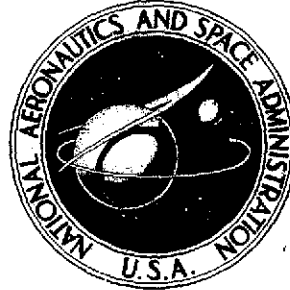


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NASA TM X-3145

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(NASA-TM-X-3145) EFFECT OF EXPOSURE
CYCLE ON HOT SALT STRESS CORROSION OF A
TITANIUM ALLOY (NASA) 22 p HC \$3.25

N75-12128

CSC 11F

Unclas

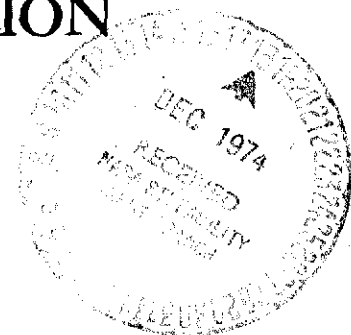
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**EFFECT OF EXPOSURE CYCLE
ON HOT-SALT STRESS-CORROSION
OF A TITANIUM ALLOY**

by Hugh R. Gray and James R. Johnston

Lewis Research Center

Cleveland, Ohio 44135



1. Report No. NASA T M X-3145	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle EFFECT OF EXPOSURE CYCLE ON HOT-SALT STRESS-CORROSION OF A TITANIUM ALLOY		5. Report Date December 1974	6. Performing Organization Code
		8. Performing Organization Report No. E-8019	10. Work Unit No. 501-21
7. Author(s) Hugh R. Gray and James R. Johnston		11. Contract or Grant No.	
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		13. Type of Report and Period Covered Technical Memorandum	
		14. Sponsoring Agency Code	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		15. Supplementary Notes	
16. Abstract The influence of exposure cycle on the hot-salt stress-corrosion cracking resistance of the Ti-8Al-1Mo-1V alloy was determined. Both temperature and stress were cycled simultaneously to simulate turbine-powered aircraft service cycles. Temperature and stress were also cycled independently to determine their individual effects. Substantial increases in crack threshold stresses were observed for cycles in which both temperature and stress or temperature alone were applied for 1 hour and removed for 3 hours. The crack threshold stresses for these cyclic exposures were twice those determined for continuous exposure for the same total time of 96 hours.			
17. Key Words (Suggested by Author(s)) Titanium; Titanium alloy; Hot-salt stress-corrosion; Stress-corrosion cracking; Cyclic exposures; Hydrogen embrittlement; Turbine-powered aircraft		18. Distribution Statement Unclassified - unlimited Category 17	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 20	22. Price* \$3.25

EFFECT OF EXPOSURE CYCLE ON HOT-SALT STRESS-CORROSION OF A TITANIUM ALLOY

by Hugh R. Gray and James R. Johnston
Lewis Research Center

SUMMARY

An investigation was conducted to determine the influence of exposure cycle on the hot-salt stress-corrosion cracking resistance of a titanium alloy. Salt-coated specimens of the Ti-8Al-1Mo-1V alloy were creep exposed at temperatures of 320° and 430° C (600° and 800° F). Both temperature and stress were cycled simultaneously to simulate a service cycle of compressor components of current turbine-powered aircraft. Temperature and stress were also cycled independently to determine their individual effects. These results were then compared with a baseline 96-hour-continuous-exposure crack threshold curve.

For 96 hours total time at temperature with a cycle in which both temperature and stress were applied for 1 hour and removed for 3 hours, crack threshold stresses were about 100 percent greater than those determined for the continuous-exposure baseline. Likewise, 96 hours exposure with a temperature cycle consisting of 1 hour on and 3 hours off at a constant stress resulted in crack threshold stresses 100 percent greater than the baseline at both the 320° C (600° F) and 430° C (800° F) exposure temperatures. Other temperature cycles (3 hr on/3 hr off, 1 hr on/1 hr off, and 3 hr on/1 hr off) and a stress cycle of 1 hour on and 3 hours off resulted in crack threshold stresses 60 to 90 percent greater than the continuous-exposure baseline at 320° C (600° F). None of these temperature cycles or the stress cycle resulted in any increase in threshold stress as compared with the baseline at 430° C (800° F).

Exposure cycle and an alloy's composition, processing conditions, and surface condition are the major variables which influence a titanium alloy's sensitivity to hot-salt stress-corrosion. Exposure cycle, surface condition, and the extensive use of the relatively immune Ti-6Al-4V alloy explain the reliable service of titanium alloys with respect to hot-salt stress-corrosion in current turbine engines.

INTRODUCTION

Numerous laboratory investigations, described in references 1 and 2, have demonstrated that titanium alloys are susceptible to embrittlement and cracking while being stressed in the presence of halides at elevated temperatures. This phenomenon has been termed hot-salt stress-corrosion and is of interest because of the extensive use of titanium alloys in gas-turbine engines. Conditions of stress, temperature, and salt-air environment which result in stress-corrosion in the laboratory can be experienced in flight by compressor components of current engines (ref. 3). Since advanced engine designs propose that titanium alloys operate at even higher stresses and temperatures than in current engines, there is concern that hot-salt stress-corrosion might become a limiting factor in the use of titanium alloys.

Although there have been cases of hot-salt stress-corrosion cracking during titanium alloy processing (ref. 4) and during engine test-stand operation (ref. 1), there have not yet been any documented in-flight service failures that could conclusively be attributed to hot-salt stress-corrosion. A research program has been conducted at the NASA Lewis Research Center to rationalize this lack of service failures and to determine whether hot-salt stress-corrosion of titanium alloys might be expected to become a problem in advanced engines.

One of the preferred laboratory test techniques for determining susceptibility to hot-salt stress-corrosion involves subjecting salt-coated titanium alloy specimens to static loads. The test temperatures range from 260° to 480° C (500° to 900° F) and the test duration is generally 100 hours. The specimens are then examined for evidence of corrosion or cracking and may be subjected to mechanical testing at room temperature, such as bend or tensile testing, to determine residual ductility. The results are then interpreted on a stress-corrosion or no-stress-corrosion basis. Thus, the boundary line separating regions of cracking from no cracking or embrittlement from nonembrittlement on a plot of exposure stress against exposure temperature has been termed the threshold curve for hot-salt stress-corrosion.

A previous investigation by the authors (ref. 5) has demonstrated that variables associated with the dynamic air environment typical of the compressor of current gas-turbine engines do not have a major effect on the hot-salt stress-corrosion cracking of titanium alloys. Specifically, decreasing air dewpoint (4° to -84° C) and salt concentration (0.3 to 0.03 mg/cm²) or increasing salt deposition temperature (200° to 430° C), air pressure (0.1 to 0.4 MN/m²), and air velocity (static to Mach 0.7) had only minor beneficial effects on the hot-salt stress-corrosion of the Ti-8Al-1Mo-1V alloy.

The variables that have been shown to have major effects are specimen surface condition (refs. 5 and 6), processing conditions, heat-to-heat variations, and the composition of the titanium alloys (ref. 6). Two of these variables, composition and surface condition, help to rationalize the lack of service failures. Most titanium alloy

compressor components currently in service are made from the Ti-6Al-4V alloy. This alloy is used at design creep stress levels which appear to be less than its hot-salt stress-corrosion crack threshold stress (ref. 6). In addition, most compressor components are shot peened or glass bead peened to produce residual compressive stresses to achieve increased resistance to fatigue. Specimen surfaces with residual compressive stresses have been shown to be more resistant to stress-corrosion than specimen surfaces that are stress free (refs. 5 and 6) or surfaces that are residually stressed in tension as a result of certain machining techniques. However, it must be emphasized that the protective influence of residual compressive stresses can anneal out during long-time, elevated-temperature exposures.

The effect of exposure cycle on an alloy's susceptibility to hot-salt stress-corrosion is certainly an important consideration. Several investigations (refs. 7 to 10) have indicated that hot-salt stress-corrosion damage is not as severe during cyclic thermal exposures as during continuous exposures for the same total times. These previous investigations have determined only the influence of thermal cycling and have not attempted to determine the role of stress cycling or the role of combined temperature-stress cycling. Since the normal mode of turbine engine operation is cyclic, the 100-hour-continuous-exposure isothermal threshold curves commonly generated in laboratory investigations represent conditions which are more severe than engine operating conditions of current and even advanced titanium alloy compressor components.

The purpose of this present investigation was to study the effects of both thermal and stress cycling on the hot-salt stress-corrosion resistance of a titanium alloy. Temperature and stress were cycled simultaneously to determine their combined effects. Temperature and stress were also cycled independently to determine their individual effects. Exposure temperatures of 320° and 430° C (600° and 800° F) and cyclic times of 1 and 3 hours were studied in detail. The alloy used was the familiar Ti-8Al-1Mo-1V alloy which is very susceptible to hot-salt stress-corrosion. This alloy has been studied quite extensively by previous investigators and by the authors. As a consequence, meaningful baseline data are available for comparison with the cyclic exposure data determined in this study.

The U.S. customary system of units was used in this investigation. Conversion to SI units was done for reporting purposes only.

MATERIAL, SPECIMENS, AND PROCEDURE

Material

A titanium - 8-wt % - aluminum - 1-wt % - molybdenum - 1-wt % - vanadium (Ti-8Al-1Mo-1V) alloy in the mill-annealed condition (790° C (1450° F) for 1 hr, air cooled)

was used in this investigation. The chemical analysis of the 2.5-centimeter- (1-in. -) diameter bar stock, as reported by the manufacturer, is given in the following table:

Element	Content, wt %
Al	7.8
Mo	1.0
V	1.0
C	.023
Fe	.05
N	.011
O	.07
H	.007
Ti	Balance

The room-temperature mechanical properties reported by the manufacturer are yield strength, 980 MN/m² (142 ksi); ultimate strength, 1020 MN/m² (148 ksi); elongation, 20 percent; reduction of area, 40 percent.

In this study, tubular specimens were used. Their room-temperature mechanical properties in the machined and chemically milled condition are as follows: ultimate tensile strength, 1030 MN/m² (150 ksi); elongation, 18 percent; and apparent reduction of area, 33 percent (based on outside diameter of an assumed solid specimen). Literature creep data (ref. 5) and the previously determined 96-hour-continuous-exposure hot-salt stress-corrosion crack threshold curve (chemically milled specimens exposed in static air) (ref. 6) for this alloy are presented in figure 1.

Specimens

Tubular specimens of the type illustrated in figure 2 were used in this investigation. The specimens were machined from as-received bar stock and then stress relieved by chemical milling (ref. 5) in a solution of 3-percent hydrofluoric acid, 30-percent nitric acid, and 67-percent water. Approximately 0.002 centimeter (0.001 in.) of metal was removed from all surfaces of these specimens.

Test Procedure

Salt coating. - All the test specimens were precoated with chemically pure sodium chloride immediately prior to stress-corrosion exposure. The average coating

amounted to about 0.1 mg/cm^2 (0.6 mg/in.^2). This concentration was within the range measured on service airfoils (ref. 11). The salt was uniformly deposited on the bore of unstressed specimens at 200° C (400° F) in the dynamic air salting apparatus illustrated in figure 3. Details of the salting technique and the dynamic air apparatus can be found in reference 5, 6, or 12.

Stress-corrosion exposure. - Subsequent to being coated with salt, specimens were creep exposed in static air in a standard lever-arm creep-loading frame. Specimens were stressed over the range 210 to 760 MN/m^2 (30 to 110 ksi). Stresses were cycled by automatically lowering and raising the load pan of the creep frame. Timers were used to control both the stress and temperature cycles. The two exposure temperatures studied were 320° and 430° C (600° and 800° F).

Specimens were subjected to one type of combined temperature and stress cycle, to four types of temperature cycle, and to one type of stress cycle. All the exposure cycles (A to F) used in this investigation are illustrated in figure 4. In all cases the total time at the 320° C (600° F) exposure temperature was 96 hours, and the total time at the 430° C (800° F) exposure temperature was 96 hours.

A quartz lamp furnace was used to reduce the time required to heat specimens to the stress-corrosion exposure temperatures. The thermal profiles resulting from the use of this furnace are shown in figure 5. Heating times from room temperature to the two exposure temperatures were 3 and 5 minutes, respectively. For the 1 hour on/1 hour off and 3 hours on/1 hour off thermal cycles, the specimens cooled to only about 75° C (170° F) instead of to room temperature (35° C (95° F)). The subsequent heating times to the two exposure temperatures for these cycles were about 2 and 3 minutes, respectively. These rapid heating and cooling rates were intended to simulate those experienced by typical turbine engine compressor components during startup and shutdown. Exposure to determine residual ductility. Tensile testing was conducted at room temperature at a constant crosshead speed of 0.01 cm/min (0.005 in./min). These tensile testing conditions had previously been determined to provide high sensitivity to embrittlement resulting from stress-corrosion (ref. 12). Elongation was measured over a 2.54-centimeter (1.00-in.) gage length. Apparent-reduction-of-area data were determined from changes of only the outside diameter of the tubular specimens. A complete listing of all test conditions and results is contained in table I.

Post-test evaluation. - After tensile testing the fracture surface of each specimen was examined under a microscope at 30X for evidence of stress-corrosion cracking. Cracks as small as 0.003 centimeter (0.001 in.) deep could be identified (ref. 6). They were covered with oxides and corrosion products and located at the origin of a distinct crescent-shaped fracture plane on the fracture surface. For example, a crack only 0.007 centimeter (0.003 in.) deep is apparent in figure 6. This type of cracking definitely occurred during the hot-salt stress-corrosion exposure. Such an examination

of the fractured specimen surfaces then allowed a crack threshold stress curve to be determined.

Measurement of deposited salt. - Concentrations of deposited salt were measured on the bore of each of the fractured specimens (table I). The reported concentrations represent the average of the values measured on each of the two broken portions. These measurements were made with a commercially available, chemical titration technique for soluble chlorides (ref. 13).

RESULTS AND DISCUSSION

Combined Temperature and Stress Cycling

One cycle was studied in which both temperature and stress were cycled simultaneously. Specimens were stressed and heated to the exposure temperatures, held for 1 hour, and then unstressed and allowed to cool to room temperature for 3 hours. This cycle was repeated 96 times so that the total exposure time for both temperature and stress was 96 hours. This cycle was chosen to simulate a time-temperature flight profile of turbine aircraft.

The hot-salt stress-corrosion crack threshold curve determined for this combined temperature and stress cyclic exposure is shown in figure 7 (cycle A). The crack threshold stresses at both exposure temperatures, 320° and 430° C (600° and 800° F), are about twice the stresses determined for continuous exposures (ref. 6). It is possible that the threshold stress at the lower exposure temperature of 320° C (600° F) may be even greater than the 760 MN/m² (110 ksi) indicated in figure 7. Normal, unsalted creep-rupture limitations of the Ti-8Al-1Mo-1V alloy precluded exposing specimens at any higher stress levels (fig. 1).

It is immediately apparent from these combined temperature and stress cyclic tests that such cyclic exposures substantially reduce the detrimental effects of hot-salt stress-corrosion. Specifically, crack threshold stresses were substantially greater for cyclic exposures than for continuous exposures for equivalent total times. However, the individual roles of cyclic temperature and cyclic stress exposures can not be ascertained from the results determined for a combined temperature and stress cycle. The following two sections of this report are concerned with the specific, individual roles of both temperature and stress.

Temperature Cycling

The crack threshold curves determined in this investigation for four different cyclic temperature exposures are also presented in figure 7. For all cycles, specimens were

stressed continuously during the test (during heating, during time at the exposure temperatures, and during cooling). For all cycles, the total time at the exposure temperature was 96 hours.

Cycle B - 1 hour on/3 hours off. - This temperature cycle resulted in crack threshold stresses approximately 100 percent greater than those determined for continuous exposures at both exposure temperatures, 320° C (600° F) and 430° C (800° F). This threshold curve is equivalent to that determined for the combined temperature and stress cycle (cycle A, 1 hour on/3 hours off) discussed in the previous section.

Cycle C - 3 hours on/3 hours off. - This temperature cycle resulted in a crack threshold stress about 90 percent greater than that determined for the continuous-exposure baseline at 320° C (600° F). However, no difference was observed between this cyclic exposure and continuous exposures at the higher temperature of 430° C (800° F).

Cycle D - 1 hour on/1 hour off. - This temperature cycle resulted in a threshold stress about 60 percent greater than that determined for continuous exposure at the lower exposure temperature of 320° C (600° F). No difference between this cyclic exposure and continuous exposure was determined at the higher exposure temperature of 430° C (800° F).

Cycle E - 3 hours on/1 hour off. - This temperature cycle resulted in a threshold curve identical to that determined for cycle D. Specifically, this temperature cycle resulted in a crack threshold stress about 60 percent greater than that determined for continuous exposures at 320° C (600° F). No difference between this cyclic exposure and continuous exposure was determined at the higher exposure temperature of 430° C (800° F).

The increases in crack threshold stresses observed for some of these cyclic temperature exposures are consistent with previously reported increases in crack nucleation times. The investigations of the effects of cyclic thermal exposures reported in the literature range from qualitative observations to elaborate simulated engine cyclic exposures. However, in all cases only the exposure temperature was cycled while the stress applied to the specimen remained constant.

It has been reported that for temperature cycling between 340° and 22° C (650° and 72° F) cracks that formed in the Ti-8Al-1Mo-1V alloy during any given cycle did not propagate during subsequent cycles - new cracks formed instead (ref. 7). Increased embrittlement was reported for the Ti-8Al-1Mo-1V alloy as the duration of each thermal cycle at 290° C (550° F) was increased from 2 to 16 hours. The total exposure times ranged from 50 to 800 hours (ref. 8). In another study (ref. 9), no cracking was observed in the Ti-8Al-1Mo-1V alloy for a cycle consisting of 2.5 hours at 290° C (550° F) and 10 minutes at 22° C (72° F) for a total exposure time of 2000 hours. Similar exposure in a continuous mode resulted in severe stress-corrosion cracking.

A more extensive investigation (ref. 10) with several titanium alloys indicated that both the cyclic time at the exposure temperature and the subsequent time at room temperature were important. Crack nucleation times were extended from 54 hours to in excess of 168 hours at 290°C (550°F) only when the time at temperature was less than that required to form the corrosion product titanium dichloride (TiCl_2) (<3 hr) and only when the time near or at room temperature was long enough to result in the decomposition of the same corrosion product (>5 hr). Therefore, it appears that titanium dichloride is the chemical species to whose formation and/or decomposition crack nucleation is related.

Additional support for this concept has been reported by other investigators. Titanium dichloride has been postulated (ref. 14) to be an intermediate corrosion product in a sequence of chemical reactions which ultimately result in the embrittling corrosion product hydrogen. Titanium dichloride is easily hydrolyzed to titanium oxide when exposed to a moist environment. Presumably, such hydrolysis would be a function of the relative humidity at or near room temperature. Therefore, not only are the effects of cyclic thermal exposures determined in this investigation consistent with the general effect of increased crack nucleation times reported in the literature, but the relation between the cyclic time at the exposure temperature and the cyclic cooling time is consistent with the role of titanium dichloride postulated by others. The results of this investigation have shown that for a significant beneficial effect to result from limiting exposure time to 1 hour per cycle, such an exposure must be followed by a cooling time of about 3 hours. For example, the 1 hour on/3 hours off cycle increased threshold stresses by about 100 percent compared with the baseline, whereas the 1 hour on/1 hour off cycle resulted in an increase in threshold stress of only 60 percent or less. As noted in the section Test Procedure, cooling cycles of 1 hour resulted in minimum specimen temperatures of about 75°C (170°F) as compared with temperatures of about 35°C (95°F) resulting from 3-hour cooling cycles. The influence of this slight temperature differential on the process of decomposition of titanium dichloride is not known by the authors and, therefore, has not been considered in this report.

It is unlikely that the beneficial effects of cycling exposure temperature are related to hydrogen other than the fact that hydrogen generation is directly controlled by the corrosion product titanium dichloride. Since the diffusion rate of hydrogen decreases during the cooling portion of the cycle, and since the specimens were stressed continuously during the entire exposure cycle, it is improbable that local concentrations of hydrogen tended to decrease. However, it is possible that the oxide formed during hydrolysis near room temperature would retard further corrosion and hydrogen absorption during subsequent reheating cycles.

Stress Cycling

The crack threshold curve determined under stress-cycling conditions is also shown in figure 7. Cycle F consisted of stressing the specimens for 1 hour and then releasing the load for 3 hours. This cycle was repeated 24 times while the specimens were held at the exposure temperatures continuously for 96 hours. A substantial increase of about 90 percent was determined for the cyclic threshold stress at 320° C (600° F) as compared with the continuously stressed baseline threshold. However, at 430° C (800° F) there was no difference between cyclic and continuous threshold stresses.

It is immediately apparent from these results that such a stress cycle is more effective in reducing hot-salt stress-corrosion cracking than either the D or E temperature cyclic exposures. In addition the threshold curve for this stress cycle is equivalent to that determined for the C temperature cycle.

There are two possible roles that stress may play in the process of hot-salt stress-corrosion cracking of titanium alloys. Stress may result in the mechanical rupture of the normally protective oxide on titanium alloys or it may influence the diffusion and segregation of corrosion-produced hydrogen.

It is the opinion of the authors that the mechanical rupture of the normally protective oxide by an applied stress plays a minor or nonexistent role in the process of hot-salt stress-corrosion of titanium alloys. There is no experimental evidence that applied stress ruptures such oxides during isothermal hot-salt stress-corrosion exposures, let alone during cyclic exposures. In addition it is unlikely that the process of mechanical rupture would be altered so drastically over the temperature range 320° to 430° C (600° to 800° F). As was pointed out previously, cycling stress had a significant beneficial effect at the lower exposure temperature and no effect at the higher exposure temperature.

On the other hand the results determined in this investigation regarding the effect of a cyclic stress exposure are consistent with several aspects of the role of hydrogen in the process of hot-salt stress-corrosion. There is experimental evidence that hydrogen is produced during hot-salt stress-corrosion (refs. 3, 6, 12, and 14 to 17) and that hydrogen segregates to highly stressed regions to concentration levels of the order of thousands of parts per million (ref. 16). Previous research reported in the literature (ref. 15) had demonstrated that initially uniformly hydrogenated, tapered titanium alloy specimens had the highest concentrations of hydrogen after creep exposure at the region of highest stress. One of the present authors (ref. 16) has demonstrated that corrosion-produced hydrogen segregates to below fracture surfaces and to the vicinity of cracks in hot-salt stress-corroded titanium alloy specimens. Local concentrations of hydrogen of several thousand ppm were measured on a microscopic scale as compared with an average bulk concentration of only 100 ppm (ref. 16).

Hence, it is apparent that the diffusion and segregation of corrosion-produced hydrogen are strongly influenced by applied stress and local stress concentrations. Therefore, cyclic applications of stress have the potential of substantially altering the distribution of hydrogen and the resultant severity of hot-salt stress-corrosion cracking. The buildup of a high local concentration of hydrogen is severely hindered because it can concentrate only during the short times when the stress is applied and then homogenization of the hydrogen occurs when the stress is removed.

We would expect such a process to be influenced by exposure temperature. At higher exposure temperatures, increased corrosion and hydrogen diffusion rates and higher hydrogen solubilities would result in an increased total hydrogen content and a more homogeneous distribution of hydrogen. These effects would tend to mask any beneficial effects of stress cycling at higher exposure temperatures, as evidenced by the greater increases in cyclic threshold stress at 320° C (600° F) than at 430° C (800° F), as compared with the continuous-exposure baseline threshold stress.

CONCLUDING REMARKS

Cyclic Exposures

This investigation has demonstrated for the first time that exposures in which simultaneous cycling of both temperature and stress occurs result in less susceptibility to hot-salt stress-corrosion cracking of titanium alloys than continuous exposure at the same temperature and stress. In addition, reduced susceptibility to cracking was also confirmed, as reported by others (refs. 7 to 10), for exposures where temperature but not stress was cycled. These cyclic effects lend additional support to the already considerable body of evidence that suggests that corrosion-produced hydrogen is the embrittling species in the process of hot-salt stress-corrosion. Some of these previously reported facts are (1) embrittlement is sensitive to test strain rate and temperature (ref. 12); (2) ductility can be recovered by vacuum annealing (ref. 12); (3) a noncorroded, brittle zone exists at the crack tip ahead of the corrosion zone (ref. 17); and (4) thousands of ppm of hydrogen have been measured in localized regions near fracture surfaces and crack tips (ref. 16).

It is suggested that the following sequence of events occurs during elevated-temperature hot-salt stress-corrosion exposures: Corrosion-produced hydrogen diffuses to regions of high triaxial stress, such as beneath corrosion pits and at crack tips. Such hydrogen-enriched regions are embrittled and crack normal to the direction of applied stress. Cracks propagate through the embrittled region until blunted by plastic deformation in the ductile matrix. Further cracking requires additional diffusion of hydrogen and embrittlement of the region in front of the new crack tip. This

sequential process can continue as long as sufficient hydrogen is supplied by the corrosion reactions occurring near the crack mouth and as long as the favorable conditions of high temperature and stress-induced diffusion are not interrupted.

It is probable that the effects of surface condition and alloy and phase composition are most significant during initial surface corrosion. Hydrogen absorption is known to be affected by alloy composition and crystal structure (refs. 18 to 20). Processing and heat-treating variables which affect alloy microstructure can exert an influence both on the hydrogen embrittlement characteristics (refs. 21 and 22) and on the crack propagation or fracture toughness characteristics of the alloy (refs. 23 to 25).

Exposure cycle has the potential of being the most influential of the variables that affect hot-salt stress-corrosion of titanium alloys. Cycling stress can reduce the embrittling influence of stress-induced diffusion and segregation of corrosion-produced hydrogen. Cycling temperature can lessen an alloy's susceptibility to stress-corrosion by retarding the production of the intermediate corrosion product titanium dichloride and thereby directly reducing the production of hydrogen. It was also suggested (ref. 14) that cyclic thermal exposures can be beneficial in reducing hydrogen absorption if protective oxides are formed during the room-temperature portion of the thermal cycle. In summary, cyclic exposures have a beneficial effect on all stages of the process of hot-salt stress-corrosion and can significantly reduce the detrimental effect of some individual stages of the stress-corrosion process.

Relation of Hot-Salt Stress-Corrosion to Turbine Engine Operation

Previous investigations by the authors (refs. 5 and 6) have demonstrated that the major variables influencing hot-salt stress-corrosion are (1) the processing conditions, heat-to-heat variations, and composition of the alloy; and (2) the specimen surface condition. This investigation has shown that exposure cycle is also a major variable.

Under simulated compressor environmental conditions, hot-salt stress-corrosion cracking of the commonly used Ti-6Al-4V alloy occurred only at stresses greater than the creep design limits of the alloy. Since most compressor components are shot peened to increase fatigue resistance, these components also exhibit increased resistance to stress-corrosion. Cyclic exposures to stress-corrosion conditions are not as detrimental as are continuous exposures for equivalent total times.

These major variables affecting susceptibility of titanium alloys to hot-salt stress-corrosion explain the lack of service failures of titanium components in current gas-turbine engines. However, there is still reason for concern that there may be some service failures in the future as developmental engines call for newer, stronger titanium alloys such as Ti-5Al-6Sn-2Zr-1Mo-0.2Si. The susceptibility of this alloy to hot-salt stress-corrosion cracking is extremely sensitive to processing conditions

(ref. 6). Such alloys are intended for use at high operating stresses and temperatures and for long cyclic periods at peak thrust. Under such operating conditions the beneficial effects of both cyclic exposures and shot peening would be reduced.

SUMMARY OF RESULTS

The purpose of this investigation was to determine the influence of exposure cycle on the hot-salt stress-corrosion cracking resistance of a titanium alloy. Salt-coated specimens of the Ti-8Al-1Mo-1V alloy were creep exposed at temperatures of 320^o and 430^o C (600^o and 800^o F). Both temperature and stress were cycled simultaneously to simulate a service cycle for current turbine-powered aircraft. Temperature and stress were also cycled independently to determine their individual effects. For all cycles, the total time at the exposure temperatures was 96 hours. The results obtained from these cyclic exposures were then compared with the baseline 96-hour-continuous-exposure hot-salt stress-corrosion crack threshold. They are as follows:

1. In general, all the cyclic exposures studied in this investigation resulted in higher hot-salt stress-corrosion crack threshold stresses than did the baseline, continuous exposure for the same total exposure time.
2. A specific cycle of both temperature and stress being applied to specimens for 1 hour and then removed for 3 hours resulted in crack threshold stresses about 100 percent greater than the continuous-exposure baseline threshold stresses at both exposure temperatures.
3. For a temperature cycle consisting of 1 hour on and 3 hours off, the crack threshold stress was 100 percent greater than the baseline at both exposure temperatures.
4. For a temperature cycle of 3 hours on and 3 hours off, the crack threshold stress was increased about 90 percent at 320^o C (600^o F). For temperature cycles of 1 hour on and 1 hour off and 3 hours on and 1 hour off, the crack threshold stress was about 60 percent greater than the baseline at 320^o C (600^o F). No change in threshold stress from the baseline was observed at 430^o C (800^o F) for any of these three cyclic temperature exposures.
5. A cyclic stress exposure of 1 hour on and 3 hours off resulted in a crack threshold stress at 320^o C (600^o F) that was about 90 percent greater than the baseline. No change in threshold stress from the continuous-exposure baseline was observed at 430^o C (800^o F) for the cyclic stress exposure.

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TABLE I. - HOT-SALT STRESS-CORROSION CRACKING CYCLIC EXPOSURE DATA

Specimen	Exposure conditions				Tensile test data						Salt concentration		Heat-tinted cracks
	Temperature		Stress		Ultimate stress		Fracture stress		Apparent reduction of area, percent	Elongation, percent	mg/cm ²	mg/in. ²	
	°C	°F	MN/m ²	ksi	MN/m ²	ksi	MN/m ²	ksi					
Cycle A - temperature and stress 1 hr on/3 hr off													
478	320	600	620	90	1020	148	910	132	34	19	0.11	0.7	No ↓ Yes
472	320	600	760	110	1110	161	990	144	32	15	.05	.3	
486	320	600	760	110	1140	165	1060	154	28	11	.08	.5	
470	430	800	280	40	1010	147	970	141	32	16	.11	.7	
477	430	800	350	50	1020	148	1020	148	14	7	.14	.9	
Cycle B - temperature 1 hr on/3 hr off													
466	320	600	620	90	1020	148	940	137	31	16	0.16	1	No ↓ Yes Yes
487	↓	↓	690	100	1040	151	920	134	33	18	.05	.3	
496	↓	↓	760	110	1100	159	990	144	27	13	.08	.5	
490	↓	↓	760	110	1080	157	940	137	35	16	.08	.5	
400	430	800	280	40	1030	150	1030	150	12	8	.16	1	
450	↓	↓	280	40	1020	148	890	129	37	18	.09	.6	
464	↓	↓	350	50	1010	146	1010	146	10	5	.14	.9	
474	↓	↓	350	50	940	137	940	137	6	1	.11	.7	
Cycle C - temperature 3 hr on/3 hr off													
499	320	600	620	90	1030	149	910	132	35	16	0.06	0.4	No No Yes ↓
485	320	600	690	100	1030	150	940	136	26	17	.05	.3	
492	320	600	760	110	1020	148	1020	148	17	11	.06	.4	
469	430	800	210	30	1020	148	1020	148	13	10	.16	1	
463	430	800	240	35	830	120	830	120	4	1	.11	.7	
391	430	800	280	40	970	141	970	141	7	2	.14	.9	
Cycle D - temperature 1 hr on/1 hr off													
482	320	600	480	70	1010	147	950	138	26	16	0.11	0.7	No No Yes Yes Yes
484	320	600	550	80	1010	147	890	129	34	19	.09	.6	
483	320	600	620	90	1010	146	1010	146	10	5	.09	.6	
455	430	800	210	30	760	110	760	110	4	1	.14	.9	
459	430	800	280	40	940	136	940	136	7	1	.08	.5	
Cycle E - temperature 3 hr on/1 hr off													
488	320	600	480	70	1030	149	920	133	33	16	0.08	0.5	No No Yes Yes Yes
494	320	600	550	80	1010	147	920	133	32	18	.11	.7	
493	320	600	620	90	1030	149	1030	149	16	10	.08	.5	
460	430	800	210	30	1020	148	1020	148	12	9	.11	.7	
442	430	800	240	35	900	131	900	131	6	1	.09	.6	
Cycle F - stress 1 hr on/3 hr off													
489	320	600	480	70	1010	146	890	129	36	19	0.09	0.6	No ↓ Yes Yes
501	↓	↓	550	80	1010	147	900	130	37	19	.06	.4	
500	↓	↓	620	90	1010	147	890	129	35	20	.08	.5	
498	↓	↓	620	90	1030	150	920	134	33	18	.14	.9	
497	↓	↓	690	100	1020	148	950	138	26	15	.09	.6	
491	↓	↓	690	100	1040	151	1040	151	17	10	.09	.6	
454	430	800	210	30	960	139	960	139	4	1	.14	.9	

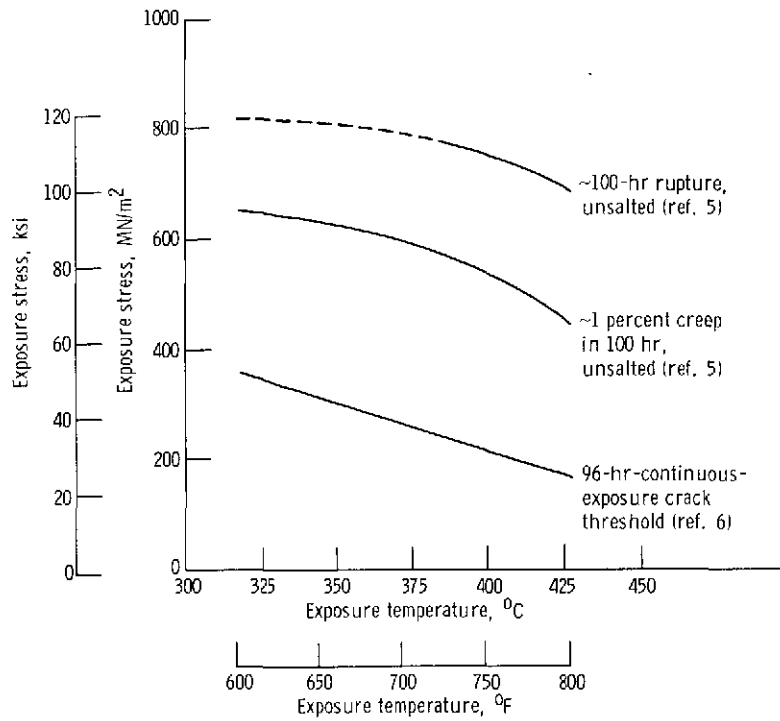


Figure 1. - Baseline creep and 96-hour-continuous-exposure hot-salt stress-corrosion crack threshold data. (Chemically milled tubular specimens tested in static air.)

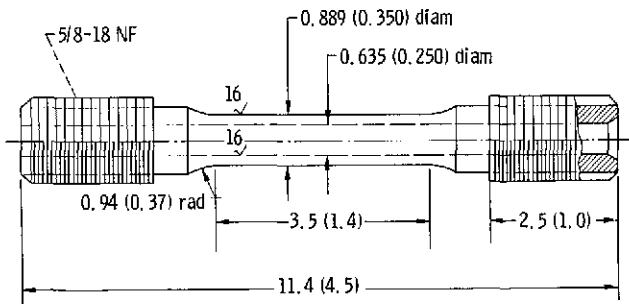


Figure 2. - Tubular, titanium alloy specimens used in this investigation. (Dimensions are in cm (in.)).

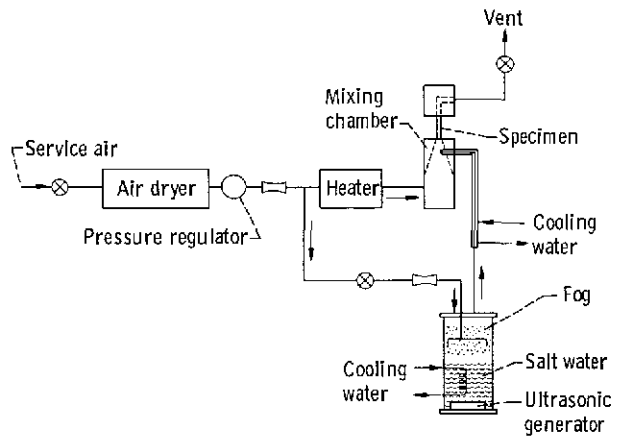


Figure 3. - Apparatus for presalting unstressed specimens.

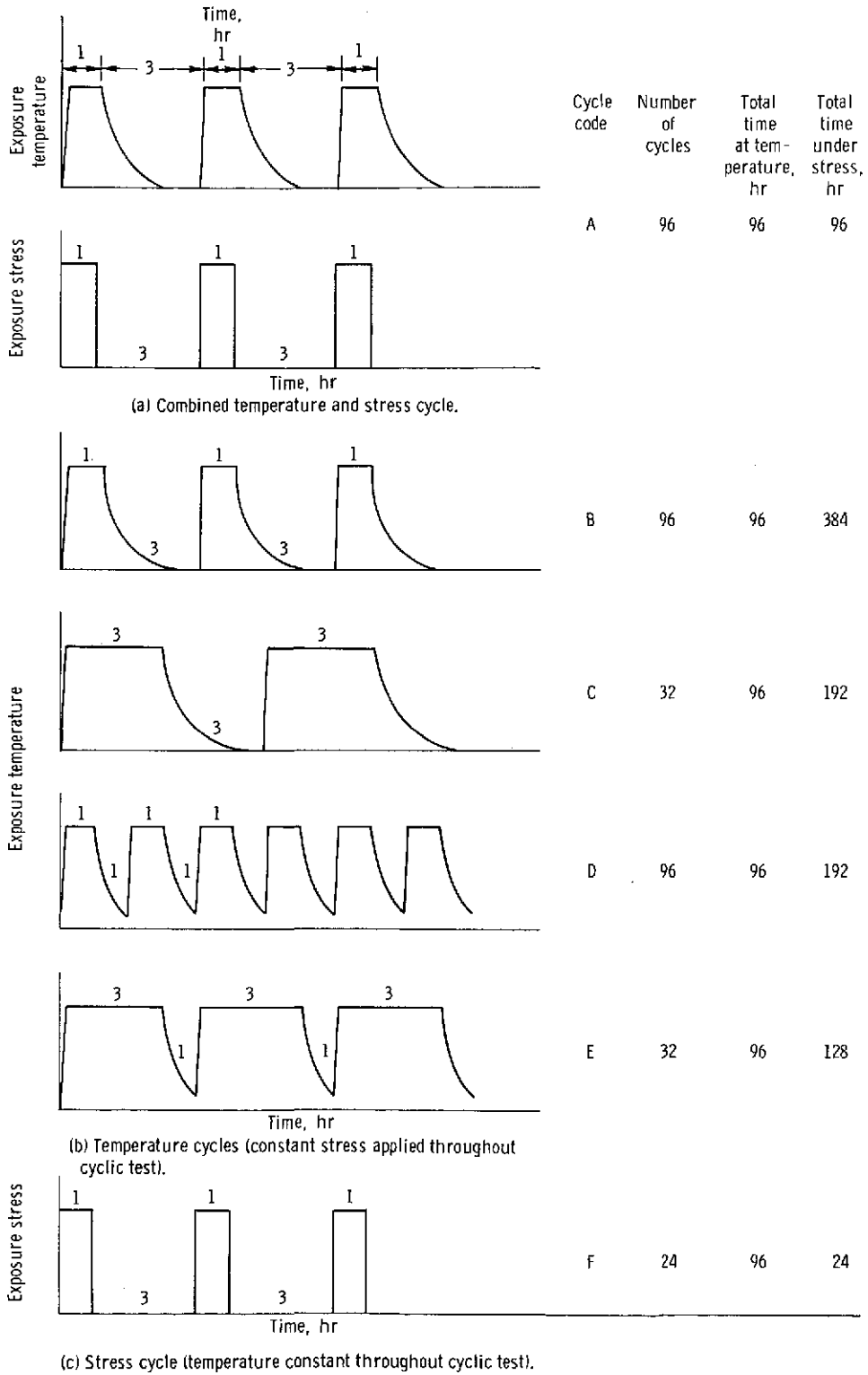


Figure 4. - Cyclic exposures used in this investigation.

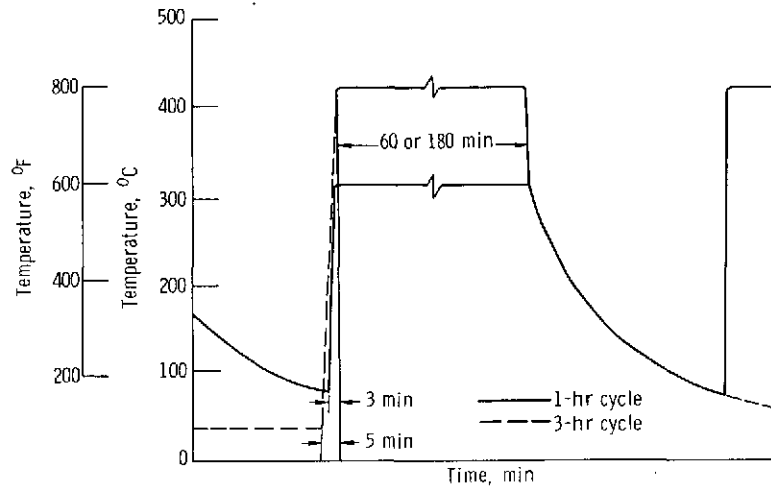


Figure 5. - Heating and cooling profiles of all thermal cycling tests.

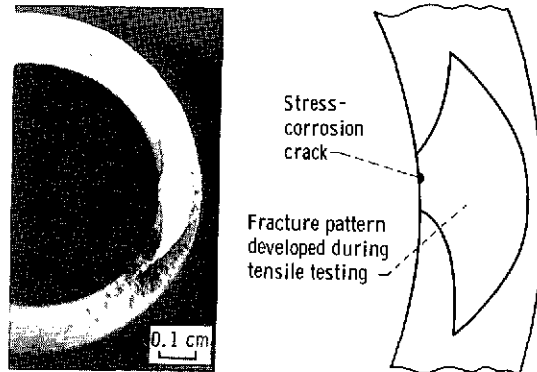


Figure 6. - Photomacrograph of hot-salt stress-corrosion crack.

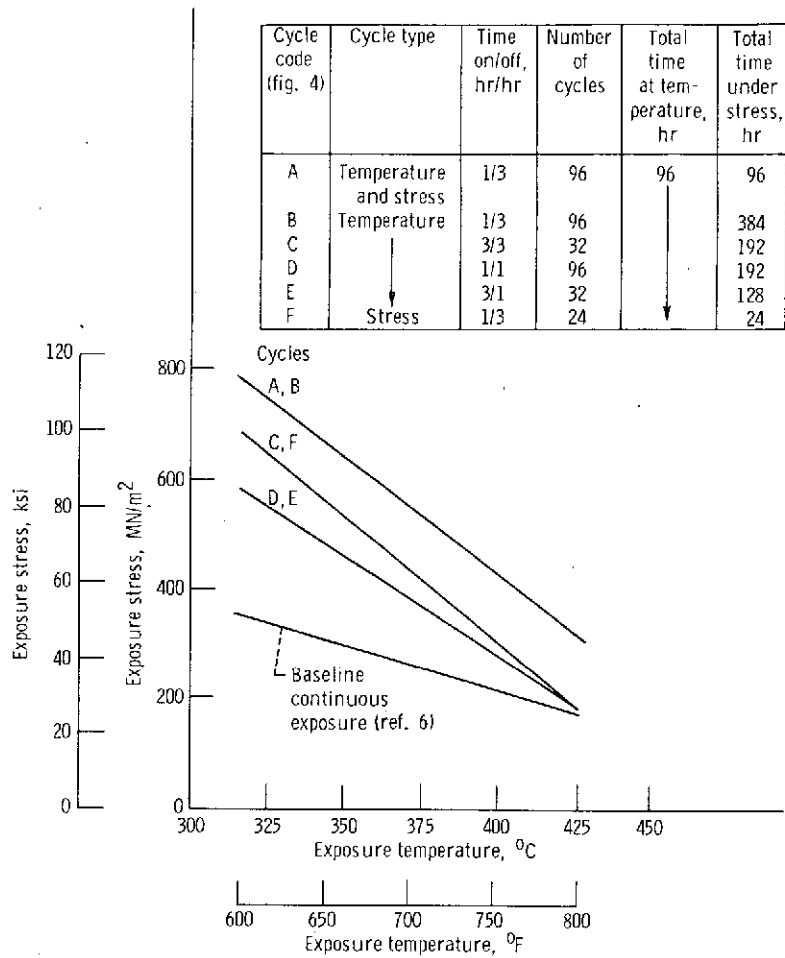


Figure 7. - Cyclic hot-salt stress-corrosion crack thresholds of Ti-8Al-1Mo-1V alloy. (Data obtained only at 320^o and 430^o C (600^o and 800^o F.))