	49
		249*	62
		270	66
		394*	203
		592*	210*
		792*	278*
		945*	295
150	1034		166*
140	965	113	55
		298	96
		453*	146
		2792*	868*
		3495	3037*
		8217*	3386*
		12468*	23376*
130	896		11044
129	889		1928*
			12083
128	883		5693*
			10057*
			⟶
127	876		⟶

⟶ denotes runout (26×10^6 cycles without failing).

* denotes failure due to sub-surface crack origin.

Table IVB

Fatigue Test Results Vacuum Melted
AISI 4340 Steel in Moist Atmospheres

S_A		Kilocycles to Fracture	
Ksi	MN/m^2	Moist Helium	Moist Air
150	1034	40	35
		41	36
		44	39
		50	51
		104	98
		454	132
		2946*	918
130	896	92	52
		94	130
		105	228
		126	683*
		189	3855
		11103*	7839
		18718*	20273*
125	862	100	19615
		123	
		147	
		170	
		188	
		24550*	
		→	
124	855		18582*

→ denotes runout (26×10^6 cycles without failing).

* denotes failure due to sub-surface crack origin.

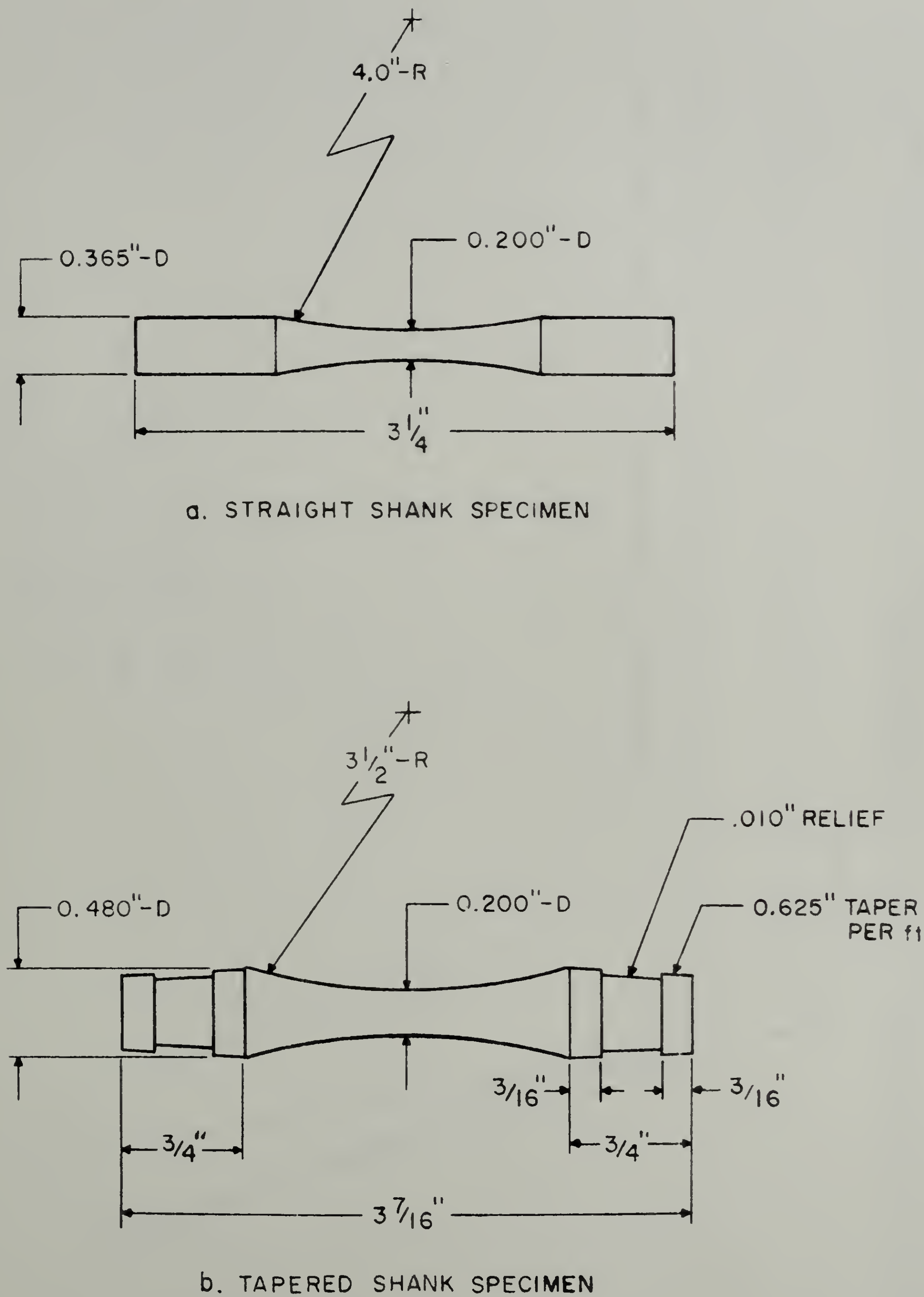

Figure 1

Fatigue Specimens

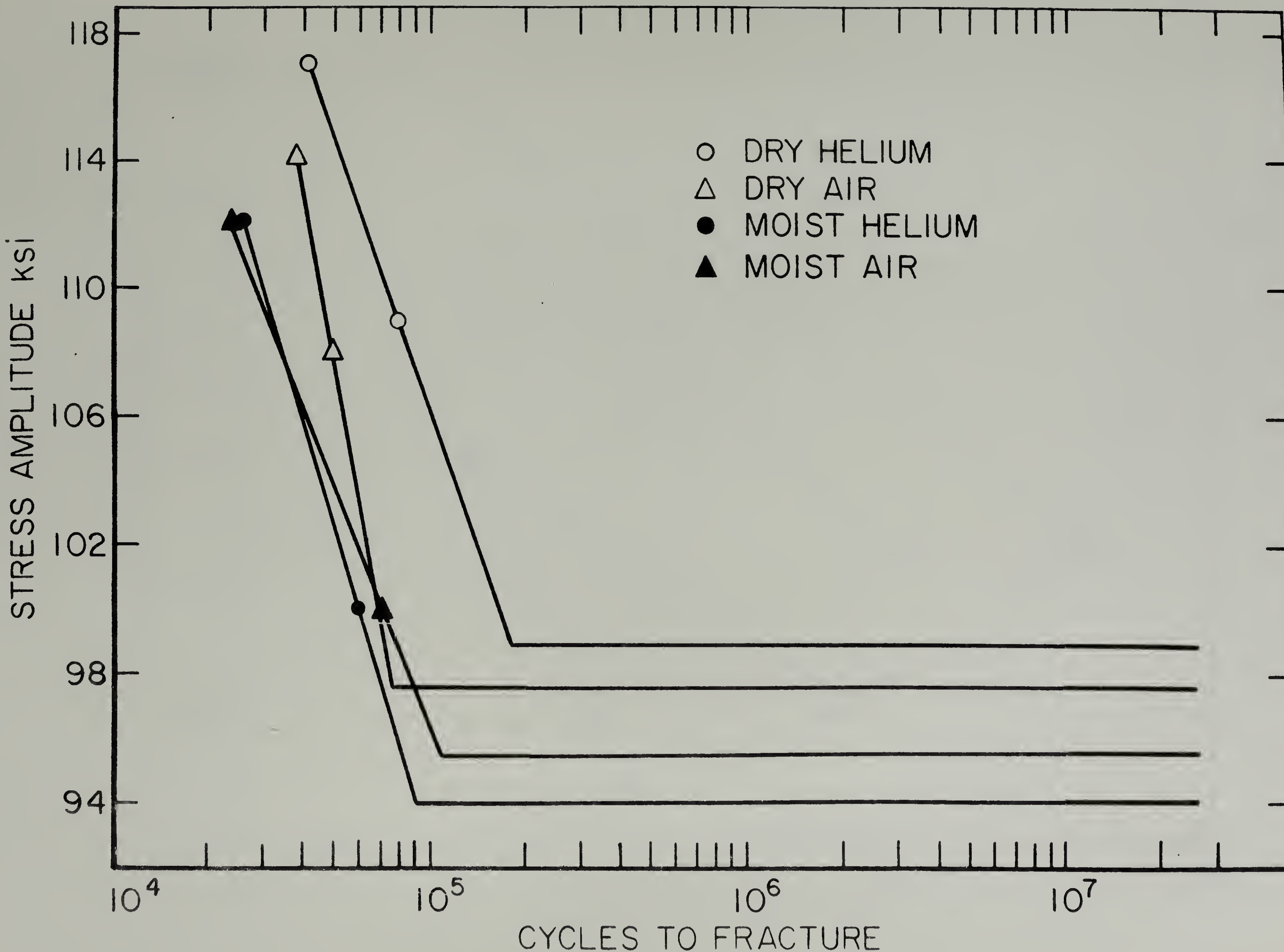

Figure 2

Effect of Environment on Fatigue Strength of Ti-4Al-4Mn

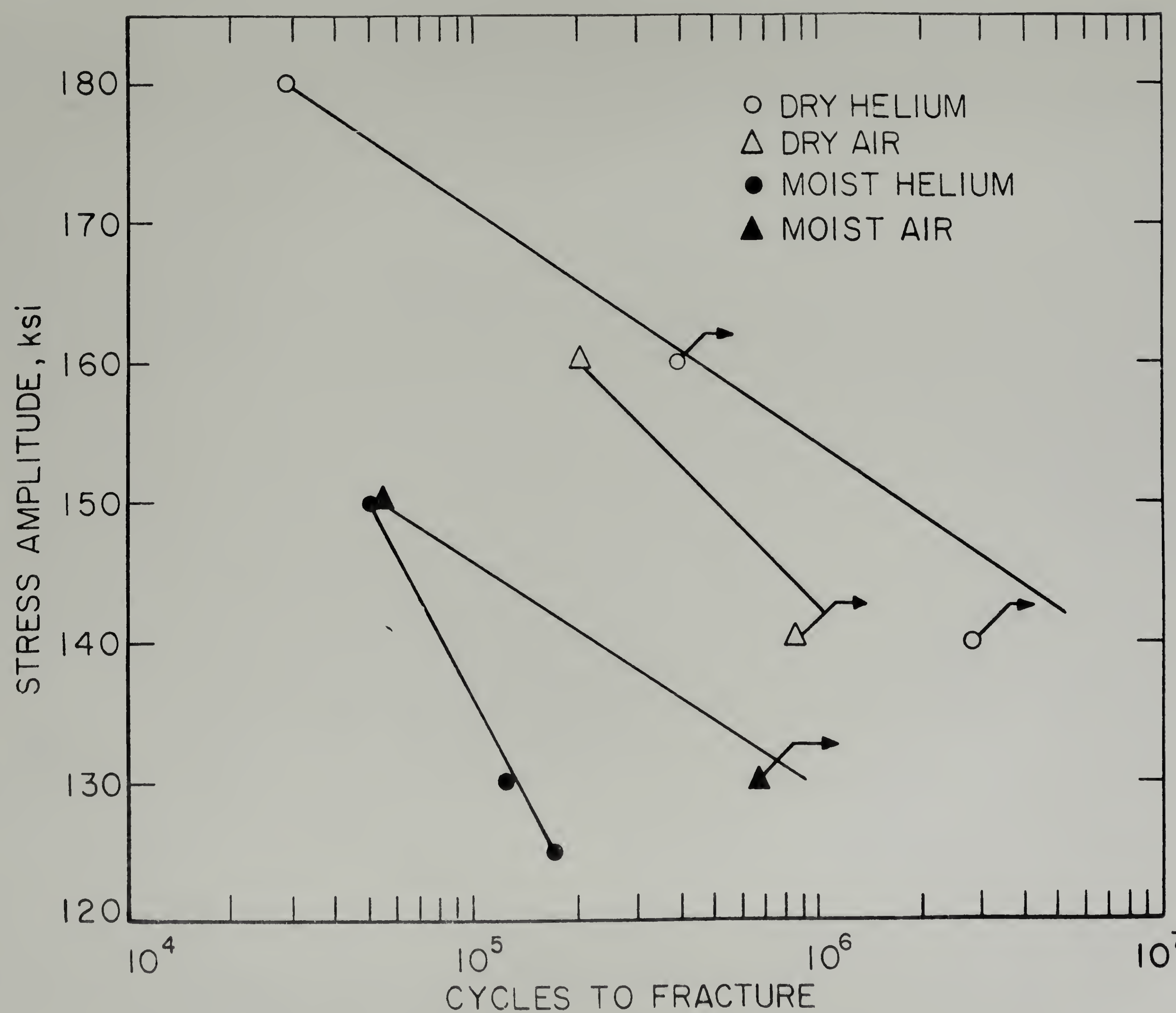

Figure 3

Effect of Environment on Fatigue Strength of 4340 Steel

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