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Stress Corrosion Behavior of Selected Types of Stainless Steels and Titanium Alloys in a Marine Environment

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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

STRESS CORROSION BEHAVIOR OF SELECTED TYPES OF STAINLESS STEELS AND TITANIUM ALLOYS IN A MARINE ATMOSPHERE

W. F. Gerhold and E. Escalante

REference: (a) Naval Air Systems Command (Bureau of Aeronautics) Aer-AE-413/121 Letter dated 23 December 1958).

INTRODUCTION

A major problem encountered in the operation of aircraft at supersonic speeds is the aerodynamic heating caused by friction between air and the external surfaces of the aircraft. At the high speeds such as are presently being encountered in certain military aircraft, this heating is great enough to produce temperatures in excess of the safe operating temperatures of certain aluminum alloys and other materials which had formerly been used in airframe construction. In order to insure safe operation at elevated temperatures, it became necessary to select materials which were capable of retaining high strength at the temperature produced by aerodynamic heating. Alternate materials were titanium base alloys, austenitic stainless steels and tool steels.

One of the primary requirements for aircraft structural materials is formability for the particular application involved. The materials must have the necessary strength at both room temperature and elevated temperatures. They must be in the softened condition for ease of fabrication and must be capable of being hardened after fabrication to obtain higher strength. The hardening treatment is often a limiting factor. Distortion in hardening, excessive oxidation or pickling of formed parts may preclude the use of a material.

While high strength is of utmost importance, since tension as well as compression strength is required over a wide temperature range for long periods of time, the material must also be free of excessive embrittlement, have adequate corrosion resistance, and be insensitive to stress corrosion cracking.

Until recent years, the combination of high strength, corrosion resistance and good resistance to stress corrosion cracking in standard chromium-nickel stainless steels could only be produced by cold working. More recently, there has been developed a group of steels commonly called age-hardening or precipitation-hardening stainless steels.

The vast majority of stress-corrosion literature is confined to tests conducted in various aqueous solutions(1). For mechanistic studies this approach is ideal. For more practical applications, actual environmental studies are more suitable and some studies have included atmospheric tests.(2,3,4) Recent failures in space vehicles has again brought to the forefront the importance of studies that simulate actual operating conditions.(5,6)

Since relatively little information was known about the long-term stress corrosion and corrosion behavior of these materials, Reference (a) requested NBS to conduct tests in the marine atmosphere to determine their corrosion and stress corrosion behavior. Included in this study also were several titanium base alloys and a magnetically soft Fe-Al-Si alloy generally used for electrical applications. This report contains the results obtained for these materials after exposure in the marine atmosphere for up to twelve years.

EXPERIMENTAL

All tests were conducted in the marine atmosphere at Kure Beach, North Carolina (80-foot and the 800-foot stations). Specimens were stressed by one of two methods, i.e., constant load (lever system) or constant strain (bent beam system).

From the standpoint of stress analysis the constant load lever system is the simplest way to apply a load to the specimen. However, it requires somewhat cumbersome and costly equipment. Stressing the specimen a predetermined amount is simply a matter of obtaining the stress vs. strain characteristics of the material and then applying the desired load to the specimen. The specimen is normally machined so that it has a reduced section where failure is most likely to occur.

In order to expose a large number of stressed specimens in a given area at a minimum of expense, the constant strain, bent beam system was used for sheet materials wherever possible. The distance between the two constraining points (slots) on the specimen holder (jig) is a constant for a given material and is dependent on the stiffness of the material. In this case determining the stress is somewhat more complicated. As before, the stress-strain relationship is determined and from this the yield strength is obtained. The approximate length of the specimen to produce the desired stress for a jig of fixed length is then calculated using methods described elsewhere(7). A specimen is machined to this calculated length, then placed in the jig where strain gages at the mid-point on the specimen are used to determine the actual stress. Once the specimen length which will give the desired stress is determined, a series of specimens are machined to various lengths. The stress for these specimens when placed in the jig is determined using the same method described above. A curve can then be drawn by plotting strain vs. specimen length (Figure 1). From this curve a specimen length can be selected which will produce the desired stress on the specimen. Calibration curves of the type shown in Figure 3 were made for each alloy and thickness for materials to be stressed using the bent-beam system. Typical curves for selected materials are shown in Figures 2, 3 and 4. Specimens were originally cut from the sheet material in strips 1-1/8"x9". These were then further machined by removing 1/16" (approximately) from each edge to a final width of 1"± 0.001" such that the edges were parallel to each other and the ends were normal to the edges and parallel to each other. Burrs were removed from the edges by using fine emery papers. Specimens were further machined by removing sufficient material from one end of the specimen to give the length for the desired stress.

All of the specimens were degreased in trichlorethylene, chemically cleaned with inhibited phosphoric acid, rinsed in distilled water and air dried. They were then heat treated in accordance with the treatments given in Table 2.

Following heat treatment, the specimens were wet grit blasted to remove any oxides that might have formed during heat treatment. Specimens were then rinsed in distilled water and air dried. During the entire specimen preparation procedure including loading and placement at the test site, care was taken at all times to handle the specimens with clean gloves. This procedure was carried out for all specimens in this study.

The predetermined stress was applied to the specimens just prior to placing them on the exposure racks. In the case of the constant load lever system, this was simply a matter of applying sufficient weight to the lever arm. For the bent beam system the specimen had to be bent just enough to allow it to be placed in the holder in its constrained position. For this purpose a special adjustable tree-point jig was designed and built which facilitated this process.

MATERIALS

Two groups of materials were investigated and will be discussed separately. The first group includes the ferrous alloys, while the second group includes only the titanium base alloys.

Ferrous Alloys: Table 1 is a compilation of the ferrous alloys and their nominal chemical compositions. All materials, in this table, except for one, are of the age hardenable type. These materials can be classified according to their more common metallurgical structures. The first includes the austenitic stainless steels, A286 and HNM. Both of these alloys work harden readily. However, their principal mode of strengthening is through aging. Table 2 lists the heat treatment used for the ferrous alloys. Neither alloy is prone to over-aging as evidenced by the higher temperature and longer time used for precipitation hardening.

The second includes the semiaustenitic alloys. They are referred to as semiaustenitic because of their dual structure which is austenitic in the annealed condition and martensitic in the hardened condition. As a whole, their heat treatment is more complicated since some of these alloys derive their strength through martensitic transformation which may involve subcooling or cold work plus some age hardening treatment or some combination of these. AM 350 is an example of an alloy where three completely different heat treatments have been used for hardening.

The third is the martensitic stainless steels which as their name implies derive their strength from a martensitic transformation on cooling. Additional heat treatment through aging increases the strength of these alloys.

The fourth in this group of ferrous alloys is made up of the one alloy which is not a precipitation hardenable stainless steel but is valuable because of its resistance to high temperature oxidation. This is called modified thermenol and its high resistivity and low oxidation characteristics make it valuable for electrical applications.

Titanium Alloys: The nominal composition and heat treatment of the titanium base alloys are given in Table 3. These alloys are subdivided according to the crystal structure.

The first is a single phase, alpha type alloy having a hexagonal structure. It is the A110 AT titanium alloy which is not hardenable by heat treatment. To increase its strength this alloy is normally hot rolled and then stress relieved. Forming is done above room temperature.

Two-phase, alpha-beta type alloys comprise the second subdivision in Table 3. The second phase, beta, imparts some beneficial characteristics to these materials. Being body centered cubic, the beta phase allows limited cold forming to be carried out. When the alloy is solution heat treated and quenched, subsequent aging treatments increase its strength.

The last is titanium alloy B120 VCA which has an all-beta type structure. This beta is meta-stable at room temperature and, thus, lends itself to heat treatment. The alloy has outstanding cold forming characteristics. This alloy is normally used in a solution heat treated and aged condition.

RESULTS

Stress Corrosion Behavior - Distance from Shore

A portion of the recent results of this study obtained at 75% of the yield strength are listed in Table 4. Data is given in this table for the two sites (80-foot and the 800-foot from the ocean at Kure Beach, North Carolina). This work is still continuing for these specimens listed as not having failed, unless otherwise specified.

Both precipitation hardening austenitic stainless steels have shown excellent resistance to stress corrosion cracking. No failures have been observed in almost thirteen years of exposure. This is in agreement with other published reports for this class of materials(2,3,Bloom). Distance from shore has no effect on its susceptibility to failure as can be seen in the table. It is pertinent to point out that both austenitic alloys in this study were fairly low strength and were not cold worked after solution heat treatment. Strength was obtained through precipitation hardening.

The semiaustenitic precipitation hardening stainless steels are quite variable in their stress corrosion behavior when stressed to 75% of their yield strength. PH 14-8Mo in this group of alloys stands out as the one material in which no failures occurred when in a CH 1050 condition. On the other hand, all specimens of the 17Cr-5Ni foil failed within 13 days whether cold rolled or cold rolled and aged. However, because special loading equipment was needed for this material, it was only exposed in the 80-foot lot. The other materials fall somewhere between these two extremes. The effect of distance was more evident in this class of alloys and without exception the susceptibility to failure decreased as the exposure distance from the water's edge increased. AM 355 DA and PH 15-7Mo CH 900 are two examples of this effect. In both cases specimens stressed to 75% of their yield strength failed in the 80-foot lot, whereas not one specimen failed in the 800-foot lot. This same situation reoccurs, though not as pronounced, in other alloy systems in this group such as AM 350 CR and 17-7 PH.

The third classification of ferrous alloys in Table 4 is the martensitic precipitation hardening stainless steels. The three alloys studied are 17-4PH, C450 and C455., none of which have shown any susceptibility to failure when stressed to 75% of their yield strength in this marine environment.

Of the three materials, only 17-4 PH has been on exposure for the full thirteen years. C450 and C455 have been on exposure for three years.

Effect of Heat Treatment

Heat treatment can have a very great effect on a material's susceptibility to stress corrosion cracking(8). Table 5 includes the materials and their heat treated condition which is described in greater detail in Table 2. The column on the extreme right of Table 5 tabulates the percent failure rate for each material. With this figure we can compare not only the effect of heat treatment on a given material, but also relative performance between alloys.

The austenitic precipitation hardening stainless steels display excellent resistance to failure in the solution treated and aged condition. Aging was done at 1350°F.

AM 350 in the semiaustenitic group of the precipitation hardening stainless steels responded favorably to the double aging treatment. Only one specimen in twenty failed in the double aged condition, whereas 95 to 100% of the specimens failed in the CR and SCT condition. Double aging improved the resistance to failure of AM 355, but not enough to make it significant. Its failure rate remained above 75%. PH 14-8Mo was completely resistant to failure in the cold rolled and tempered condition while 55% of the specimens given the subcooling and aging treatment failed under the same conditions. Six heat treatments were used on the PH 15-7Mo alloy. Two of the six, TH 1050 and CH 900, had a failure rate of 80% and 65% respectively. Figure 4 graphically displays the rate of failure versus tempering temperature of the remaining four heat treatments involving subcooling and tempering. Increasing the tempering temperature from 950° to 1100°F reduced the susceptibility to failure by better than two orders of magnitude, but even at best the failure rate is still 60%. The 17Cr-5Ni foil had a failure rate of 100% in both the cold rolled and cold rolled and aged conditions. 17-7 PH was treated in the same manner as PH 15-7Mo. The response, however, was different. The TH 1050 was only slightly better than the CH 900 treatment. Neither had a failure rate greater than 45% as shown in Table 5. Subcooling and tempering markedly improved the alloys' stress corrosion resistance. Figure 4 is an illustration of this effect. Notice that tempering at 1075°F or above reduced the failure rate to zero in the marine environment.

There were no failures of the martensitic alloys during the entire period. All three heat treatments given the 17-4 PH stainless steel were outstanding in their resistance to failure. C450 and C455 alloys in the hardened condition also have displayed resistance to failure in the exposure times shown. These materials, along with others that have not failed, are still exposed at Kure Beach.

Modified thermenol, heat treated for improved ductility, had a failure rate over 69% in both the transverse and longitudinal direction. At least 60% of these failures were attributed to exfoliation rather than stress corrosion. The exfoliation occurred in those specimens exposed for the longer periods of time.

Effect of Stress Level

It is well established that the tendency for stress corrosion increases with increasing stress level(9). In determining how much stress a material can sustain in an environment without failure and within a given length of time, threshold stress is often used. This has been defined by Logan as "the stress to which specimens may be subjected without failure for a specified exposure period in the corrosive environment"(9). Figure 5 is an example of the distribution of data on a stress vs. failure time curve for PH 14-8Mo. No failures occurred in specimens stressed to 50% of the yield strength, and only one specimen failed when stressed at 75% of the yield strength. The threshold stress for this instance is something above 50% but less than 75% of the Y.S. The choice is an average of the two or 62.5% of the yield strength. Figure 6 is a similar curve of the data obtained for three heat treatments for PH 15-7Mo. It may be seen that in the CH 900 condition specimens did not begin to fail until practically all specimens in the RH 1075 condition had failed. The first failure of specimens stressed at 50% of the yield strength and exposed in the CH 900 condition did not occur for almost six years. A compilation of the threshold stresses under the conditions of this study is listed in Table 6. Where no failures occurred on specimens stressed up to and including 100% of the yield strength, the threshold stress is listed as greater than 100% of the yield strength of the material. Conversely, if even one specimen failed at 50% of the yield strength, the threshold is stated as being less than 50% of the yield strength.

Visual and Metallographic

The general surface appearance of all specimens was good considering the length of exposure. Specimens exposed over ten years now have developed a surface tranish or at most a very thin but visible layer of rust.

Visual inspection of failures reveals that essentially all failures originated at an edge, or in a very few cases at pits or other surface imperfections. Two distinct patterns were observed. In one case cracks traversed directly across the specimen along a line perpendicular to its sides. In the second case cracks originated at areas perpendicular to a side but then curved away from their original direction. These patterns were characteristic within any given material. However, no relationship was found between the visual crack pattern to other characteristics of the material such as strength, hardness, and crack type (i.e., transgranular or intergranular).

Metallographic examination of the alloys revealed somewhat complex structures typical of multiphase materials. On a few occasions this made it difficult to get good grain boundary definition through normal etching techniques. In general grains were small and equiaxed having an average ASTM grain size of 10. The crack path was found to follow a combination of transgranular and intergranular directions with one type generally predominating over the other.

The following results are typical of the metallographic information obtained for these alloys:

It was found that AM 350-SCT stressed to 90% of its yield strength failed intergranularly as shown in Figure 5a. The same alloy in the double aged condition (DA) failed through a mixture of transgranular and intergranular cracking as seen in Figure 5b. Note further the fine structure within the grains which made examination difficult.

17-7 PH in the RH 950 condition also revealed a mixed mode of fracture as seen in Figure 6a. The ferrite phase is visible in this micrograph. As the tempering temperature is increased to 1075°F this phase is no longer visible as shown in Figure 6b. The ferrite reverts to austenite as the tempering temperature is raised above 1050°F(10). Also shown in this micrograph are cube shaped titanium nitride inclusions which were found distributed throughout the alloy.

As mentioned above most failures in modified thermenol have been attributed to exfoliation rather than stress corrosion. This form of corrosion develops a blister-like appearance on the material with alternate layers of corrosion product separated by thin layers of thermenol making up the blister.

Titanium Alloys

The titanium alloys have shown outstanding resistance to stress corrosion cracking. There were no failures of specimens exposed for twelve years in the marine atmosphere. Table 7 lists the alloys exposed at the 80-foot lot in Kure Beach, while Table 8 lists those at the 800-foot lot.

Summary and Discussion

Since relatively little information was available concerning the stress-corrosion behavior of age-hardening or precipitation-hardening stainless steels in marine environments, NBS was requested by NASC to conduct studies in the marine atmosphere with several alloys used or contemplated for use in air-frame construction. Other materials included in these studies were several commercial titanium alloys and an Fe-Al-Si alloy.

This report contains the results obtained for these materials after exposure for up to twelve years in the 80-foot lot at Kure Beach, N. C. It is important to point out that the atmosphere encountered in service is a complex combination of normal atmospheric corrodents plus the chemical, mechanical, and thermal conditions contributed by the aircraft itself during manufacture and use.(11) This must be kept in mind by both the researcher and the engineer.

There is general agreement of results between the data obtained in this study and other published data(2,3,4,8,13). The few differences that exist have been pointed out. Because this study was planned and implemented in the early 1960's, developments in improved heat treatments and alloying after that period are not included here. However, these are mentioned where they are known. Also new testing techniques employing fracture mechanics had not been fully developed at the time this study was initiated and were therefore no part of the program. Moreover, since most of the materials included in this program were thin sheet material, fracture mechanics techniques could not have been readily adapted for use in this study.

The precipitation hardening stainless steels have demonstrated excellent resistance to stress corrosion failure in this study. However, their alloying content is higher and their strength is lower than that of the other materials as seen in Tables 1 and 2. Alloy A-286 is useful up to 1300°F.

Of the eight semiaustenitic alloys studied, three have shown excellent resistance to failure. AM 350 in the double aged condition is one of these three alloys. In this work AM 355 has indicated somewhat inferior resistance to failure. Recent work on improving its carbide distribution has developed a heat treatment that is an improvement over that used in this study(12). This new full hard SCT 1000 treatment for AM 355 may, thus, make it comparable to AM 350 DA and other resistant alloys(13). AM 357 in a CRT condition had poor resistance in all phases of this exposure. It is interesting to note that the main difference between these alloys is that the chromium content increases as one goes from AM 357 to 355 to 350. PH 14-8Mo and PH 15-7Mo are similar in composition but quite different in their susceptibility to cracking. 14-8Mo in the CH 1050 condition is one of the three alloys mentioned as having excellent resistance to failure. Conversely, 17Cr-5Ni was almost as prone to failure as AM 357. 17-7 PH was very good in conditions RH 1075 and RH 1100, and particularly resistant to cracking in the latter condition as no failures were noted in thirteen years. Other workers have indicated that PH 15-7Mo is more resistant to stress corrosion than 17-7 PH even though the stress corrosion stress intensity threshold, K_{Iscc}, they determined is the same for both materials(14). Our own findings clearly indicate that 17-7 PH RH 1100 is superior to all heat treatments of PH 15-7Mo studied. Correlation with their work is complicated because it is not clear what environment they used for their smooth specimens.

The precipitation hardening martensitic stainless steels have shown complete resistance to cracking. 17-4 PH had not failed in any of the four conditions studied in thirteen years. C450 and C455 have had no failures in the two years of exposure. Titanium and titanium alloys have been reported to stress crack in the laboratory at elevated temperatures when subjected to stress above the yield point in the presence of chlorides in one form or another(15). Other laboratory studies have successfully caused cracking in methanol vapors with no detectable presence of chlorides(16). These studies serve as a caution that under some very special conditions titanium alloys can fail by stress corrosion cracking. The atmospheric work reported here has produced no failures in the entire time of exposure. This is further supported by the fact that there have been no known failures of these alloys in service.

REFERENCES

1. Latanison, R. M., and Staehle, R. W., "Stress Corrosion Cracking of Iron-Nickel-Chromium Alloys" (Review). Proc. Conf. Fundamental Aspects of Stress Corrosion Cracking, Ohio State University, 1967, p. 214.
2. Slunder, C. J., "Stress-Corrosion Cracking of High Strength Stainless Steels in Atmospheric Environments," DMIC Report 158 (September 15, 1961).
3. Phelps, E. H., and Loginow, A. W., "Stress Corrosion of Steels for Aircraft and Missiles," Corrosion 16, 325 (1960).
4. Bloom, F. K., "Stress Corrosion Cracking of Hardenable Stainless Steels," Corrosion 11, 315t (1955).
5. Williamson, J. G., "Stress Corrosion: Saturn V Fights Back," Materials Engineering 69, 34 (1968).
6. Raymond, L., and Kendall, E. G., "Why Titan's Bolts Failed," Metal Progress 93 (Jan.), 103 (1968).
7. "Stress Corrosion Testing Methods," Stress Corrosion Testing (ASTM publication STP 425), p. 12, 1967.
8. Denhard, E. E., Jr., "Stress Corrosion Cracking of High Strength Stainless Steels," (Review). Agard, Proc. Symp. Stress Corrosion Cracking in Aircraft Structural Materials No. 18, 1967.
9. Logan, H. L., The Stress Corrosion of Metals, The Corrosion Monograph Series (John Wiley & Sons, Inc., New York, 1966).
10. Burnett, H. C., Duff, R. H., and Vacher, H. C., "Identification of Metallurgical Reactions and Their Effect on Mechanical Properties of 17-7PH Stainless Steel," Journal of Research 66C (1962).

11. Astley, W., and Scott, J., "The Environment Encountered in Aircraft Service," Agard, Proc. Symposium on the Engineering Practice to Avoid Stress Corrosion Cracking No. 53, 1969.

12. Aggen, G. N., and Kaltenhanser, R. H., "Relationship between Metallurgical Structure and Properties of Precipitation Hardening Stainless Steel," Advances in the Technology of Stainless Steels and Related Alloys (ASTM publication STP 369), 1963.

13. Williamson, J. G., "Stress Corrosion Studies of AM355 Stainless Steel," NASA Technical Memorandum, NASA TM X-53317, 1965.

14. Carter, C. S., Farwick, D. G., Ross, A. M., and Uchida, J. M., "Stress Corrosion Properties of High Strength Precipitation Hardening Stainless Stainless Steel," Corrosion 27 (1971).

15. Cotton, J. B., "Stress Corrosion of Titanium Alloys," Agard, Proc. Symposium Stress Corrosion Cracking in Aircarft Structural Materials No. 18, 1967.

16. Ambrose, J. R., and Kruger, J., "The Stress Corrosion of Titanium and Ti 8Al-1Mo-1V in Methanol Vapor," Corrosion Science 8, 119 (1968).

Table 1. Nominal chemical compositions of ferrous alloys.

Alloy	Cr	Ni	Mo	Al	Mn	Cu	Ti
A286	15	26	1		1.5		2
HNM	18	9.5			3.5		
AM350	16.5	4	3				
AM355	15.5	4	3				
AM357	14	4	3				
PH14-8Mo	14	8	2.5				
PH15-7Mo	15	7	1				
17Cr-5Ni	17	5			1		
17-7PH	17	7		1			
17-4PH	16.5	4				3	
C450	15	6	1			1	
C455	12	9				2	1
Modified thermenol			3.5	16			

Table 2. Heat treatment for the ferrous alloys.

Alloy[a]	Condition	Solution or Conditioning Treatment		Transformation	Aging Treatment		Mechanical Properties		
		Temp °F	Time		Temp °F	Time	Tensile Strength ksi	Yield Strength ksi	% Elongation
Austenitic									
A286	STA	1800	1 hr	Air cool	1325	16 hrs	151.3	107.4	23
HNM	TH1350	2050	1/2 hr	Air cool	1350	16 hrs	128.0	72.8	22.5
Semi-Austenitic									
AM350	DA	1710	10 min	Air cool, 1375-2 hrs	850	2 hrs	176.8	145.2	10
	SCT	1710	10 min	Air cool, -100°F-3	850	3 hrs	203.8	158.6	8.7
	CR	1950	10 min	Air cool, cold roll 30%	850	3 hrs	232.2	231.5	15.5
AM355	DA	1710	10 min	Air cool, 1375-2	850	2 hrs	193.8	159.2	8.8
	SCT	1710	10 min	Air cool, -100°F-3 hrs	850	3 hrs	214.6	164.8	9.3
AM355 (wire)	-			Condition unknown			-	375.0	-
AM357	CRT			Cold roll 50%	800	3 hrs	335.6	281.4	5.2
PH14-8Mo	SRH1050	1700	1 hr	Air cool, -100°F-8 hrs	1050	1 hr	219.6	213.6	12.3
	CH1050			Cold rolled at mill (Cond. C)[b]	1050	1 hr	249.7	242.4	5.3
PH15-7Mo	RH950	1750	10 min	Air cool, -100°F-8 hrs	950	1 hr	244.0	212.0	6
	RH1050	1750	10 min	Air cool, -100°F-8 hrs	1050	1 hr	212.0	206.0	5.5
	RH1075	1750	10 min	Air cool, -100°F-8 hrs	1075	1 hr	204.0	199.0	5.3
	RH1100	1750	10 min	Air cool, -100°F-8 hrs	1100	1 hr	195.0	190.0	7.5
	TH1050	1400	1-1/2 hr	Air cool, 50°-60°-1/2 hr	1050	1-1/2 hr	214.0	199.0	6.5
	CH900			Cold rolled at mill 60% (Cond. C)[b]	900	1 hr	256.0	190.0	7.5
17-7PH (wire)	CR			Cold rolled at mill[b]			313.8	280.0	
	CRA			Cold rolled and aged at mill[b]			332.5	310.3	
17-7PH	RH950	1750	10 min	Air cool, -100°F-8 hrs	950	1 hr	227.0	214.0	7.2
	RH1050			Air cool, -100°F-8 hrs	1050	1 hr	194.8	178.3	10
	RH1075			Air cool, -100°F-8 hrs	1075	1 hr	185.1	170.3	10.3
	RH1100			Air cool, -100°F-8 hrs	1100	1 hr	172.0	151.8	11.5
	TH1050	1400	1-1/2 hr	Air cool, 50°-60°-1/2 hr	1050	1-1/2 hr	189.9	175.3	8.7
	CH900			Cold rolled at mill 60% (Cond. C)[b]	900	1 hr	274.9	265.7	11.5
17-7Ph (wire)	CH[b]			0.020 diam wire			316.7		
	CH[b]			0.039 diam wire			331.7		
	CH[b]			0.055 diam wire			320.8		
	CH[b]			0.120 diam wire			301.8		
Martensitic									
17-4PH	TH925			Cold rolled at mill 45%[b]	925	4 hrs	184.7	180.2	3.8
17-4PH (forging)	TH925	2150	1 hr	Air cool, 1900°-1 hr[b]	925	4 hrs	178.4	165.4	6.75
	TH1025	2150	1 hr	Air cool, 1900°-1 hr[b]	1025	4 hrs	160.3	152.5	7.5
	TH1025	2150	1 hr	Air cool, 1900°-1 hr[b]	1150	4 hrs	138.4	112.5	12
C450	Hardened	1900	1/2 hr	Quench[b]	900	4 hrs	179.2	172.0	11.1
C450	Hardened	1525	1/2 hr	Quench[b]	1000	4 hrs	225.5	219.8	8.7
Modified Thermenol									
Transverse				Rolled at 1070°	1340	1 hr[b]	151.6	-	1.0
Longitudinal							135.2	123.8	1.9

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[a] Sheet material unless otherwise specified.

[b] As received.

Table 3. Nominal chemical composition of the titanium base alloys.

Alloy[a]	Al	V	Other	Condition	Treatment
A110AT	5	1	2.5Sn	HCR	Hot rolled, annealed
C115VA	4	1	3Mo	STA	Soln H.T.,[b] 925°-12 hrs
C105VA	2.5	16		STA	Soln H.T.,[b] 950°-4 hrs
Ti6Al4V	6	4		STA	Soln H.T., 950°-4 hrs[b]
B120VCA	3	14	11Cr	STA	Soln H.T.,[b] 900°-48 hrs

[a] Sheet material.

[b] As received.

Table 4. Stress corrosion behavior of ferrous alloys stressed to 75% of their yield strength at Kure Beach, N.C.

Alloy[a] and Condition	Exposure Stress ksi	Stress Direction	80-ft Lot			800-ft Lot			Exposure Time of Unfailed Specimens[c] (years)
			Number of Specimens		Average Time to Failure (days)	Number of Specimens		Average Time to Failure (days)	
			Exposed	Failed		Exposed	Failed		
Austenitic									
A286 STA	80.6	T[f]	5	0	NF[e]	5	0	NF	12.8
HNM TH1350	54.6	T	5	0	NF	5	0	NF	12.8
Semi-Austenitic									
AM350 DA	108.9	T	5	0	NF	5	0	NF	12.8
SCT	119.0	T	5	5	19	5	5	104	-
CR	173.6	T	5	5	44	5	3	967[b]	12.8
AM355 DA	119.4	T	3	3	2863	3	0	NF	12.8
SCT	123.6	T	3	3	3	3	3	18	-
AM355 unknown .090 wire	280.0	T	3	3	241	-	-	-	-
AM357 CRT	211.4	T	5	5	3	5	5	3	-
PH14-8Mo SRH1050	160.2	T	5	1	2536[b]	5	0	NF	10.2
CH1050	181.8	T	5	0	NF	5	0	NF	10.2
PH15-7Mo RH950	159.0	T	5	5	9	5	5	20	-
RH1050	154.5	T	5	5	49	5	5	350	-
RH1075	149.3	T	5	5	220	5	4	795[b]	12.8
RH1100	142.5	T	5	2	2160[b]	5	0	NF	12.8
TH1050	149.3	T	5	5	680	5	5	750	-
CH900	186.8	T	5	5	2742	5	0	NF	12.8
17Cr-5Ni CR	210.0	T	3	3	8	-	-	-	-
CRA	235.5	T	3	3	13	-	-	-	-
17-7PH RH950	160.5	T	5	5	5	5	5	20	-
RH1050	133.5	T	5	2	1793[b]	5	0	NF	12.8
RH1100	114.0	T	5	0	NF	5	0	NF	12.8
TH1050	131.3	T	5	3	1966	5	0	NF	12.8
CH900	199.5	T	5	5	707	5	2	1297[b]	12.8
17-7PH CH .020 wire[h]	237.5	T	2	2	60	-	-	-	-
.039 wire[h]	248.8	T	3	0	NF	-	-	-	9.9[d]
.055 wire[h]	236.3	T	3	2	1614	-	-	-	9.9[d]
.120 wire[h]	227.2	T	3	3	532	-	-	-	-
Martensitic									
17-4PH TH925	135.2	T	5	0	NF	5	0	NF	12.8
17-4PH TH925 forging	124.4	T	3	0	NF	3	0	NF	12.8
TH1025 forging	114.4	T	3	0	NF	3	0	NF	12.8
TH1150 forging	84.4	T	3	0	NF	3	0	NF	12.8
C450 hardened	129.0	T	5	0	NF	5	0	NF	2.3
C455 hardened	164.9	T	5	0	NF	5	0	NF	2.3
Modified thermenol									
Transverse[h]	113.7	T	5	5	195	5	5	122	-
Longitudinal	92.9	L	4	2-(2E)[g]	2383	4	3-(2E)[g]	648	12.8

[a] Sheet material unless otherwise specified.
[b] One or more specimens still on exposure.
[c] Specimens still under exposure unless otherwise specified.
[d] Experiment ended at time shown.
[e] No failure.
[f] Transverse.
[g] Number of specimens failed by exfoliation.
[h] Stressed to % of tensile strength.

Table 5. Stress corrosion behavior of ferrous alloys exposed at 80-foot lot at Kure Beach, North Carolina.

Alloy[a] and Condition		Stress Direction	50% of Yield Strength			75% of Yield Strength			90% of Yield Strength			100% of Yield Strength			Exposure Time of Unfailed Specimens[c] (years)	Failure Rate %
			Number of Specimens		Average Time to Failure (days)	Number of Specimens		Average Time to Failure (days)	Number of Specimens		Average Time to Failure (days)	Number of Specimens		Average Time to Failure (days)		
			Exposed	Failed		Exposed	Failed		Exposed	Failed		Exposed	Failed			
Austenitic																
A286	STA	T[f]	5	0	NF[e]	5	0	NF	5	0	NF	5	0	NF	12.8	0
HNM	TH1350	T	5	0	NF	5	0	NF	5	0	NF	5	0	NF	12.8	0
Semi-Austenitic																
AM350	DA	T	5	0	NF	5	0	NF	5	1	2311[b]	5	0	NF	12.8	5
	SCT	T	5	5	131	5	5	19	5	5	16	5	5	16	-	100
	CR	T	5	4	204[b]	5	5	44	5	5	22	5	5	25	12.8	95
AM355	OA	T	3	0	NF	3	3	2863	3	3	325	3	3	1166	12.8	75
	SCT	T	3	3	15	3	3	3	3	3	3	3	3	3	-	100
AM355	.090 wire	T	3	3	592	3	3	241	3	1	364	-	-	-	11.3[d]	78
AM357	CRT	T	5	5	4	5	5	3	5	5	3	5	5	4	-	100
PH14-8Mo	SRH1050	T	5	0	NF	5	1	2536[b]	5	5	1013	5	5	376	10.2	55
	CH1050	5	5	0	NF	5	0	NF	5	0	NF	5	0	NF	10.2	0
PH15-7Mo	RH950	T	5	5	56	5	5	9	5	5	12	5	5	4	-	100
	RH1050	T	5	3	3144	5	5	49	5	5	37	5	5	22	12.8	90
	RH1075	T	5	0	NF	5	5	220	5	5	28	5	5	80	12.8	75
	RH1100	T	5	0	NF	5	2	2160[b]	5	5	1343	5	5	975	12.8	60
	TH1050	T	5	1	4446[b]	5	5	680	5	5	115	5	5	98	12.8	80
	CH900	T	5	0	NF	5	5	2742	5	4	1512[b]	5	4	2905[b]	12.8	65
17Cr-5Ni	CR	T	3	3	16	3	3	8	3	3	4	-	-	-	-	100
	CRA	T	3	3	20	3	3	13	3	3	13	-	-	-	-	100
17-7PH	RH950	T	5	5	29	5	5	5	5	5	3	5	5	2	-	100
	RH1050	T	5	0	NF	5	2	1793[b]	5	5	1777	5	5	1505	12.8	60
	RH1075	T	5	0	NF	5	0	NF	5	1	4173	5	0	NF	12.8	5
	RH1100	T	5	0	NF	5	0	NF	5	0	NF	5	0	NF	12.8	0
	TH1050	T	5	0	NF	5	3	1966	5	3	2818[b]	5	3	2359	12.8	45
	CH900	T	5	2	3559[b]	5	5	707	5	5	199	5	5	18	12.8	85
17-7PH	CH .020 wire[h]	T	3	3	258	2	2	60	3	3	68	-	-	-	-	100
	.039 wire[h]	T	3	0	3.7 yrs[d]	3	0	9.9 yrs[d]	3	3	351	-	-	-	-	33
	.055 wire[h]	T	3	0	9.9 yrs[d]	3	2	9.9 yrs[d]	3	3	172	-	-	-	9.9[d]	56
	.120 wire[h]	T	3	3	96	3	3	532	2	2	89	-	-	-	-	100
Martensitic																
17-4PH	TH925	T	4	0	NF	5	0	NF	5	0	NF	5	0	NF	12.8	0
17-4PH	TH925 (forging)	T	3	0	NF	3	0	NF	3	0	NF	3	-	NF	12.8	0
	TH1025 (forging)	T	3	0	NF	3	0	NF	3	0	NF	3	0	NF	12.8	0
	TH1150 (forging)	T	3	0	NF	3	0	NF	3	0	NF	3	0	NF	12.8	0
C450	Hardened	T	5	0	NF	5	0	NF	5	0	NF	5	0	NF	2.3	0
C455	Hardened	T	5	0	NF	5	0	NF	5	0	NF	5	0	NF	2.3	0
Modified Thermenol																
Transverse[h]		T	5	4-(3E)[g]	264[b]	5	5	195	5	5	42	5	5-(1E)[g]	118	12.8	95
Longitudinal		L	4	4-(3E)[g]	1293	4	2-(2E)[g]	2383[b]	4	4-(1E)[g]	533	4	3-(2E)[g]	1160[b]	12.8	69

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[a] Sheet material unless otherwise specified.
[b] One or more specimens still on exposure.
[c] Specimens still under exposure unless otherwise specified.
[d] Experiment ended at time shown.
[e] No failure.
[f] Transverse.
[g] Number of specimens failed by exfoliation.
[h] Stressed to % of tensile strength.

Table 6. Threshold stress of ferrous alloys exposed at the 80-foot lot in Kure Beach, North Carolina.

Alloy[a]	Condition	Threshold Stress, σ_T		Exposure Time to Unfailed Specimens[d] (years)
		% of Yield Strength	ksi	
A286	STA	>100	>107.4	12.8
HNM	TH1350	>100	> 72.8	12.8
AM350	DA	$75<\sigma_T<90$	102.9-130.7 ∼120	12.8
	SCT	<50	<79.3	-
	CR	<50	<115.7	12.8
AM355	DA	$50<\sigma_T<75$	100	12.8
	SCT	<50	∼ 82.4	-
AM355	.090 wire	<50	<187.5	11.3[b]
AM357	CRT	<50	<140.7	-
PH14-8Mo	SRH1050	$50<\sigma_T<75$	∼133.5	10.2
	CH1050	>100	>242.4	10.2
PH15-7Mo	RH950	<50	<106	-
	RH1050	<50	<103	12.8
	RH1075	$50<\sigma_T<75$	∼124	12.8
	RH1100	$50<\sigma_T<75$	∼119	12.8
	TH1050	<50	< 99.5	12.8
	CH900	$50<\sigma_T<75$	∼119	12.8
17Cr-5Ni	CR	<50	<140	-
	CRA	<50	<155.1	-
17-7PH	RH950	<50	<107	-
	RH1050	$50<\sigma_T<75$	∼111	12.8
	RH1075	$75<\sigma_T<90$	∼140	12.8
	RH1100	>100	>151.8	12.8
	TH1050	$50<\sigma_T<75$	∼110	12.8
	CH900	<50	<132.8	12.8
17-7PH	.020 wire[c] CH	<50	<158.3	-
	.039 wire[c] CH	$75<\sigma_T<90$	∼274	9.9[b]
	.055 wire[c] CH	$50<\sigma_T<75$	∼200	9.9[b]
	.120 wire[c] CH	<50	<151	-
17-4PH	TH925	>100	>180.2	12.8
17-4PH (forging)	TH925	>100	>165.4	12.8
(forging)	TH1025	>100	>152.5	12.8
(forging)	TH1150	>100	>112.5	12.8
C450	Hardened	>100	>172.0	2.3
C455	Hardened	>100	>219.8	2.3
Modified Thermenol				
Transverse[c]	-	<50		12.8
Longitudinal	-	<50	<61.9	12.8

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[a] Sheet material unless otherwise specified.
[b] Experiment ended at time shown.
[c] Stressed to % of tensile strength.
[d] Specimens still on exposure unless otherwise specified.

Table 7. Stress corrosion behavior of titanium alloys exposed at 80-foot lot in Kure Beach, North Carolina.

Alloy[a] and Condition	Stress Direction	50% of Yield Strength			75% of Yield Strength			90% of Yield Strength			100% of Yield Strength			Exposure Time of Unfailed Specimens[d] (years)	Failure Rate %
		Number of Specimens		Average Time to Failure (days)	Number of Specimens		Average Time to Failure (days)	Number of Specimens		Average Time to Failure (days)	Number of Specimens		Average Time to Failure (days)		
		Exposed	Failed		Exposed	Failed		Exposed	Failed		Exposed	Failed			
A110AT HRS	T[b]	5	0	NF[c]	5	0	NF	5	0	NF	5	0	NF	12.8	0
C115VA STA	T	5	0	NF	5	0	NF	5	0	NF	5	0	NF	12.8	0
C105VA STA	T	5	0	NF	5	0	NF	5	0	NF	5	0	NF	12.8	0
Ti6Al4V STA	T	5	0	NF	5	0	NF	5	0	NF	5	0	NF	11.8	0
B120VCA STA	T	5	0	NF	5	0	NF	5	0	NF	5	0	NF	12.8	0

[a] Sheet material.
[b] Transverse.
[c] No failure.
[d] Specimen still on exposure.

Table 8. Stress corrosion behavior of titanium alloys stressed to 75% of their yield strength at the 800-foot lot in Kure Beach, North Carolina.

Alloy[a] and Condition		Exposure Stress ksi	Stress Direction	Number of Specimens		Average Time to Failure (days)
				Exposed	Failed	
A110AT	HRA	93.2	T[b]	5	0	NF[c]
C115VA	STA	129.5	T	5	0	NF
C105VA	STA	130.8	T	5	0	NF
Ti6Al4V	STA	131.3	T	5	0	NF
B120VCA	STA	132.8	T	5	0	NF

[a] Sheet material.
[b] Transverse.
[c] No failure.

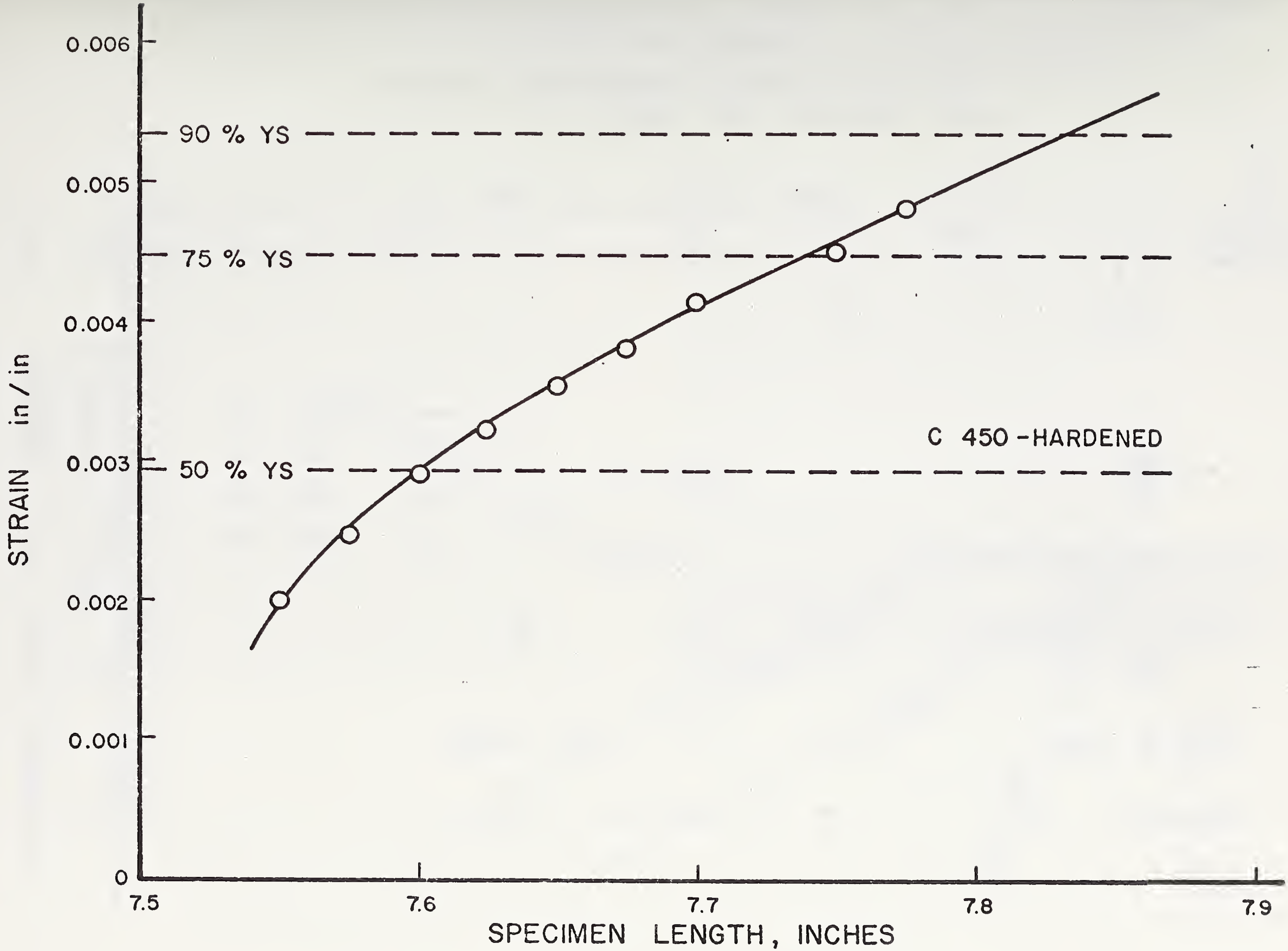


FIGURE 1. Strain vs specimen length of C450 alloy in hardened condition

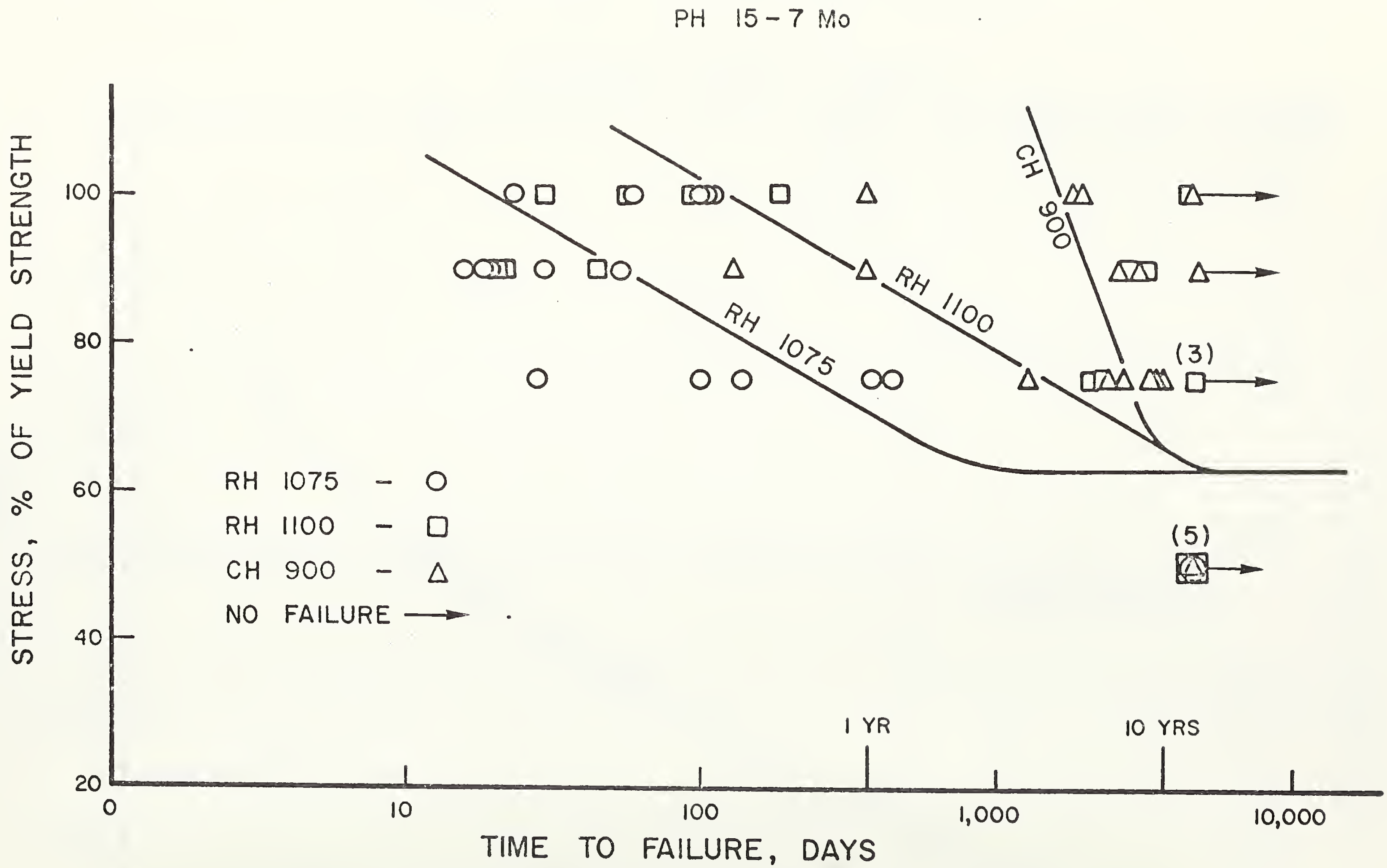


FIGURE 2. Stress vs time to failure of PH 15-7 Mo for three heat treatments

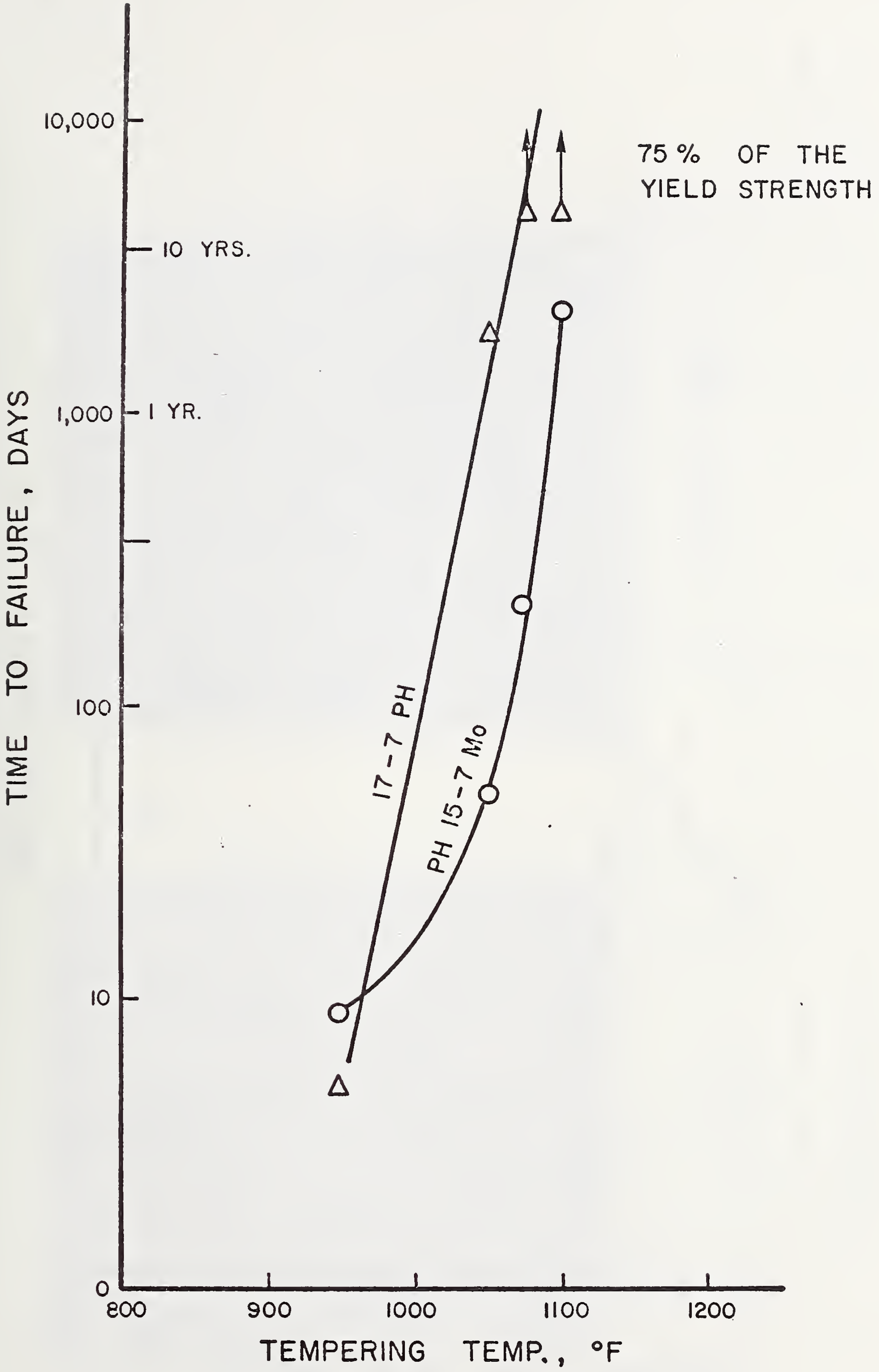


FIGURE 3. Stress corrosion behavior of PH 15-7 Mo - RH and 17-7 PH - RH as a function of tempering temperature

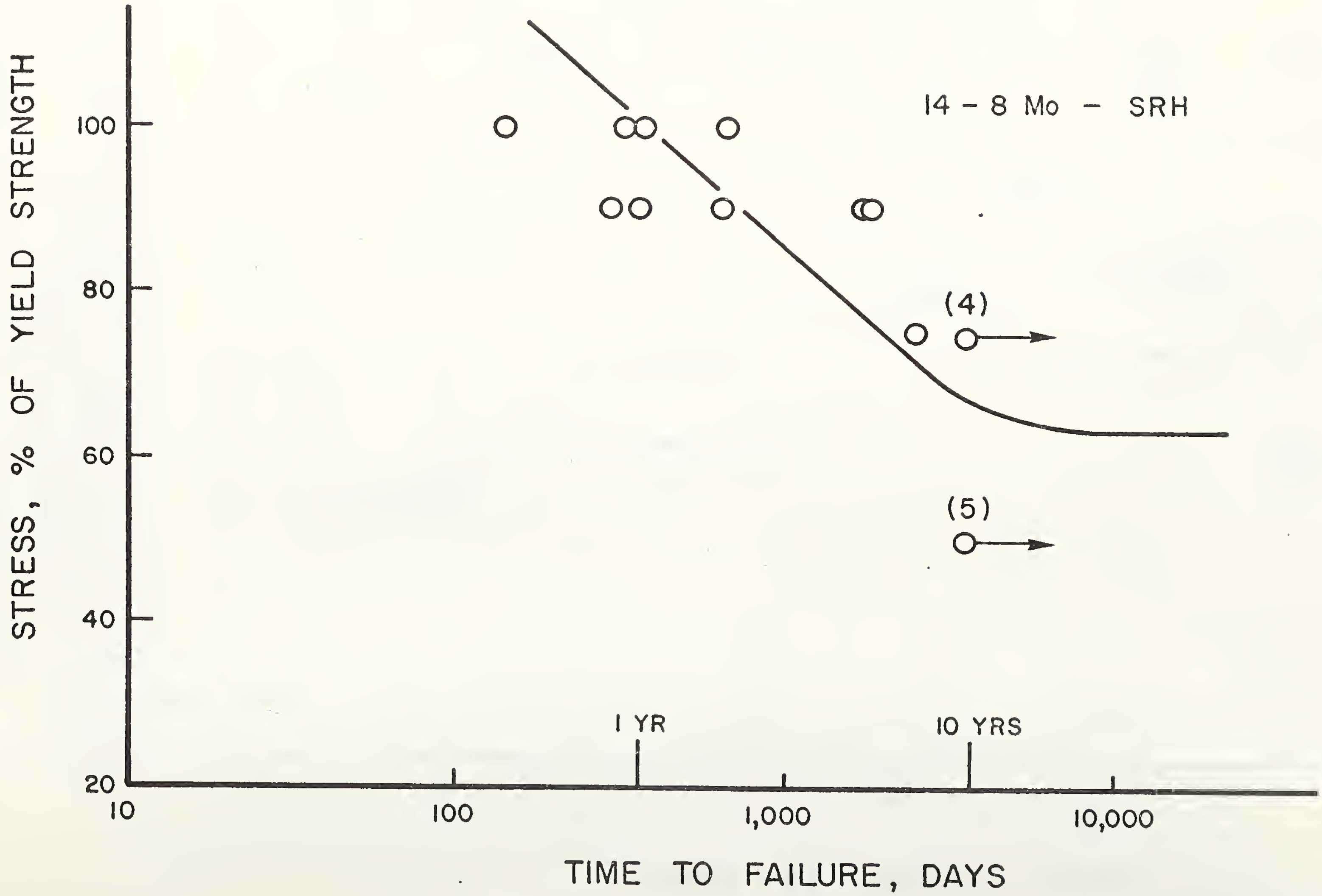
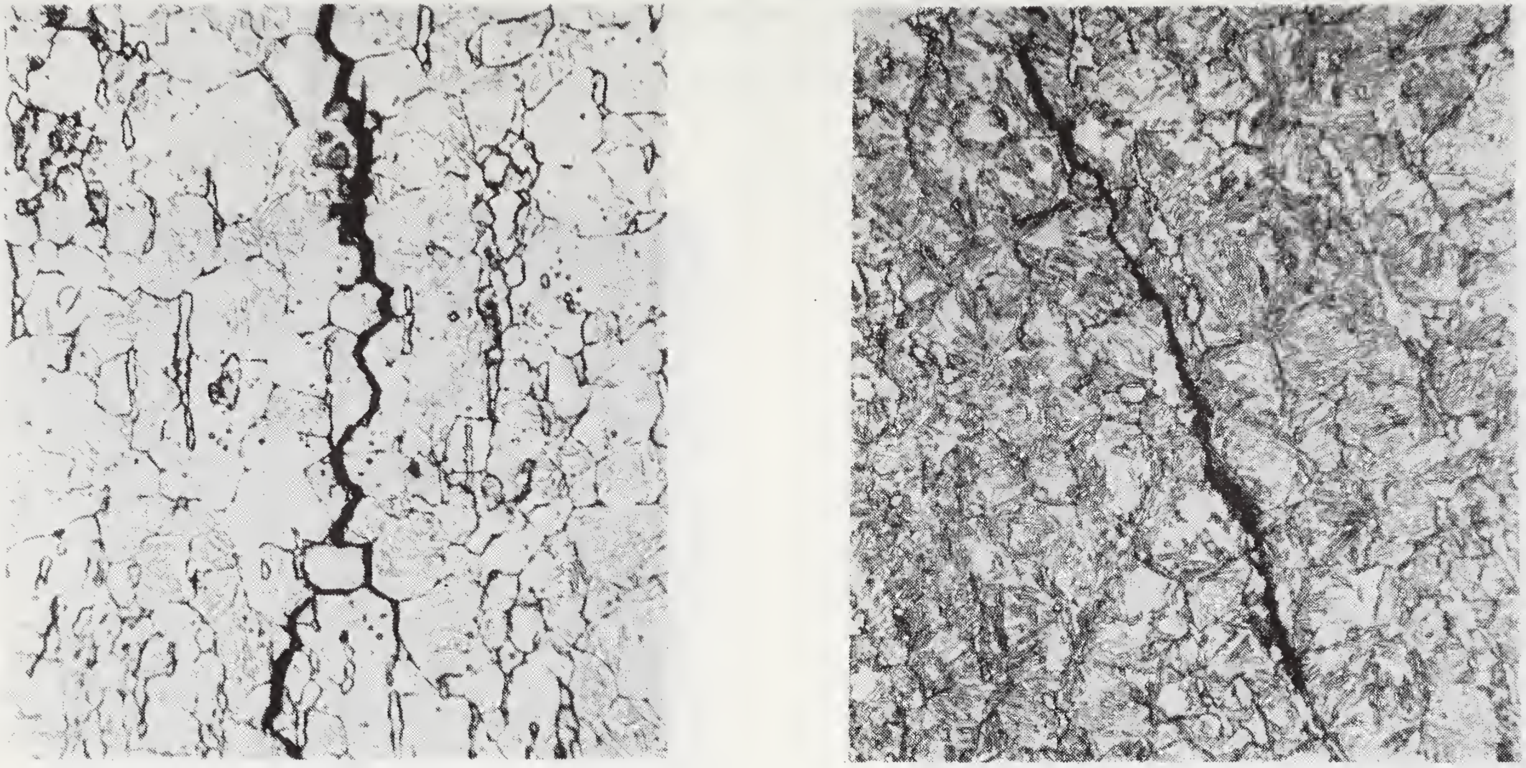


FIGURE 4. Stress vs time to failure of 14-8 Mo - SRH



(a)

(b)

Figure 5 Cracks observed on AM 350 alloy steel specimens.

(a) AM 350-SCT stressed to 90% of its yield strength. Crack is intergranular, Etched, HF-HNO_3.x500.

(b) AM 350-DA stressed to 90% of its yield strength. Crack is both intergranular and transgranular. Etched, HF-HNO_3.x500.

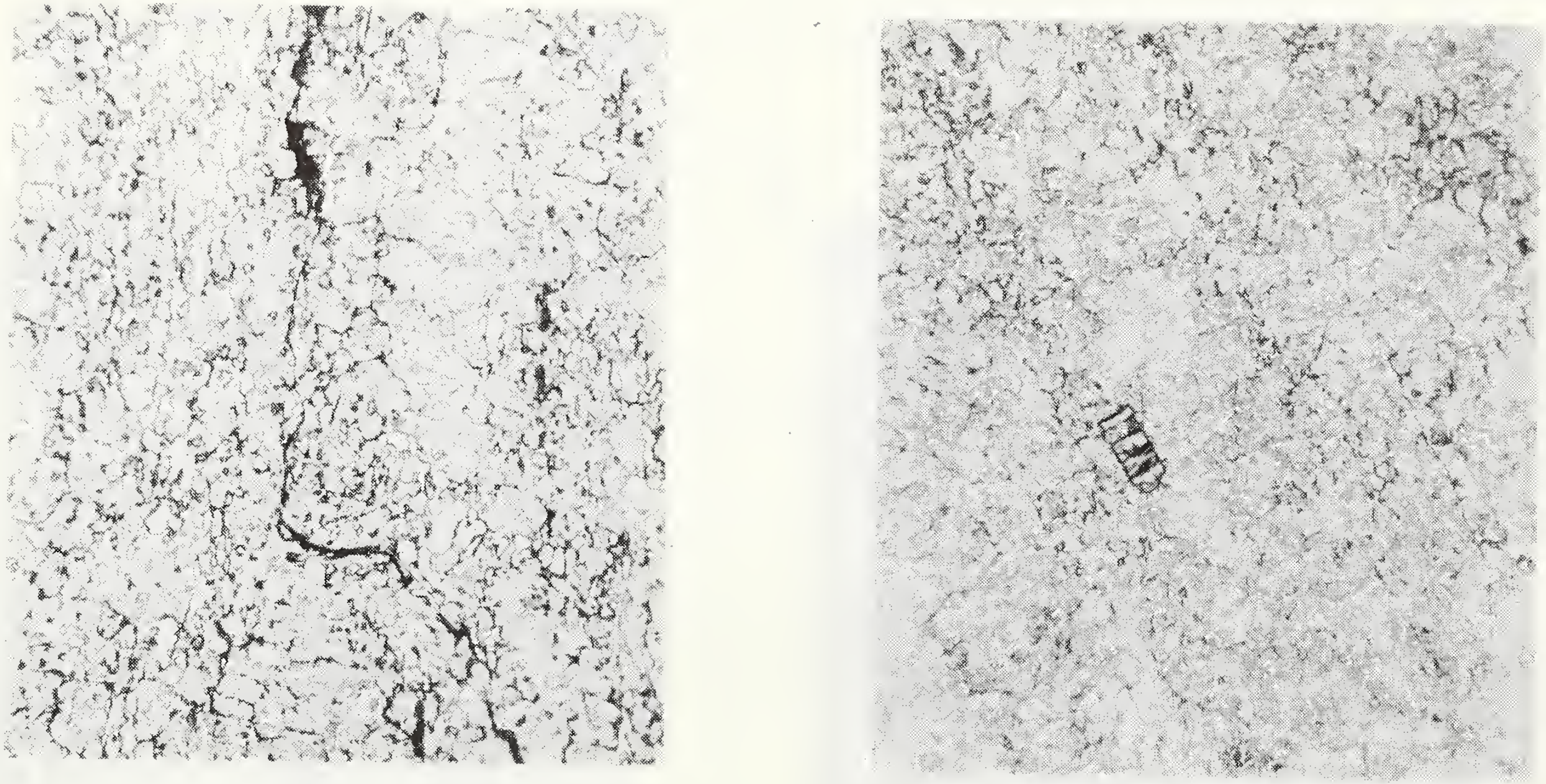


Figure 6 Microstructures of 17-7 PH alloy steel specimens.

(a) 17-7 PH in the RH 950 condition. Crack shown is both intergranular and transgranular. Note ferrite phase. Etched, $HF-HNO_3$.x500.

(b) 17-7 PH in the RH 1075 condition. Note that for this alloy as the tempering temperature is increased from 950° F (as in 6a) to 1075° F that the ferrite phase reverts to austenite. Etched, $HF-HNO_3$.x500.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Stress corrosion data are presented for selected stainless steels and titanium alloys exposed for up to twelve years in a marine atmosphere environment. Of the ferrous materials included in this study, all except one were of the age hardenable type. Variables studied included the effect of heat treatment applied stress.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Atmosphere; heat treatment; marine; stainless steels; stress corrosion; threshold stress; titanium alloys

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