NASA TECHNICAL NOTE

NASA TN D-4674

NASA TN D-4674
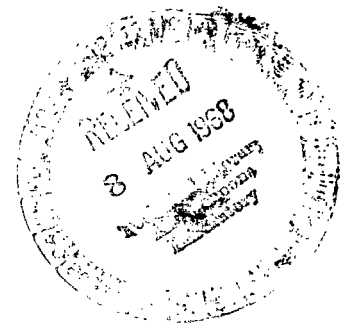
HOT-SALT-STRESS-CORROSION CRACKING AND ITS EFFECT ON TENSILE PROPERTIES OF Ti-8Al-1Mo-1V TITANIUM-ALLOY SHEET

by Dick M. Royster

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1968

HOT-SALT-STRESS-CORROSION CRACKING

AND ITS EFFECT ON TENSILE PROPERTIES OF

Ti-8Al-1Mo-1V TITANIUM-ALLOY SHEET

By Dick M. Royster

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

HOT-SALT-STRESS-CORROSION CRACKING

AND ITS EFFECT ON TENSILE PROPERTIES OF

Ti-8Al-1Mo-1V TITANIUM-ALLOY SHEET

By Dick M. Royster
Langley Research Center

SUMMARY

The concluding phase of an extensive experimental investigation of hot-salt-stress corrosion of the Ti-8Al-1Mo-1V titanium alloy was conducted on self-stressed and tensile specimens of a 0.050-inch- (1.3-mm) thick Ti-8Al-1Mo-1V titanium-alloy sheet (duplex annealed). The self-stressed specimens, with stresses of 50, 25, and 15 ksi $\left(340, 170, \text{ and } 100 \text{ MN/m}^2\right)$, were dipped in a 3.4 percent sodium chloride (NaCl) solution and exposed at temperatures from 400° to 600° F (480° to 590° K) for exposures up to 20 000 hours. Stress-corrosion cracking was obtained after approximately 17 hours at 600° F (590° K) for the 50 ksi $\left(340 \text{ MN/m}^2\right)$ stress, but no stress-corrosion cracking was noted at 400° F (480° K) at any stress level investigated. The threshold stresses decrease with an increase in exposure temperature and time.

The tensile corrosion specimens were coated with a thin layer of salt (NaCl) and exposed at temperatures from 500° to 600° F (530° to 590° K) at 50 ksi $\left(340 \text{ MN/m}^2\right)$ stress for exposures up to 800 hours to develop and grow stress-corrosion cracks. The presence of stress-corrosion cracks resulted in a large drop in elongation and a moderate decrease in tensile strength. The properties deteriorated more for the transverse specimens than for the longitudinal tensile specimens. The residual tensile properties appeared to be dependent only on the depth of the cracks, regardless of the temperature or time at which the cracks were developed. The stress-corrosion cracks were intergranular, and maximum crack depth could be correlated with exposure time at 550° and 600° F (560° and 590° K).

INTRODUCTION

The susceptibility of various titanium-alloy sheet materials to hot-salt-stress corrosion has been of considerable concern with regard to their possible use as skin materials for a supersonic transport airplane operating at speeds up to Mach 3 (refs. 1 and 2). Such a transport will fly in and out of airports located along sea coasts; therefore, the structure may be subject to salt coating or salt accumulation. This salt,

combined with the normal flight conditions of the supersonic transport in which the skin may be subjected to stresses of 25 ksi (170 MN/m^2) or higher and to temperatures up to 600° F (590° K), produces an environment conducive to salt-stress corrosion.

The initial program to study the susceptibility of titanium alloys to hot-salt-stress corrosion was started at the NASA Langley Research Center in 1962 (ref. 3), and the results indicated that several of the alloys were susceptible to this type of corrosion. Consequently, an extensive investigation of the hot-salt-stress corrosion of titanium-alloy sheets was undertaken. The Ti-8Al-1Mo-1V alloy in the duplex annealed condition was emphasized because of its desirable strength and stiffness properties. Test results obtained on Ti-8Al-1Mo-1V titanium alloy through 1965 are summarized in reference 4, which includes stress-corrosion data and environmental effects for exposures up to 6400 hours at 400° to 600° F (480° to 590° K). The investigation of this alloy has continued and exposures up to 20 000 hours have now been completed. Reference 5 reported on the susceptibility of residually stressed Ti-8Al-1Mo-1V titanium-alloy sheet to hot-salt-stress corrosion. Another recent investigation (ref. 6) reported on coatings and surface treatments for long-time protection of Ti-8Al-1Mo-1V titanium-alloy sheet from hot-salt-stress corrosion.

The present paper summarizes the results of the investigation of hot-salt-stress-corrosion cracking of Ti-8Al-1Mo-1V titanium-alloy sheet in the 400° to 600° F (480° to 590° K) range for exposures up to 20 000 hours and stresses of 50, 25, and 15 ksi $(340,$ 170, and 100 $\text{MN/m}^2)$. Data are shown on the exposure times, stresses, and temperatures where salt-stress-corrosion cracking is initiated. Also included are the extent, depth, and effect of stress-corrosion cracks on the room-temperature residual tensile properties after exposure at 500° to 600° F (530° to 590° K) for up to 800 hours at a stress of 50 ksi (340 MN/m^2).

The units used for the physical quantities defined in the paper are given both in U.S. Customary Units and in the International System of Units (SI) (ref. 7). Factors relating the two systems are given in appendix A.

SPECIMENS AND EXPERIMENTAL PROCEDURES

Material

All specimens were fabricated from Ti-8Al-1Mo-1V titanium-alloy sheets (0.050-inch (1.3-mm) nominal thickness) supplied in the duplex annealed condition. Duplex annealing consists of 8 hours at 1450° F (1060° K) with a furnace cool to room temperature followed by 15 minutes at 1450° F (1060° K) with air cooling to room temperature. The following information on the chemical composition of this material was supplied by the producer:

2

Element	Weight, percent
Al	7.9
Mo	1.1
V	1.0
Fe	0.11
C	0.026
N	0.011
H_2	0.003 to 0.006
Ti	Balance

Specimens

Self stressed.- For the self-stressed specimens (fig. 1(a)), flat strips were sheared from the titanium-alloy sheet so that the longitudinal axis was parallel to the rolling direction. The strips were then run through a commercial vibratory cleaning and deburring process to remove shearing burrs. Next, the strips were machined to desired dimensions and vibratorily cleaned and deburred a second time.

In general, the self-stressed specimen is constructed by bending up the ends of each 1/4 by 4 inch (0.60 by 10.20 cm) strip to some predetermined bend angle and clamping and spotwelding the ends together to induce a uniform curvature. Bending stresses corresponding to this curvature are determined from geometrical and stress-strain relationships (ref. 8) by using the measured value d, which is the distance between the strips. (See fig. 1(a).) Stresses are increased by increasing the bend angle of the strip thus increasing d. The self-stressed specimens were designed for room-temperature maximum outer fiber tensile stresses of 50, 25, and 15 ksi $(340, 170, 100$ MN/m$^2)$. The table in figure 1 shows the calculated tensile stresses for each value of d. Specific details of the fabrication and cleaning processes are given in reference 3.

Inasmuch as the vibratory treatment was subsequently found to be effective in preventing stress corrosion (ref. 6), elimination of this effect was necessary in order to study the stress-corrosion characteristics. Etching 1 mil (25 μm) from each surface with a solution of 18 percent HNO_3, 3 percent HF, and 79 percent H_2O, by volume, proved sufficient for this purpose.

Tensile corrosion.- For the tensile specimen's, blanks were sheared from the titanium-alloy sheet in both the longitudinal and transverse directions of rolling, and the specimens were machined into the desired configuration (fig. 1(b)). The tensile specimen conforms to the specification prescribed by the American Society for Testing and Materials (ref. 9).

Salt Coating

Self-stressed specimens.- Salt coatings were applied to the self-stressed specimens by dipping the specimens at room temperature twice in a 3.4 percent by weight solution of sodium chloride and distilled water. The first dip wetted one of the two curved portions of the specimen and was followed by an air drying cycle in an oven at 200° F (370° K). The specimens were then turned over and the remaining curved portion was dipped, after which the specimens were again subjected to a second drying cycle at 200° F (370° K). In this manner a thin film of salt crystals was formed on both curved portions of the self-stressed specimens.

Tensile corrosion specimens.- Salt coatings were applied to the tensile corrosion specimens by suspending them horizontally, with a flat surface up, and depositing the salt solution over the entire reduced section with an eye dropper. The specimens were suspended over the opening of a vertical tube furnace to accelerate drying. After drying, the specimens were turned over and the process was repeated. In this manner a thin film of salt crystals was formed in the reduced section on both flat surfaces of the tensile corrosion specimens.

Temperature Exposure

Self-stressed specimens.- Salt-dipped and control (no salt) specimens were subjected to continuous heating at 400°, 450°, 500°, 550°, or 600° F (480°, 500°, 530°, 560°, or 590° K) in circulating air ovens for various exposures up to 20 000 hours. Specimens were removed from the ovens after selected exposure times and mechanically tested at room temperature.

Tensile corrosion specimens.- The salt-coated tensile corrosion specimens were exposed at 500°, 550°, or 600° F (530°, 560°, or 590° K) at a stress of 50 ksi $\left(340 \text{ MN/m}^2\right)$ for selected exposure times up to 800 hours in deadweight loading machines equipped with tube furnaces to develop and grow stress-corrosion cracks. After selected exposures, the specimens were removed from the furnaces and deadweight loading machines and tested in tension at room temperature. Control specimens (no salt) were exposed in the deadweight loading machines at 600° F (590° K) for 800 hours at a stress of 50 ksi $\left(340 \text{ MN/m}^2\right)$ to determine the effect of the elevated temperature exposure on the residual material properties.

Mechanical Tests

Self-stressed specimens.- The effects of the hot-salt-stress corrosion on specimen shortening were determined from compression tests at room temperature on the self-stressed specimens. The specimens were loaded in a 120-kip (530 kN) capacity testing machine. A special fixture (ref. 10) was used to aline upper and lower clamps with the

4

specimen. The clamps supported the specimen vertically in the hydraulic testing machine during the compression test. The load was applied at a constant head speed of 0.1 in./min (40 μm/sec) until the maximum load was reached. Then an increased head speed of 0.4 in./min (170 μm/sec) was applied until fracture occurred at which time loading was stopped. The head displacement, which is equivalent to specimen shortening, was then measured with a 6-inch (15-cm) scale having 0.01-inch (0.25-mm) graduations.

Figure 2 is a schematic drawing which illustrates the specimen configuration obtained in the room-temperature compression test of self-stressed specimens and the effect of stress-corrosion cracking on the shortening. A more detailed discussion of this test is found in reference 4. In general, the results obtained can be explained by the following discussion and figure 2. The uncoated, unexposed specimens develop the maximum shortening δ_0. If stress-corrosion cracking occurs in the salt-dipped and exposed specimens, the specimens are damaged and fracture will occur at a reduced amount of shortening. Uncoated specimens that have been exposed in the ovens together with the salt-dipped specimens are defined as control specimens. The change in shortening of the control specimens after the different oven exposures is a measure of the effect of the exposures on the bend ductility of the material. If the material is affected by the exposure, the shortening of the control specimens may also be affected. The ratio δ/δ_0, the shortening of the exposed specimens to that for the uncoated, unexposed specimens, is a measure of the stress-corrosion cracking or bend ductility of the material or both. This ratio is defined as relative shortening.

Tensile corrosion specimens.- The residual strength of stress-corrosion cracked tensile specimens of Ti-8Al-1Mo-1V was determined by room-temperature tensile tests after the elevated-temperature stress exposure. These tests were conducted under controlled strain-rate conditions in a hydraulic testing machine of 100-kip (445 kN) capacity and equipped with a load-strain recorder. A strain rate of 0.005 per minute was maintained through yield stress at which point the rate was increased to 0.050 per minute until fracture occurred. Two linear variable differential transformer strain gages were employed in the room-temperature tests to measure strain over a gage length of 1 inch (2.54 cm). In order to avoid possible mechanical damage to the transformer strain gages, wire strain gages were used for the transverse specimens on which fracture might be expected to occur before the yield stress was reached. The uniform elongation over 1 inch (2.54 cm) was measured from the increase in length between transverse parallel lines spaced 0.25 inch (0.60 cm) apart on the reduced section of the specimen in the region where necking did not occur. The elongation measurements in 2 inches (5 cm) included the necked-down and fracture region of the test specimen. The measurements were made with a 6-inch (15 cm) scale having 0.01-inch (0.25-mm) graduations.

Crack Detection and Measurements

To detect the presence of salt-stress-corrosion cracks in the titanium-alloy speci-
mens, several crack identification methods, including red-dye and fluorescent-dye pene-
trants and chemical etches were used.

Penetrant inspection is a simple, nondestructive process applicable only to surface
defects. First, the material to be inspected is cleaned. Second, a colored liquid pene-
trant is applied to the surface of the material and is allowed to remain until it penetrates
into cracks or defects open at the surface; however, the finest imperfections may not
always be penetrated. Third, the excess penetrant on the surface is removed and an
absorbent, light-colored, powdered material called a developer is applied to the surface.
This developer acts as a blotter and draws out a portion of the colored penetrant which
has seeped into the surface openings. As the penetrant is drawn out, it diffuses into the
coating of the developer and forms positive indications of cracks or surface defects.
Ultraviolet light is required to detect the cracks when fluorescent-dye penetrants are
used, because the cracks are observed by the glow of fluorescent material that is drawn
out of the cracks by the developer.

An etch that has been used in chemical milling of titanium alloys was found to be
very effective in revealing stress-corrosion cracks. The etch consists of 1 part concen-
trated hydrofluoric acid (HF), 6 parts hydrogen peroxide (H_2O_2) (30 percent concentra-
tion), and 3 parts water, by volume. The specimens to be etched are dipped in the solu-
tion at room temperature for 30 seconds, then removed and washed in distilled water. If
cracks are present, they are revealed without additional surface preparation and can be
readily seen at low magnification or with the naked eye.

Neither the penetrants nor special etch methods are satisfactory for determining
details of the depth and metallurgical characteristics of the cracks. For this type of
examination, specimens are edge mounted in plastic and wet ground to remove about
1/8 inch (0.3 cm) of material from the edge. The specimens were polished and then
chemically etched at room temperature for 15 seconds with a solution of 97 percent
water, 2 percent nitric acid (HNO_3), and 1 percent hydrofluoric acid (HF), by volume.
In a few instances further grinding and polishing were needed before cracks could be
located in the specimens. Crack penetration was measured with a microscope having a
filar micrometer eyepiece. The number of cracks on the surface of the specimen, mag-
nified 50X, were counted by using a microscope. Specimens were also mounted face up to
study the extent of surface cracking. Most of these specimens had been mechanically
tested prior to examination; however, a few specimens were examined prior to loading.

RESULTS AND DISCUSSION

Hot-Salt-Stress-Corrosion Crack Initiation

The results of the salt-stress-corrosion tests of Ti-8Al-1Mo-1V titanium-alloy sheet stressed at 50, 25, and 15 ksi $\left(340, 170, \text{ and } 100 \text{ MN}/\text{m}^2\right)$ and exposed up to 20 000 hours at 400° to 600° F (480° to 590° K) are shown in figure 3. (Results up to 5000 hours are reported in reference 4.) Data for both salt-dipped and control (no salt) specimens are shown in figure 3. The curves were drawn approximately through the average of the test points. The increasing severity of the salt-stress-corrosion cracking with exposure time is evidenced by a reduction in the relative shortening δ/δ_0. Also shown in figure 3 is the approximate threshold for salt-stress-corrosion cracking for the stresses and temperatures investigated. This threshold is defined as the approximate time when the relative shortening curve for the salt-dipped specimens begin to deviate significantly from the relative shortening curve for the control specimens. It should be noted that because of the nature of the results, crack initiation times cannot be determined precisely. The existence of stress-corrosion cracks in the specimens for exposures to the right of the threshold of the curves was verified by microscopic examination. In general, specimens exposed for combinations of temperature, time, and stress to the left of the threshold showed no cracks after exposure and mechanical testing. The thresholds were selected with consideration of both the relative shortening curves in figure 3 and the microscopic examination of the test specimens.

The titanium alloy appears to be relatively unaffected by the different exposure conditions as indicated in figure 3 by the small reduction in relative shortening of the control specimens. This reduction (no more than 10 percent) appears to be due to a slight aging effect in the duplex annealed titanium alloy. Microscopic examination of the control specimens after exposure showed no evidence of cracking.

The most severe stress-corrosion cracking noted in this investigation occurred at the highest temperature (600° F (590° K)) and stress $\left(50 \text{ ksi } \left(340 \text{ MN}/\text{m}^2\right)\right)$. (See fig. 3(a).) The results indicate that salt-stress-corrosion cracking may be expected after approximately 17 hours exposure at 600° F (590° K) for a 50 ksi $\left(340 \text{ MN}/\text{m}^2\right)$ stress. Stress-corrosion cracking is initiated at 550°, 500°, and 450° (560°, 530°, and 500° K) in approximately 200, 1600, and 2500 hours, respectively, for the 50 ksi $\left(340 \text{ MN}/\text{m}^2\right)$ stress. No evidence of stress-corrosion cracking was found at 400° F (480° K) for the three stresses investigated. (See fig. 3(e).) In general, the severity of the corrosion cracking decreases with a decrease in stress and temperature.

Threshold curves for the initiation of salt-stress-corrosion cracking for Ti-8Al-1Mo-1V titanium-alloy sheet are shown in figure 4. The curves were constructed from the threshold data in figure 3. The faired curves (fig. 4) give the temperatures for

the initiation of stress-corrosion cracks for exposures up to 20 000 hours and stresses up to 50 ksi $\left(340 \text{ MN/m}^2\right)$. To the left of any particular curve, no stress-corrosion cracking occurred; to the right, stress-corrosion cracking can be expected. No threshold curve is shown for 400° F (480° K) because no stress corrosion was found at that temperature for the stresses and exposure times investigated. At 450° F (500° K) stress-corrosion cracking is initiated in 5000 hours at a stress of about 35 ksi $\left(240 \text{ MN/m}^2\right)$ and for the same stress at 550° F (560° K) corrosion cracking is initiated in approximately 1000 hours.

The threshold stresses for salt-stress-corrosion cracking (fig. 4) are represented by a family of smooth curves decreasing in a consistent manner with temperature. This systematic trend in the data suggests that time-temperature parameters may be applicable. Accordingly, both Larson-Miller and the Orr-Sherby-Dorn parameters (ref. 11) were investigated to determine their suitability for correlating the stress-corrosion crack initiation data. The Larson-Miller parameter indicated a satisfactory correlation at 50 ksi $\left(340 \text{ MN/m}^2\right)$ for 500° F (530° K) and above; however, poor correlation was obtained at the lower stresses and temperatures. Improved correlation was obtained with the Orr-Sherby-Dorn parameter and the results are shown in figure 5. In this figure the stresses for crack initiation are plotted against the logarithmic form of the Orr-Sherby-Dorn parameter $\left(\log t - \dfrac{\Delta H}{2.3 R T_K}\right)$ where t is the time in hours, ΔH is activation energy (calculated to be 20 000 cal/mole (83.7 kJ/mole), R is the gas constant (2.0 cal/mole °K (8.4 J/mole °K)) and T_K is the temperature in degrees Kelvin. The data points indicate NASA data reported in this study and the bracket at 100 ksi $\left(690 \text{ MN/m}^2\right)$ indicates the range of data obtained at the Savannah River Laboratory (ref. 12). The cross-hatched area encompasses all the data except one NASA test result. A straight line or master curve averages these data points. Although some scatter in the results exists, particularly at 50 ksi $\left(340 \text{ MN/m}^2\right)$, the correlation of the data through the application of the time-temperature parameter appears feasible. Note particularly that excellent correlation exists between the NASA data and that obtained in reference 12. It thus appears that hot-salt-stress-corrosion-crack initiation can be predicted approximately over a broad range of stresses, times, and temperatures with the use of the Orr-Sherby-Dorn time-temperature parameter.

Effect of Stress-Corrosion Cracking on Tensile Properties

The results of the room-temperature tensile tests of the exposed, salt-coated tensile specimens as well as for the uncoated, unexposed and control specimens (no salt) are given in table I. Figure 6 shows the effect of the salt-stress corrosion cracks on residual tensile and yield strengths and uniform elongation at room temperature after an 800-hour exposure at 50 ksi $\left(340 \text{ MN/m}^2\right)$ stress and at temperatures from 500° to

600$^{\text{O}}$ F (530$^{\text{O}}$ to 590$^{\text{O}}$ K). The data for the uncoated, unexposed specimens and the control (no salt) specimens are also shown in figure 6. The tensile strength of the corrosion cracked specimens was reduced in both the longitudinal and transverse directions (figs. 6(a) and (b)) with a maximum reduction of 12 and 22 percent, respectively, after the 600$^{\text{O}}$ F (590$^{\text{O}}$ K) exposure. This reduction in strength is based on the strength of the uncoated, unexposed specimens. For the same exposure the control specimens showed only a slight reduction in tensile strength, which indicates that this combination of temperature and time had little or no effect on the tensile properties of the material. There was little effect on the yield strength of the corrosion cracked specimens in the longitudinal direction (fig. 6(a)); however, except for all the results at 500$^{\text{O}}$ F (530$^{\text{O}}$ K) (fig. 6(b)) and the exceptions noted at the other temperatures in table I, the transverse specimens fractured before the yield stress was reached.

In contrast to the moderate decrease in tensile strength, a large drop in uniform elongation was obtained for the salt-coated specimens. (See fig. 6.) A severe embrittlement of the material due to the corrosion cracks is thus indicated. The transverse specimens (fig. 6(b)) had zero elongation at 600$^{\text{O}}$ F (590$^{\text{O}}$ K), and the longitudinal specimens (fig. 6(a)) were only slightly better with an elongation of approximately 1 percent. On the basis of the loss in tensile strength and large reduction in elongation above 500$^{\text{O}}$ F (530$^{\text{O}}$ K), stress-corrosion cracking can have very detrimental effects on residual tensile properties.

Crack Detection and Characterization

Crack detection.- An extensive study was made of the corrosion cracks which developed in the tensile corrosion specimens after exposure at 500$^{\text{O}}$ to 600$^{\text{O}}$ F (530$^{\text{O}}$ to 590$^{\text{O}}$ K). Red-dye and fluorescent-dye penetrants were utilized to detect the presence of corrosion cracks in the specimens.

Of the two penetrants utilized, the fluorescent dye penetrant gave the best indication of the presence of surface cracks. A photograph of Ti-8Al-1Mo-1V titanium-alloy specimen containing corrosion cracks detected by this method is shown in figure 7(a). The 20× enlargement (fig. 7(b)) is from the center portion of the specimen. The cracks are seen as the blurred white areas in the photograph. Surface flaws such as scratches, pits, and abrasions are also detectable by this method.

The chemical etch was found to give positive identification of corrosion cracks without special surface preparation. Surface cracks could be observed in the specimens without the use of visual aids. The 50× enlargement (fig. 8) of the area adjacent to the fracture shows how readily this method can be used for crack identification and for counting the number of cracks present in a specimen. This method is not applicable to a detailed study of the cracks because their original size and shape is enlarged slightly by the etch.

Crack characteristics.- Once cracks have been detected, they can be readily studied in detail by mounting, polishing, and lightly etching the specimen. (This method is described in the section entitled "Specimens and Experimental Procedures.")

The photographs of the surfaces adjacent to the fracture of four tensile specimens illustrate the use of this method (fig. 9). These specimens were tested at room temperature after they had been salt coated and exposed for 800 hours at 550° and 600° F (560° and 590° K) at 50 ksi $\left(340 \text{ MN/m}^2\right)$ stress. The load was applied horizontally in relation to the photographs in figure 9, and the cracks are normal to the applied load. This figure illustrates the characteristic small size and large number of surface cracks obtained under these conditions. The cracks are usually more visible and numerous near the edge of the fracture, which is on the left side of each photograph. The cracks are not dispersed uniformly across the specimen surface even though the entire surface was salt coated. Control specimens which had been loaded to failure in tension showed no evidence of cracking.

Typical crack penetration in the Ti-8Al-1Mo-1V titanium alloy is shown in figure 10(a) for an edge-mounted transverse tensile specimen which had been exposed with a 50 ksi $\left(340 \text{ MN/m}^2\right)$ stress at 600° F (590° K) for 600 hours and tested at room temperature. An enlargement of one of the cracks (fig. 10(b)) shows that the corrosion attack is intergranular.

Although the number of surface cracks observed (such as illustrated in fig. 9) could not be correlated with temperature and exposure times, a correlation was found between crack penetration and temperatures for the different exposure times as shown in figure 11. The curves give the maximum crack depths for the tensile specimens in the longitudinal and transverse directions obtained at 550° and 600° F (560° and 590° K) for exposures up to 800 hours at 50 ksi $\left(340 \text{ MN/m}^2\right)$ stress. Approximately 12 measurements were obtained for each test condition and the curves faired through the maximum depths. After 800 hours at 550° and 600° F (560° and 590° K) the maximum crack depths are approximately 15 and 19 mils (380 and 480 μm), respectively, for the transverse specimens. Crack penetrations were not as great in the longitudinal specimens. Maximum depths were only 10 and 12 mils (250 and 300 μm) for the 550° and 600° F (560° and 590° K) tests, respectively. Since the alloy sheet was only 0.05 inch (50 mils (1.3 mm)) thick, the cracks penetrated nearly 40 percent through the sheet in the most severe cases.

An attempt was made to correlate the average crack depth with exposure time and temperature. All the cracks at one cross section were counted for each of the edge-mounted specimens. The number of cracks counted varied from a few at 500° F (530° K) to 200 for the transverse specimens at 600° F (590° K). Regardless of the total number of cracks present at each cross section, nearly half of the cracks were small; thus, the average crack depth for each specimen was approximately 2 to 3 mils (50 to 80 μm)

10

irrespective of exposure time and temperature. Consequently, the average crack depth is considered to be independent of the exposure time and temperature.

Correlation of Crack Penetration With Residual Tensile Properties

In figure 12 the various tensile properties are plotted as a function of the maximum crack depth obtained during the exposures at 550° and 600° F (560° and 590° K). The curves are faired through the test points. Elongation was greatly affected by the presence of cracks. The results show that small cracks (4 mils (100 μm)) drop the elongation from 9 percent for the unexposed, uncracked material to 3 percent. Residual tensile properties appear to be independent of the temperature or time required to grow the crack and depend only on the depth of the crack. There is a moderate loss in tensile strength with increased crack depth, but there is little or no effect of crack depth on the yield strength of the material for the test conditions where the yield was obtained. As noted previously, the transverse specimens for the longer exposures at and above 550° F (560° K) fractured before the yield was reached. Although crack penetration does not have an effect on yield strength it does cause a moderate decrease in residual tensile strength and a large drop in elongation.

CONCLUDING REMARKS

The susceptibility of Ti-8Al-1Mo-1V titanium-alloy sheet (duplex annealed) to hot-salt-stress-corrosion cracking and the effect of corrosion cracks on residual tensile properties are summarized for exposures up to 20 000 hours at temperatures from 400° to 600° F (480° to 590° K) with stresses from 15 to 50 ksi (100 to 340 MN/m^2). The following observations are based upon the findings in this investigation.

1. Stress-corrosion cracking occurred after approximately 17 hours exposure at 600° F (590° K) and at a 50 ksi $\left(340 \text{ MN/}m^2\right)$ stress. No stress-corrosion cracking was found at 400° F (480° K) for exposures up to 20 000 hours. The threshold stresses decrease with an increase in exposure temperature and time. It appears that hot-salt-stress-corrosion crack initiation can be predicted approximately over a broad range of stresses, times, and temperatures through the use of the Orr-Sherby-Dorn time-temperature parameter.

2. The room-temperature tensile elongation properties of the Ti-8Al-1Mo-1V sheet were seriously affected by the development of salt-stress-corrosion cracks. There was a moderate decrease in tensile strength. The properties deteriorated more for the transverse than for the longitudinal tensile specimens. The residual tensile properties appeared to be dependent only on the depth of the cracks, regardless of the temperature or time at which the cracks were developed.

11

3. The stress-corrosion cracks were intergranular. Maximum crack depth could be correlated with exposure time at 550° and 600° F (560° and 590° K).

Langley Research Center,
  National Aeronautics and Space Administration,
    Langley Station, Hampton, Va., February 6, 1968,
      129-03-06-06-23.

APPENDIX A

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures in Paris, October 1960. (See ref. 7.) Factors required for converting the U.S. Customary Units used herein to the International System of Units (SI) are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit (**)
Force	lbf	4.44822	newtons (N)
Length	in.	0.0254	meters (m)
Stress.	ksi	6.895×10^6	newtons/meter^2 $\left(N/m^2\right)$
Temperature . . .	°F	$\frac{5}{9}(F + 459.67)$	degrees Kelvin (°K)
Energy	cal	4.184	joules (J)

*Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI unit.

**Prefixes to indicate multiples of units are as follows:

Prefix	Multiple
giga (G)	10^9
mega (M)	10^6
kilo (k)	10^3
centi (c)	10^{-2}
milli (m)	10^{-3}
micro (μ)	10^{-6}

REFERENCES

1. Heimerl, George J.; and Hardrath, Herbert F.: An Assessment of a Titanium Alloy for Supersonic Transport Operations. Proceedings of the Conference on Aircraft Operating Problems, NASA SP-83, 1965, pp. 215-226.

2. Raring, Richard H.; Freeman, J. W.; Schultz, J. W.; and Voorhees, H. R.: Progress Report of the NASA Special Committee on Materials Research for Supersonic Transports. NASA TN D-1798, 1963.

3. Braski, David N.; and Heimerl, George J.: The Relative Susceptibility of Four Commercial Titanium Alloys to Salt Stress Corrosion at 550° F. NASA TN D-2011, 1963.

4. Heimerl, G. J.; Braski, D. N.; Royster, D. M.; and Dexter, H. B.: Salt Stress Corrosion of Ti-8Al-1Mo-1V Alloy Sheet at Elevated Temperatures. Stress-Corrosion Cracking of Titanium, Spec. Tech. Publ. No. 397, Am. Soc. Testing and Mater., c.1966, pp. 194-214.

5. Dexter, Howard B.: Salt Stress Corrosion of Residually Stressed Ti-8Al-1Mo-1V Alloy Sheet After Exposure at Elevated Temperatures. NASA TN D-3299, 1966.

6. Stein, Bland A.; Dexter, H. Benson; and Royster, Dick M.: Coatings and Surface Treatments for Long-Time Protection of Ti-8Al-1Mo-1V Alloy Sheet from Hot Salt Stress Corrosion. NASA TN D-4319, 1968.

7. Comm. on Metric Prac.: ASTM Metric Practice Guide. NBS Handbook 102, U.S. Dep. Com., Mar. 10, 1967.

8. Heimerl, George J.; and Braski, David N.: A Stress Corrosion Test for Structural Sheet Materials. Mater. Res. and Stnd., vol. 5, no. 1, Jan. 1965, pp. 18-22.

9. Anon.: Tentative Methods of Tension Testing of Metallic Materials. ASTM Designation. E8-61T. Pt. 30 of 1964 Book of ASTM Standards With Related Material. Am. Soc. Testing Mater., c.1964, pp. 127-143.

10. Braski, David N.: Preliminary Investigation of Effect of Environmental Factors on Salt Stress Corrosion Cracking of Ti-8Al-1Mo-1V at Elevated Temperatures. NASA TM X-1048, 1964.

11. Clauss, Francis J.: An Examination of High-Temperature Stress-Rupture Correlating Parameters. Proc. Am. Soc. Testing Mater., vol. 60, 1960, pp. 905-927.

12. Rideout, S. P.: The Initiation of Hot-Salt Stress Corrosion Cracking of Titanium Alloys. Paper presented at ASTM Symposium on Applications Related Phenomena in Titanium Alloys. (Los Angeles, Calif.), Apr. 18-19, 1967.

14

TABLE I.- TENSILE PROPERTIES AND RESIDUAL TENSILE PROPERTIES

OF Ti-8Al-1Mo-1V TITANIUM-ALLOY SHEET

[Exposure stress, 50 ksi]

(a) Longitudinal properties of salt-coated tensile specimens

Specimen	Exposure time, hr	Temperature		Yield strength		Tensile strength		Percent of uniform elongation
		^oF	^oK	ksi	MN/m^2	ksi	MN/m^2	
1	800	600	590	122.4	840	125.7	870	1
2	800			122.4	840	125.6	870	[a]1
3	600			125.2	860	131.4	910	[a]1
4	600			124.6	860	134.3	930	2
5	400			124.2	860	132.0	910	[a]1
6	400			123.8	850	138.5	950	[a]1
7	200			124.8	860	136.6	940	[a]1
8	200			124.7	860	138.5	950	[a]2
9	800	550	560	127.8	880	133.0	920	1
10	800			127.5	880	134.0	920	1
11	600			126.2	870	133.2	920	1
12	600			126.2	870	133.6	920	1
13	400			127.0	880	140.3	970	2
14	400			126.9	880	137.0	940	1
15	200			126.3	870	142.8	980	3
16	200			127.0	880	140.3	970	2
17	800	500	530	128.0	880	143.0	980	2.5
18	800			128.0	880	145.8	1010	5
19	600			128.0	880	146.5	1010	8
20	600			128.3	880	145.8	1010	[a]5.5
21	400			127.8	880	146.5	1010	8
22	400			128.8	890	144.3	1000	[a]4

[a]Fractured outside 2-inch (5-cm) gage length.

TABLE I.- TENSILE PROPERTIES AND RESIDUAL TENSILE PROPERTIES

OF Ti-8Al-1Mo-1V TITANIUM-ALLOY SHEET — Continued

(b) Transverse properties of salt-coated tensile specimens

Specimen	Exposure time, hr	Temperature		Yield strength		Tensile strength		Percent of uniform elongation
		°F	°K	ksi	MN/m²	ksi	MN/m²	
1	800	600	590	(a)		113.0	780	0
2	800			(a)		111.3	770	0
3	600			(a)		114.5	790	[b]1
4	600			(a)		123.7	850	1
5	400			(a)		116.2	800	[b]1
6	400			(a)		110.4	760	[b]1
7	200			126.7	870	141.1	970	1
8	200			127.2	880	142.0	980	1
9	800	550	560	(a)		114.5	790	0
10	800			(a)		126.9	870	1
11	600			(a)		128.5	890	0
12	600			(a)		121.5	840	1
13	400			128.0	880	130.3	900	[b]2
14	400			128.2	880	131.7	910	3
15	200			128.3	890	142.8	990	3
16	200			130.0	900	148.4	1020	3
17	800	500	530	130.0	900	144.8	1000	3
18	800			129.7	900	148.8	1020	[b]7
19	600			131.8	910	146.9	1010	5
20	600			127.7	880	147.8	1020	9
21	400			128.0	880	145.8	1010	6
22	400			127.7	880	147.6	1020	10

[a]Specimen fractured before yield stress was reached.

[b]Fractured outside 2-inch (5-cm) gage length.

TABLE I.- TENSILE PROPERTIES AND RESIDUAL TENSILE PROPERTIES OF Ti-8Al-1Mo-1V TITANIUM-ALLOY SHEET — Concluded

(c) Longitudinal and transverse properties of control (no salt) tensile specimens

Specimen	Exposure time, hr	Temperature		Yield strength		Tensile strength		Percent of uniform elongation
		°F	°K	ksi	MN/m²	ksi	MN/m²	
Longitudinal								
1	800	600	590	129.8	890	142.6	980	8
2	800	600	590	130.5	900	144.0	990	8
Transverse								
3	800	600	590	129.9	900	138.8	960	9
4	800	600	590	129.4	890	138.0	950	8

(d) Uncoated, unexposed tensile specimens

Specimen	Yield strength		Tensile strength		Young's modulus		Percent of elongation	
	ksi	MN/m²	ksi	MN/m²	psi	GN/m²	Uniform	2 in. (5 cm)
Longitudinal								
1	130.0	900	143.5	990	18.07	124.7	9	11.5
2	130.0	900	142.5	990	18.00	124.2	8	11.0
Transverse								
3	130.8	900	144.6	1000	18.63	128.6	9	14.0
4	131.4	910	145.3	1000	18.70	129.0	9	14.0

(.13)
.05

(.64)
.25

4.0
(10.2)

Machined strip

.75
(1.91)

2.50
(6.35)

Bend angle
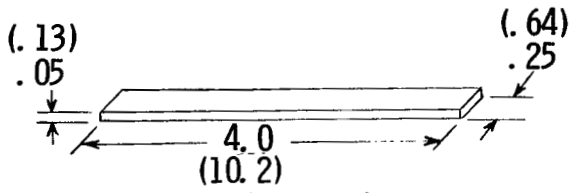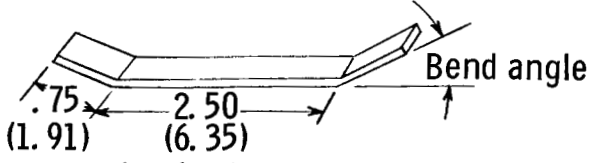
Strip with bent ends

Distance between strips, d		Calculated tensile stress	
in.	cm	ksi	MN/m^2
0.1740	0.442	50	340
.0872	.222	25	170
.0522	.133	15	100

(.48)
.19

d

Spot weld
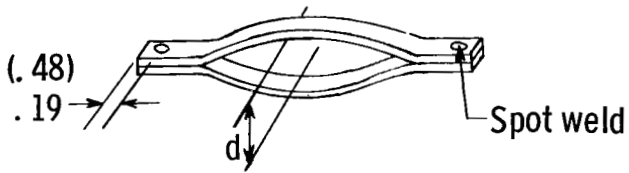
Completed specimen

(a) Construction of self-stressed specimen and calculated tensile stresses.

(61.0)
24.0

(3.18)
1.25

(6.35)
2.50

1
(2.54)

.50
(1.27)

Radius= 3.0
(7.6)

Diameter= .40
(1.03)
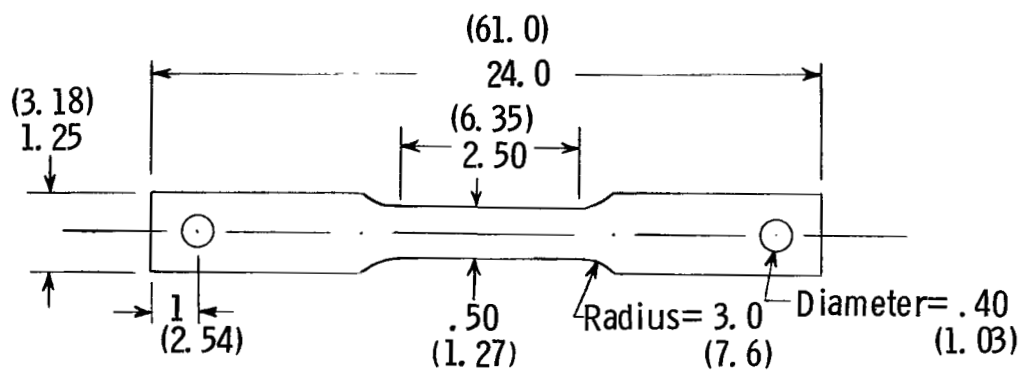
(b) Tensile corrosion specimen.

Figure 1.- Self-stressed and tensile specimens. (Dimensions are shown in inches and parenthetically in centimeters.)

18

Before test

After test

$$\delta_o \quad \text{— Shortening —} \quad \delta$$
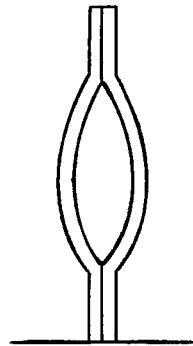
Fracture

Original
specimen
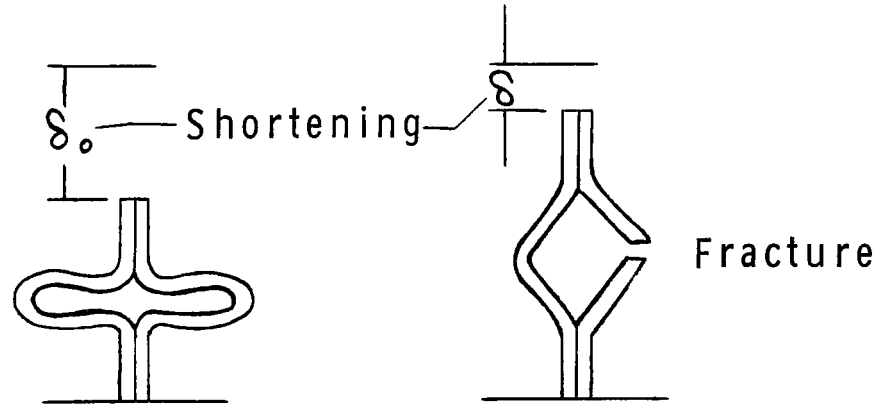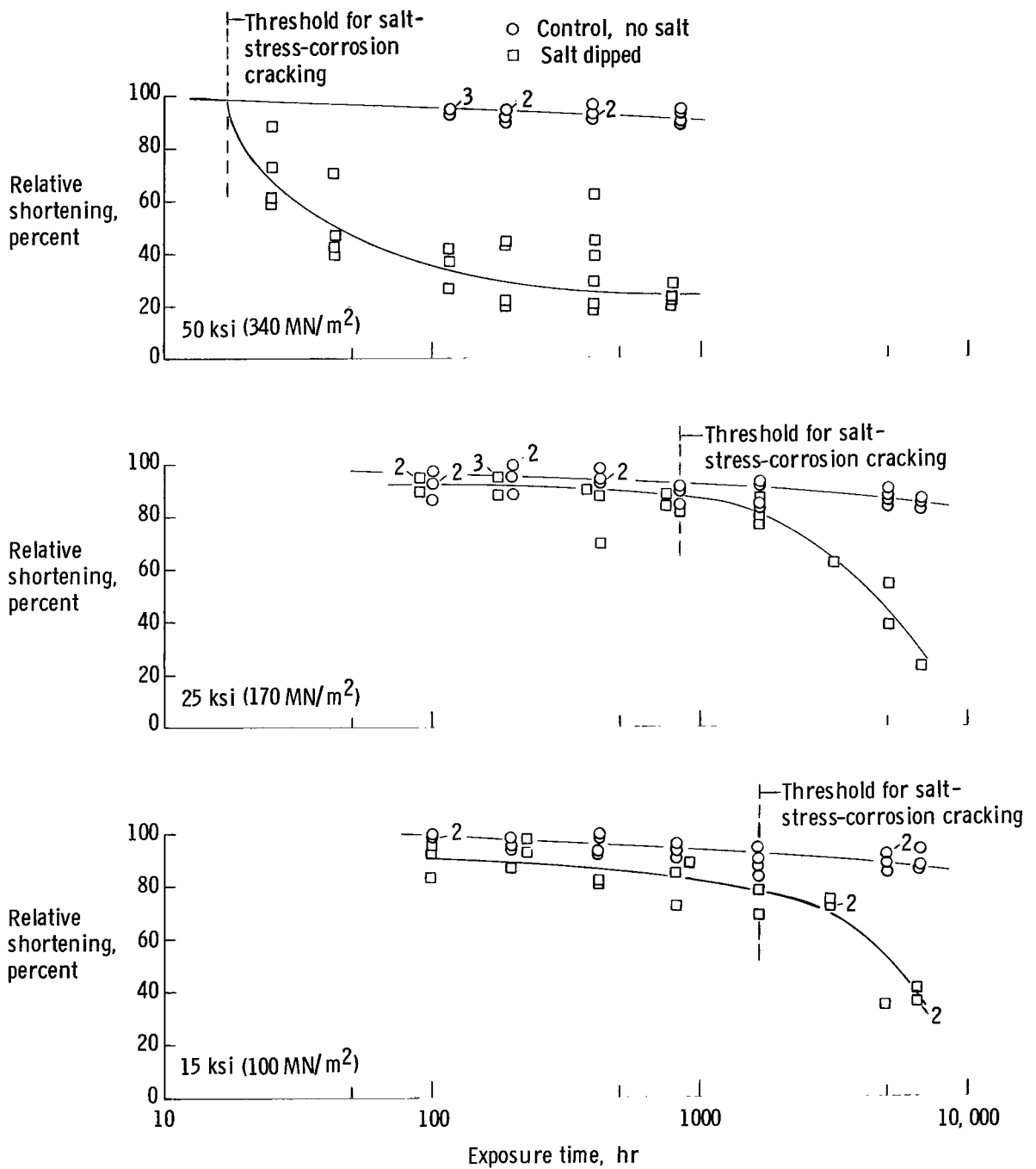
Uncoated,
unexposed

Salt dipped
or control,
exposed
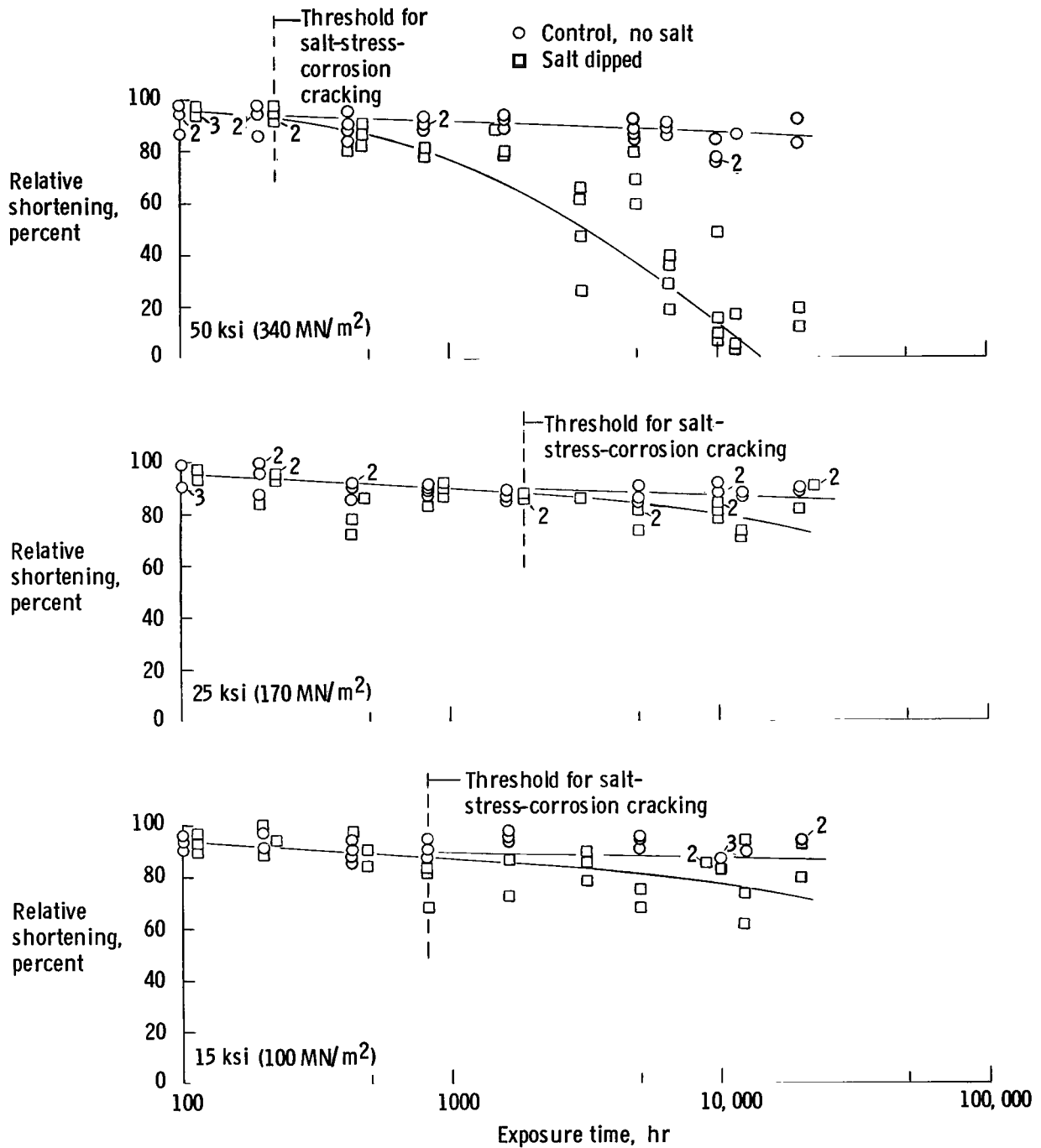
Figure 2.- Specimen configuration before and after room-temperature compression test.

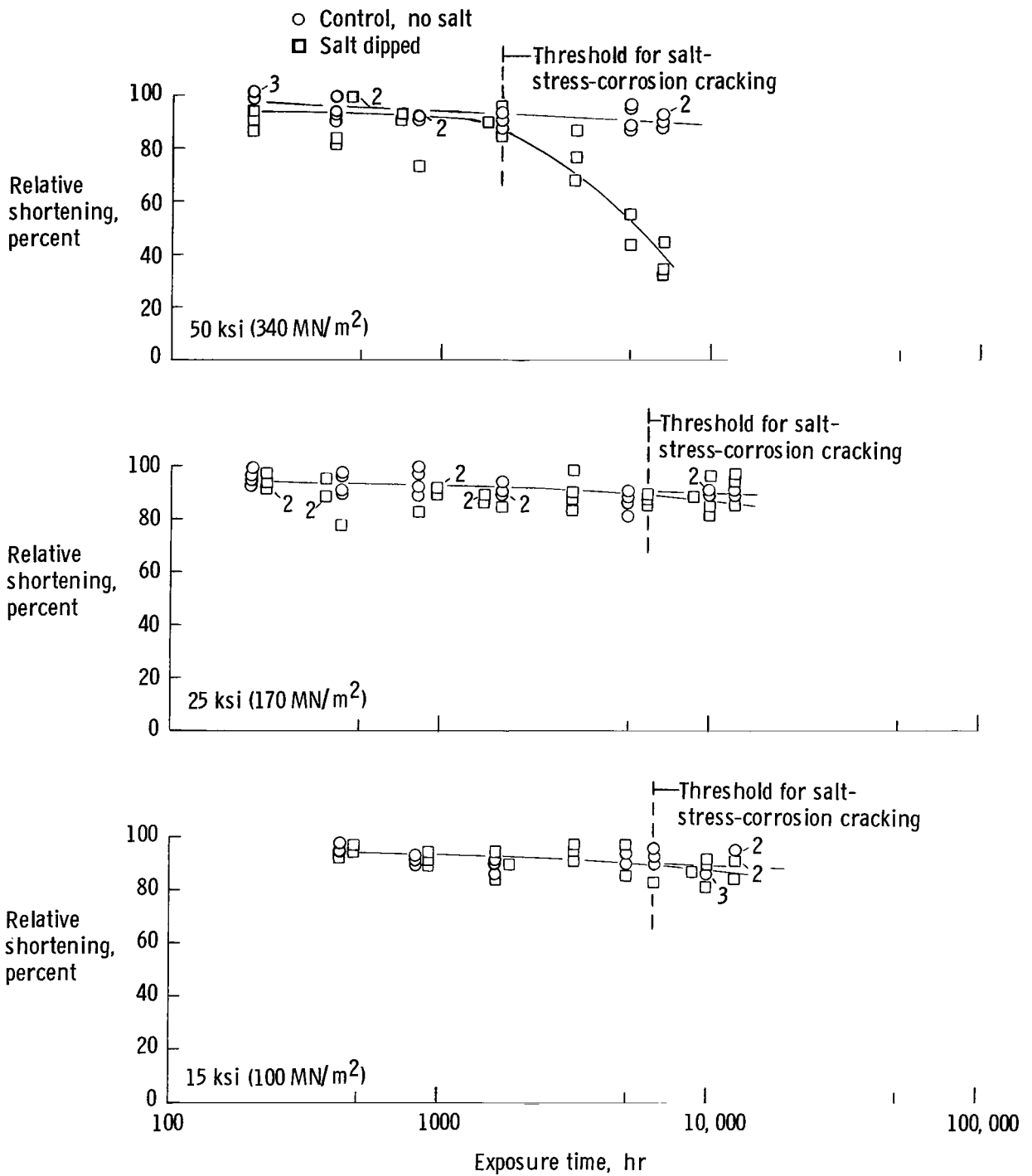Figure 3.- Effect of various temperatures on hot-salt-stress corrosion of self-stressed specimens of duplex annealed Ti-8Al-1Mo-1V alloy sheet for 50, 25, and 15 ksi (340, 170, and 100 MN/m²) stress. (Numbers adjacent to test points indicate duplicate data.)
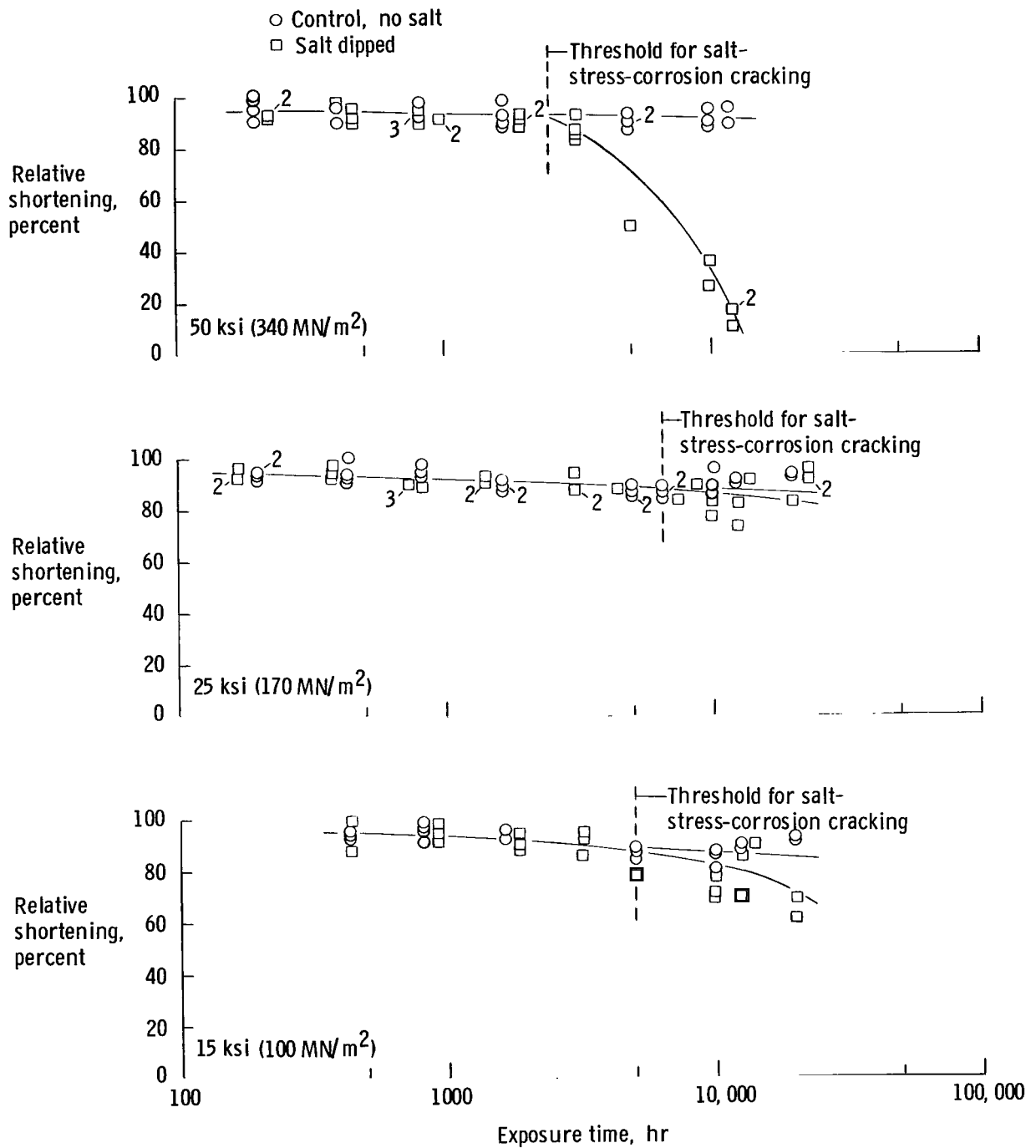
Threshold for
salt-stress-
corrosion
cracking

○ Control, no salt
□ Salt dipped

Relative
shortening,
percent

100
80
60
40
20
0

2 3 2

2

2

2

2

2

50 ksi (340 MN/m²)

Threshold for salt-
stress-corrosion cracking

Relative
shortening,
percent

100
80
60
40
20
0

3

2 2

2

2

2

2

2

2

25 ksi (170 MN/m²)

Threshold for salt-
stress-corrosion cracking

Relative
shortening,
percent

100
80
60
40
20
0

2

2

3

2

15 ksi (100 MN/m²)

100   1000   10,000   100,000

Exposure time, hr

(b) 550° F (560° K).

Figure 3.- Continued.

(c) 500° F (530° K).

Figure 3.- Continued.

(d) 450° F (500° K).

Figure 3.- Continued.

Legend:
- ○ Control, no salt
- □ Salt dipped

50 ksi (340 MN/m^2)

Relative shortening, percent

25 ksi (170 MN/m^2)

Relative shortening, percent

15 ksi (100 MN/m^2)

Relative shortening, percent

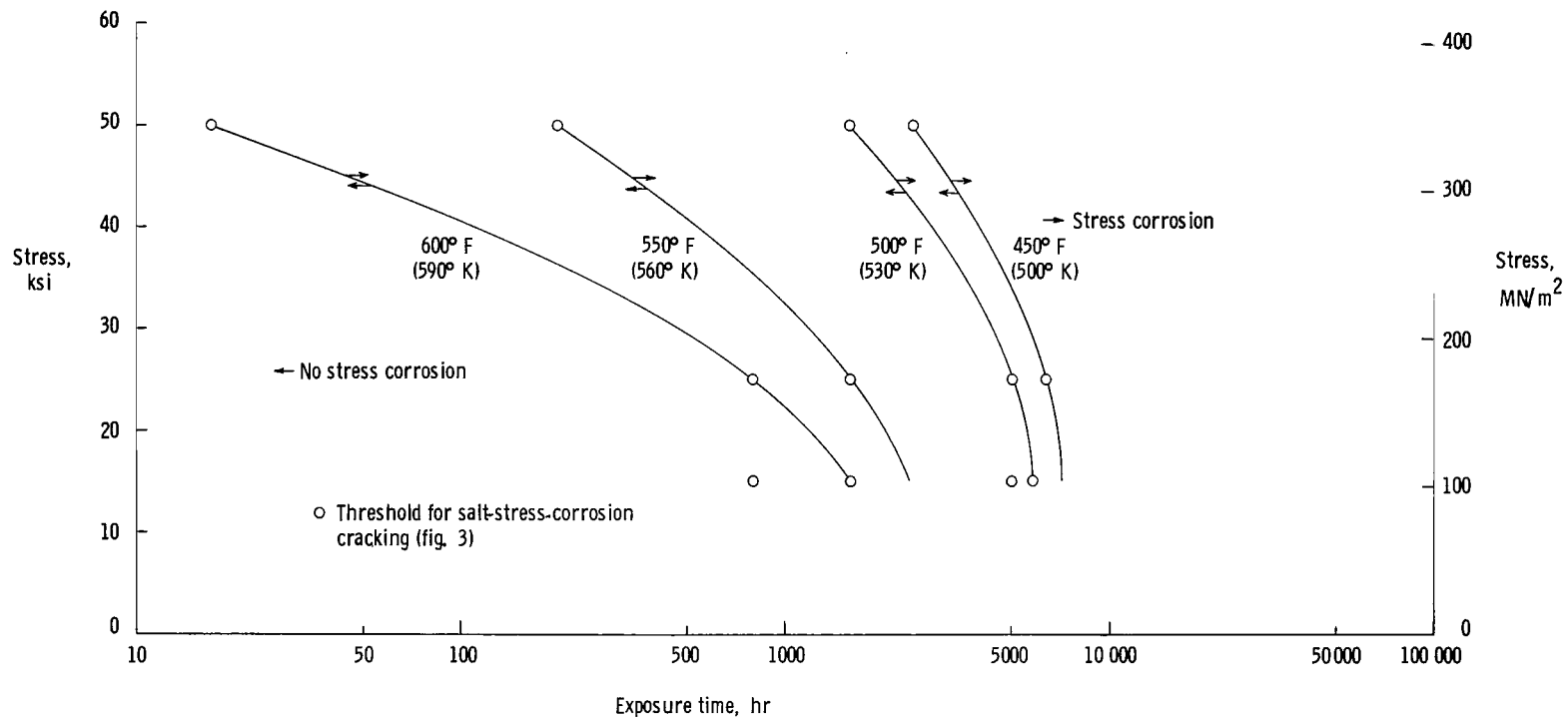Exposure time, hr
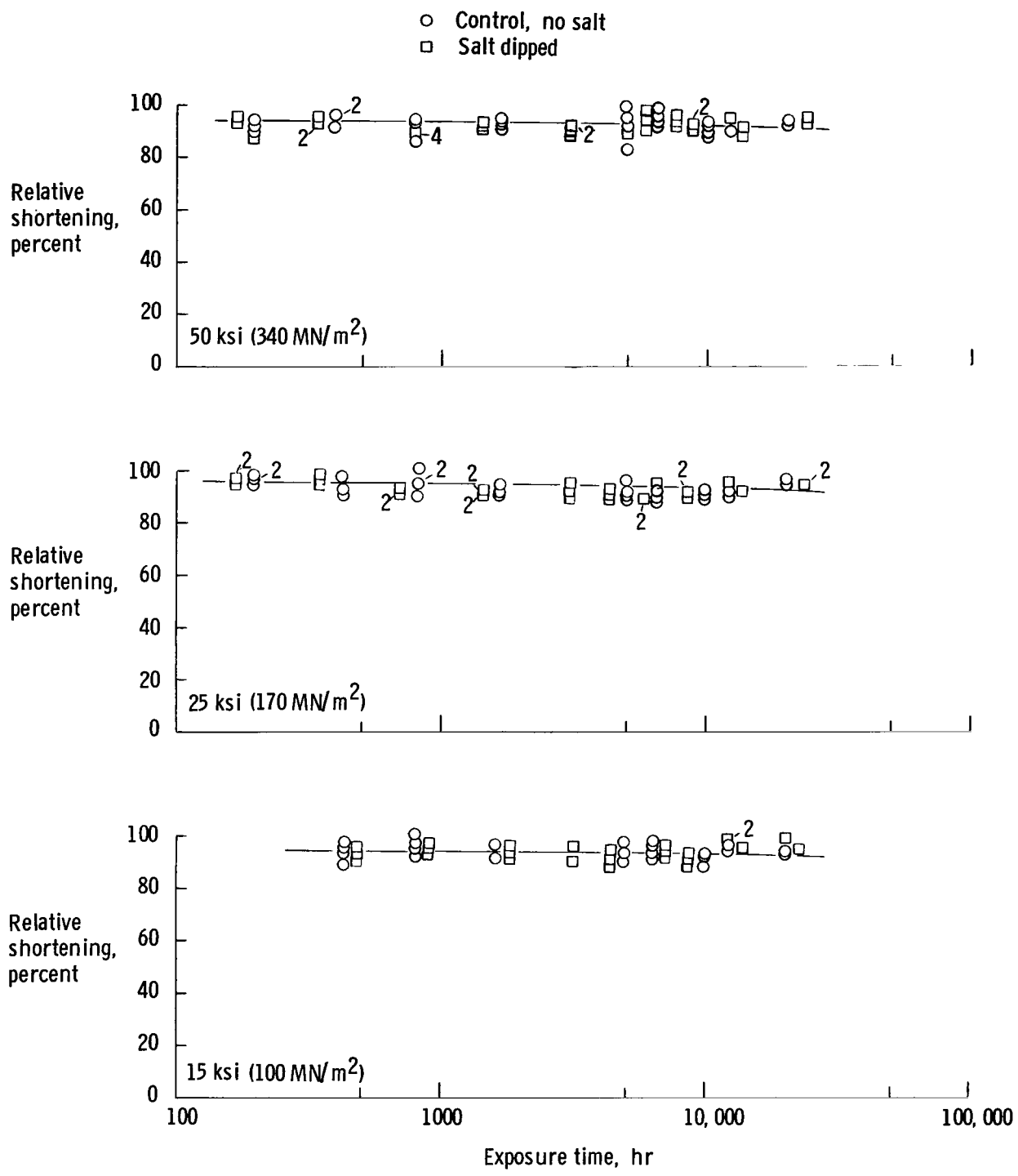
(e) 400° F (480° K).

Figure 3.- Concluded.

Figure 4.- Hot-salt-stress-corrosion crack threshold curves for Ti-8Al-1Mo-1V titanium-alloy sheet exposed up to 20000 hours.
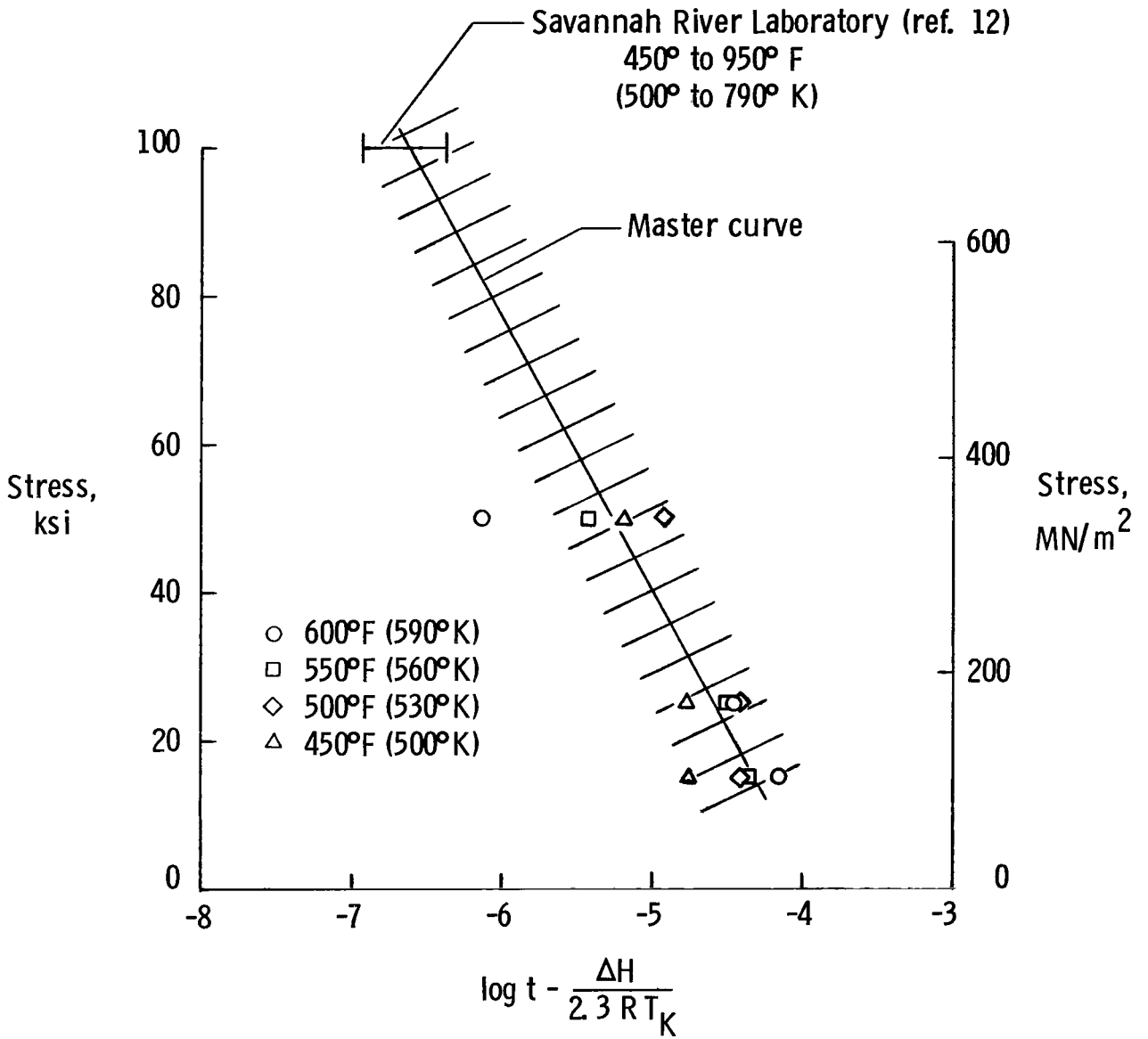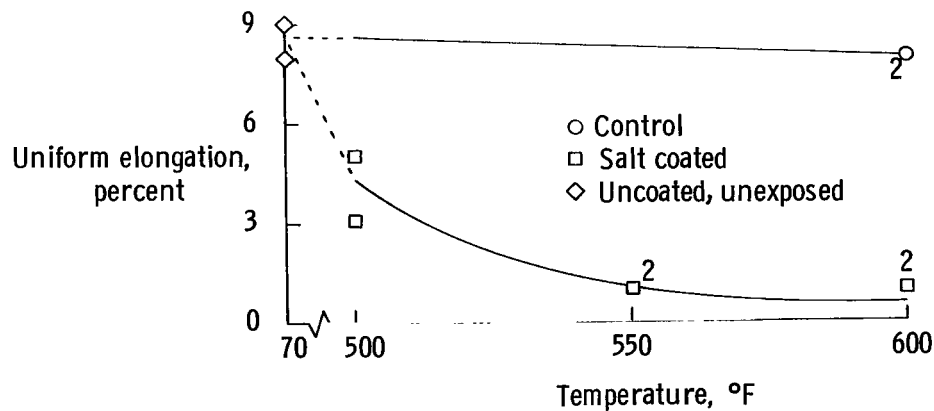
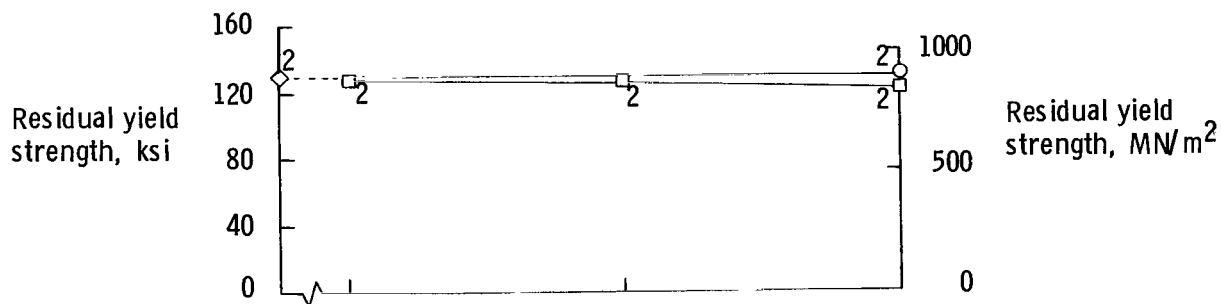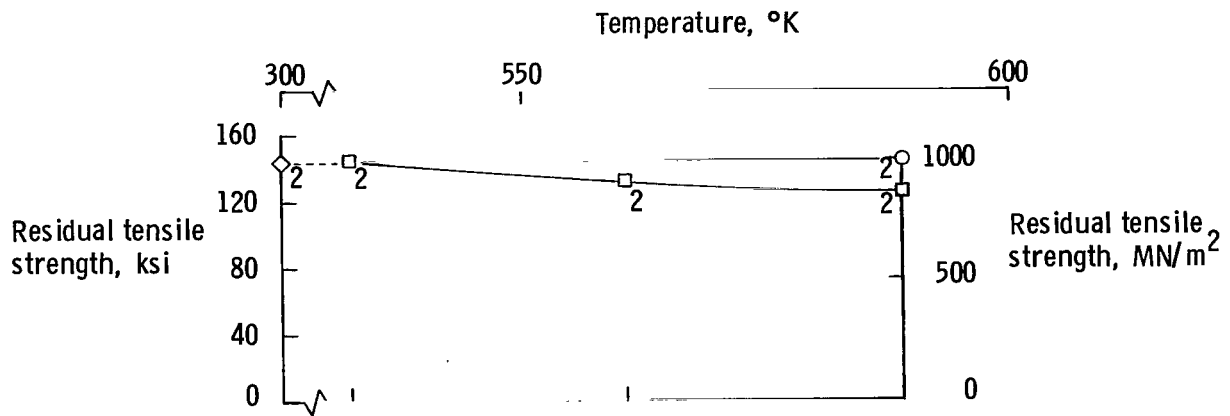Figure 5.- Application of Orr-Sherby-Dorn parameter for predicting stress-corrosion cracking initiation in Ti-8Al-1Mo-1V titanium-alloy sheet.

Savannah River Laboratory (ref. 12)
450° to 950° F
(500° to 790° K)

Master curve

Stress, ksi

100

80

60

40

20

0

○ 600°F (590°K)
□ 550°F (560°K)
◇ 500°F (530°K)
△ 450°F (500°K)

Stress, MN/m^2

600

400

200

0

-8   -7   -6   -5   -4   -3

$$\log t - \frac{\Delta H}{2.3\, R\, T_K}$$

Temperature, °K

300   550   600

160
Residual tensile
strength, ksi   120
80   Residual tensile
strength, MN/m²
40   500
0   0

160
Residual yield
strength, ksi   120
80   Residual yield
strength, MN/m²
40   500
0   0

9
Uniform elongation,
percent   6   ○ Control
□ Salt coated
◇ Uncoated, unexposed
3
0   70 500   550   600

Temperature, °F

(a) Longitudinal specimens.

Figure 6.- Residual tensile properties for salt-corrosion cracked and control (no salt) Ti-8Al-1Mo-1V titanium-alloy sheet after exposures for 800 hours at 50 ksi (340 MN/m²) stress.
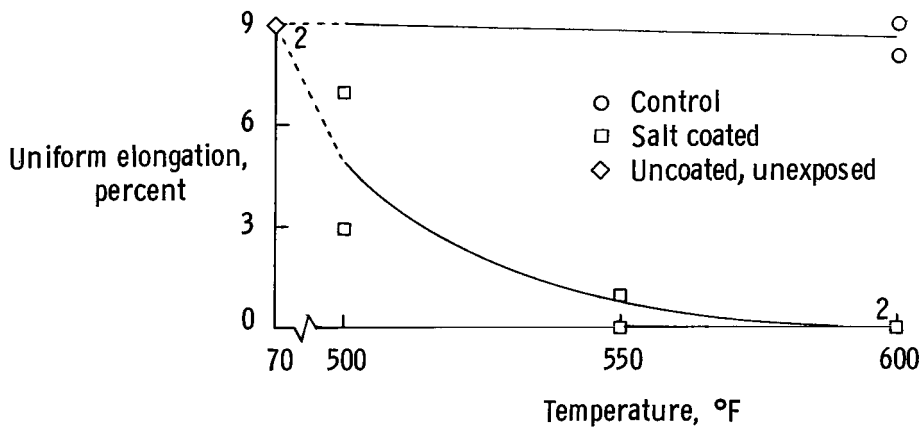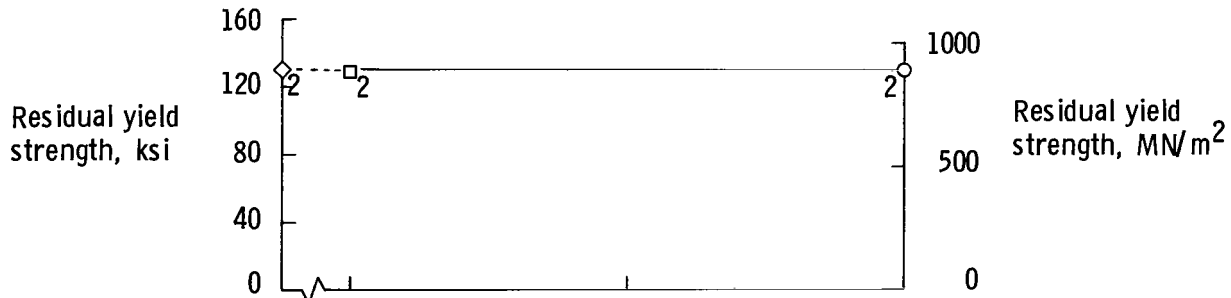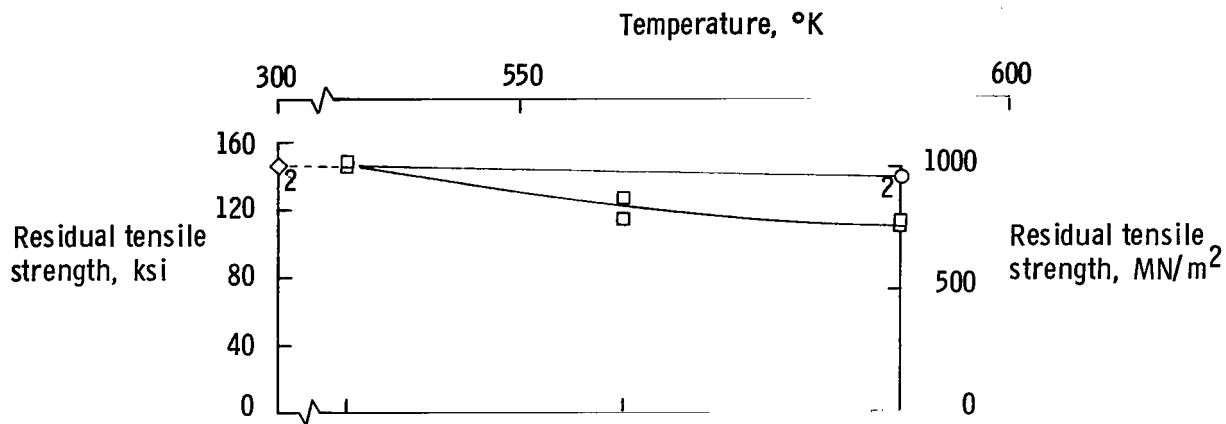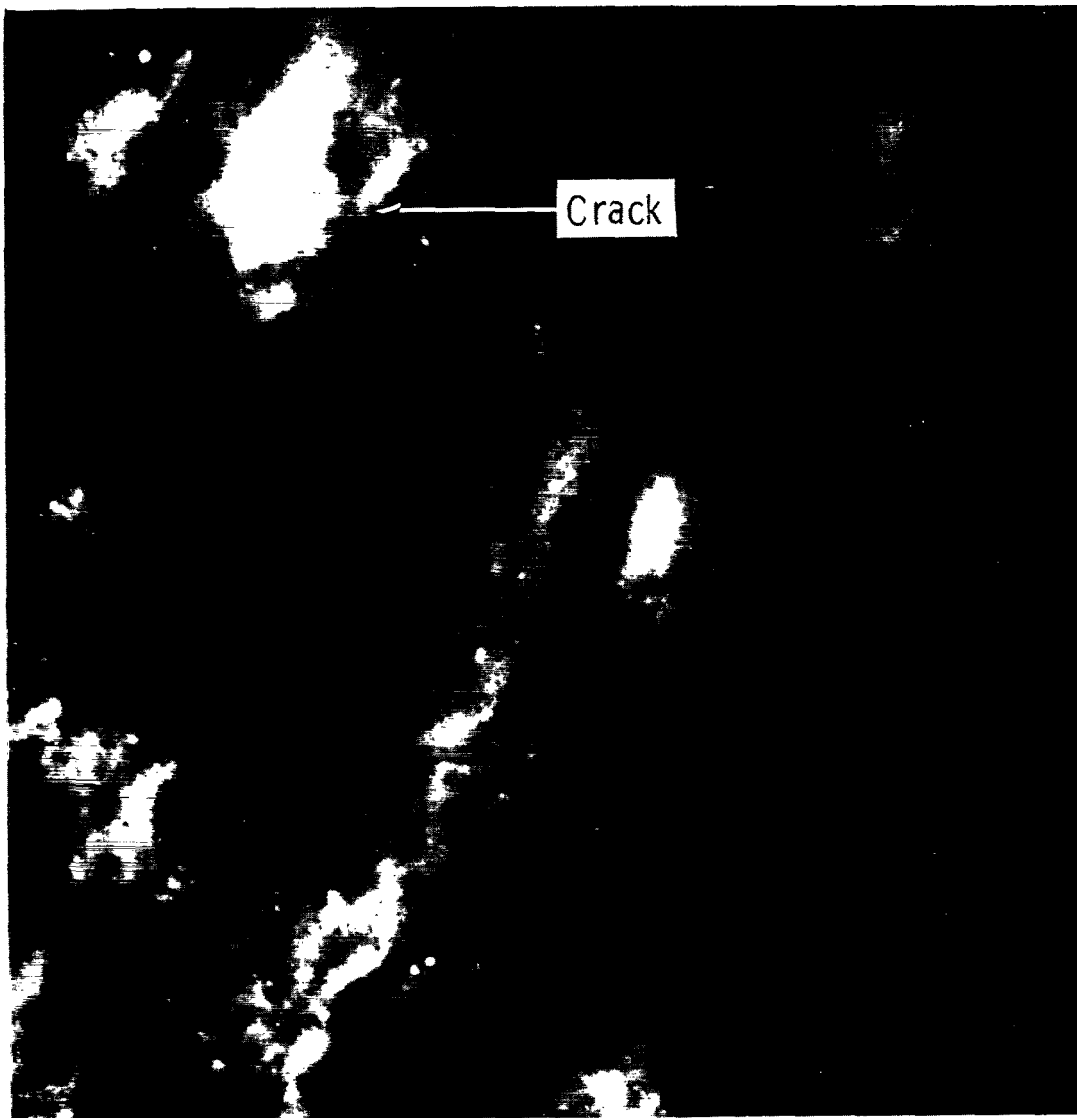
(b) Transverse specimens.

Figure 6.- Concluded.

(a) Magnified 2×.

(b) Magnified 20×.   L-68-841

Figure 7.- Hot-salt-stress-corrosion cracks in self-stressed specimen of Ti-8Al-1Mo-1V titanium-alloy sheet detected on the surface of fluorescent-dye penetrants.
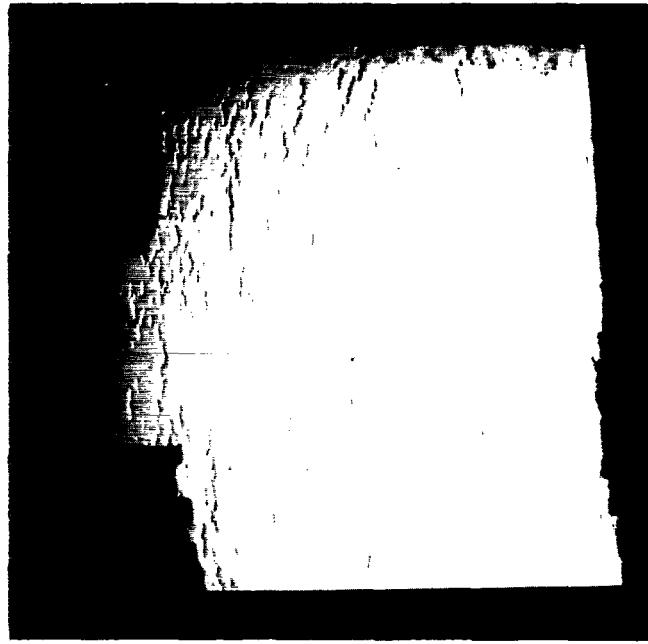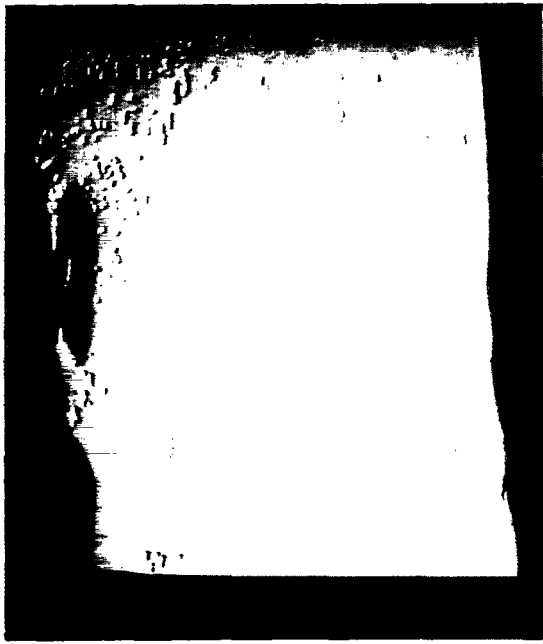
(a) Magnified 5×.

(b) Magnified 50×.   L-68-842

Figure 8.- Hot-salt-stress-corrosion cracks detected on the surface of a self-stressed specimen of Ti-8Al-1Mo-1V titanium-alloy sheet by a chemical etch.

30

Longitudinal
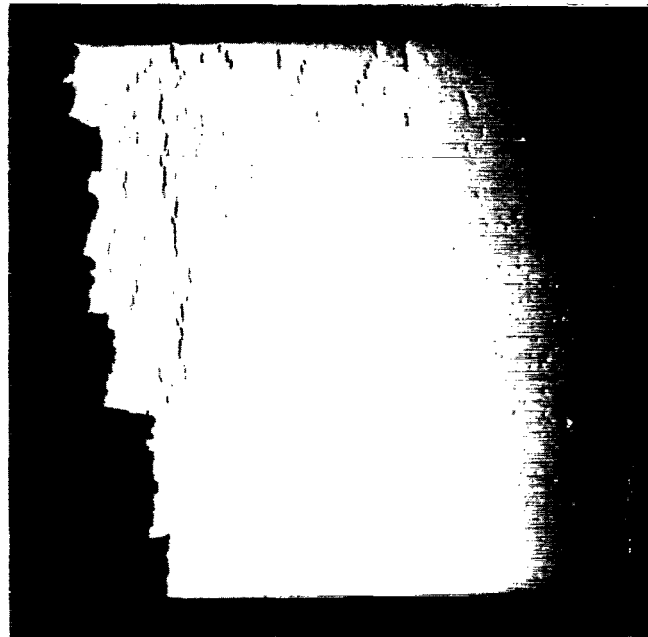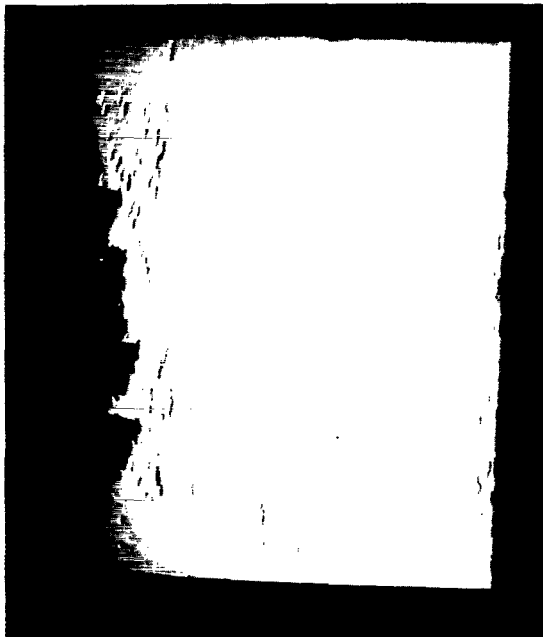
Transverse

550°F (560°K)   600°F (590°K)

Figure 9.- Hot-salt-stress-corrosion surface cracks in tensile specimens of Ti-8Al-1Mo-1V titanium-alloy sheet after 800 hours exposure at 50 ksi (340 MN m²) stress. Fracture surface to the left of each photograph. Magnified 6×.
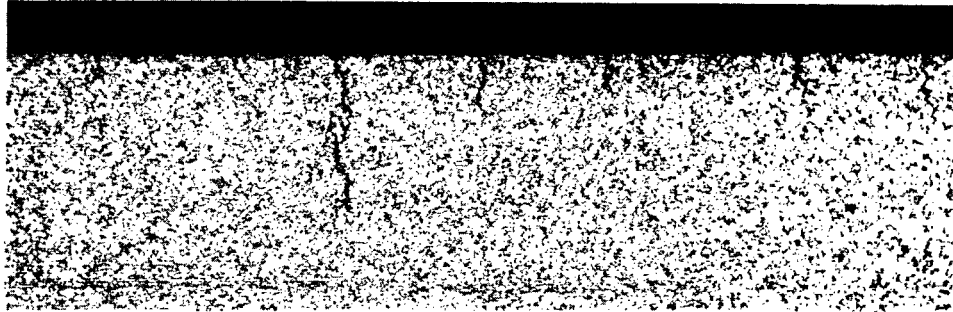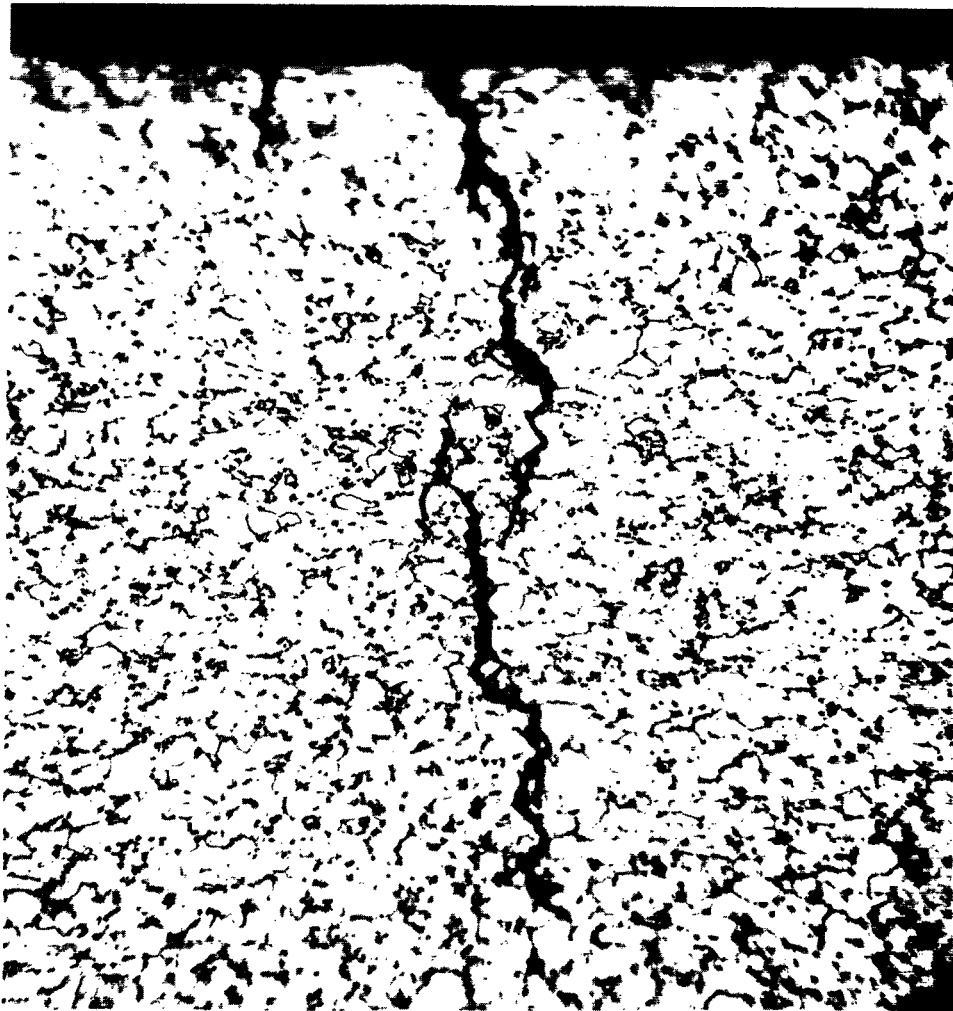
(a) Magnified 100×.

(b) Magnified 500×.   L-68-844

Figure 10.- Edge view of hot-salt-stress-corrosion cracks in Ti-8Al-1Mo-1V titanium-alloy sheet longitudinal tensile specimen exposed at 50 ksi (340 MN/m^2) and 600° F $(590^\circ$ K) for 600 hours.
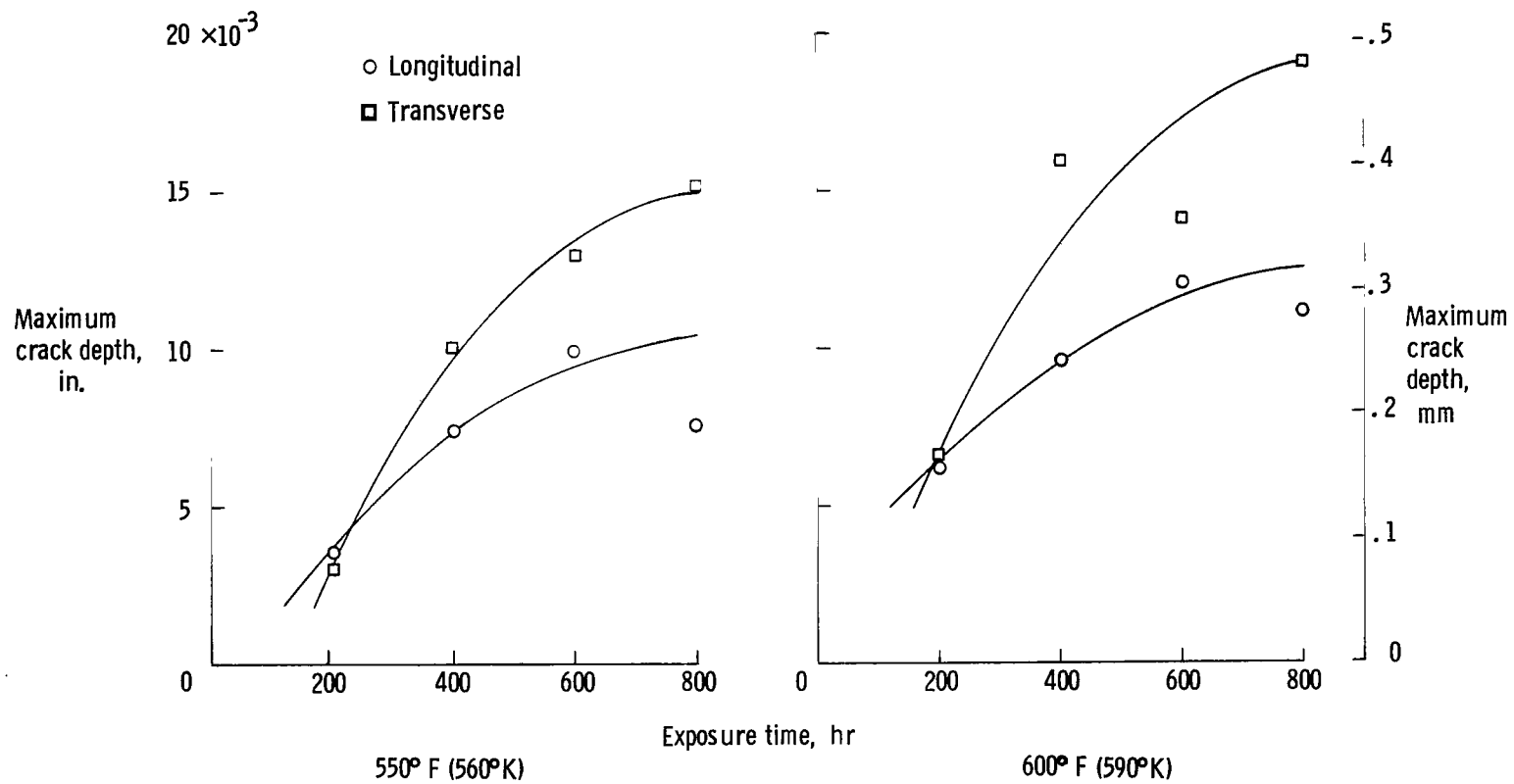
Figure 11.- Salt-stress-corrosion maximum crack penetration for Ti-8Al-1Mo-1V titanium-alloy sheet tensile specimens for exposures up to 800 hours at 50 ksi (340 MN/m^2) stress.

Maximum crack depth, mm
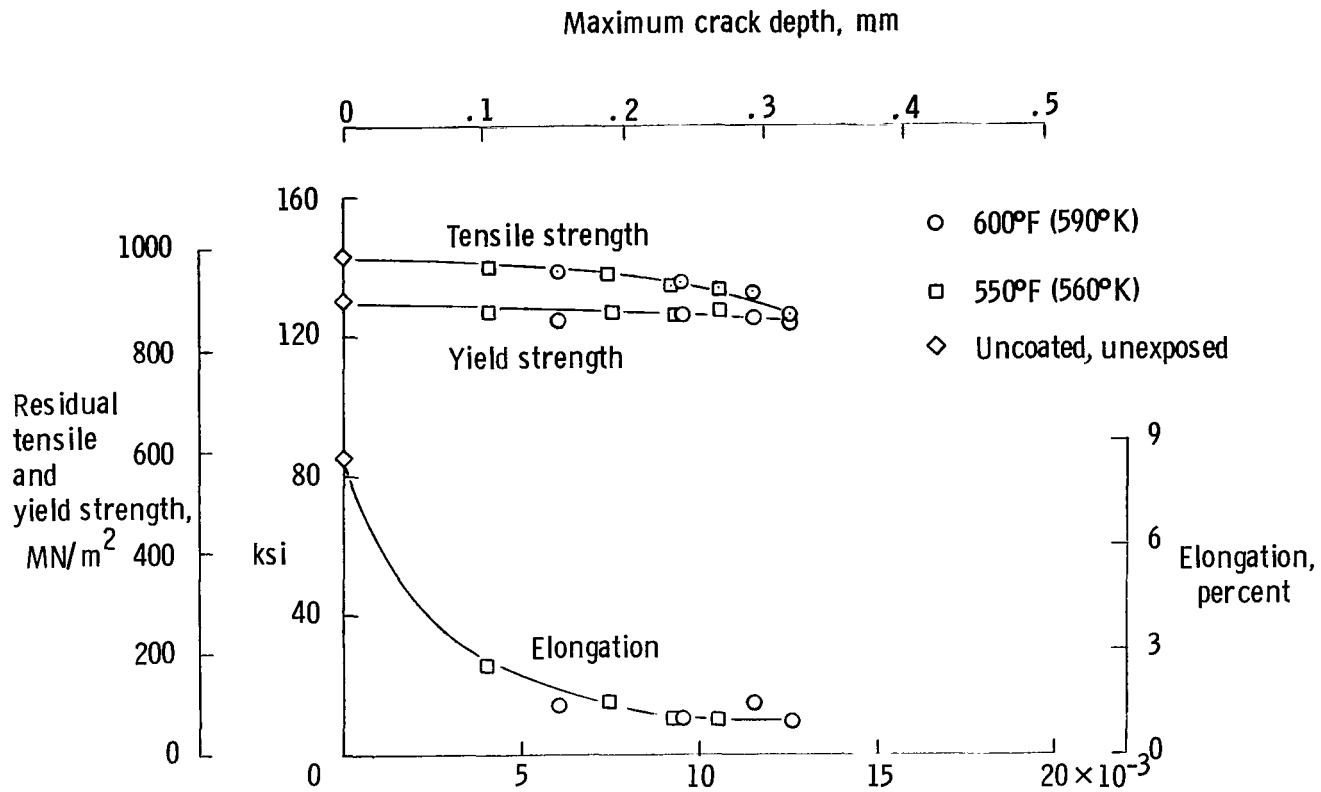
(a) Longitudinal specimens.

(b) Transverse specimens.

Figure 12.- Variations of residual tensile properties with maximum crack depth for Ti-8Al-1Mo-1V titanium-alloy sheet (duplex annealed).

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administra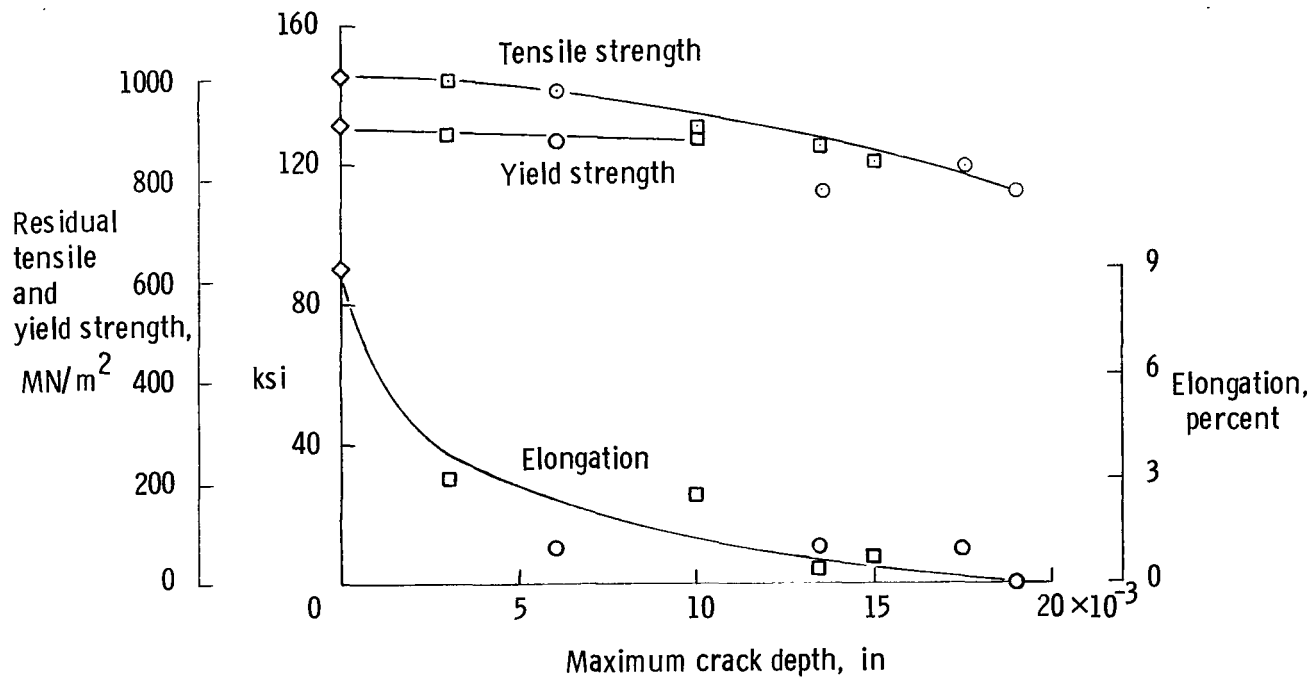tion shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546