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METALLURGICAL STABILITY OF THE TITANIUM ALLOYS 8Al-1V-1Mo, 6Al-6V-2Sn, 4Al-3Mo-1V, AND 6Al-4V

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ABSTRACT

Four commercial alloys - Ti 8Al-1Mo-1V, Ti 6Al-6V-2Sn, Ti 4Al-3Mo-1V, and Ti 6Al-4V - ~~have been~~ were evaluated to determine the effect of SST environmental conditions on mechanical properties. Test data for materials subjected to stressed thermal exposures for times from 1000 hours to 30,000 hours are compared to as-heat treated properties for most of the common heat treatment conditions (solution treated and overaged, mill annealed and air cooled, and duplex annealed with air cooling) of these alloys. It was found that of the alloys examined, only Ti 6Al-4V is not detrimentally affected by the exposure conditions tested. The test results indicate that furnace cooling (at 80°F/hour to 800°F in this study) from either the annealing temperature or the aging - stabilization treatment imparts the required metallurgical stability for SST usage of the other three alloys - Ti 8Al-1Mo-1V, Ti 6Al-6V-2Sn, and Ti 4Al-3Mo-1V. Property changes resulting from exposure are satisfactorily explained by changes in microstructural features as determined using transmission electron microscopy and X-ray diffraction.

KEY WORDS

Metallurgical Stability, Titanium Alloys, Ti 8Al-1Mo-1V, Ti 6Al-6V-2Sn, Ti 4Al-3Mo-1V, Ti 6Al-4V, Strength, Fracture Toughness, Stress Corrosion, Transmission Electron Microscopy, X-ray Diffraction Percent Beta Phase Measurements.

1.0 INTRODUCTION

The ability to retain desirable heat treated mechanical properties after long time stressed exposure at service temperature is a necessary material design requirement. Selection of alloyed titanium as the primary structural material for current supersonic transport designs has stimulated concern that these materials be able to withstand the stringent environmental conditions (stress, atmosphere, temperature) that are anticipated. As a group, the alloys most seriously considered for SST application can be classified as alpha-beta alloys with the alpha (HCP) phase being the predominant phase. Despite the high melting temperature of these alloys ($\sim$3100°F for C.P. titanium), the existence of the allotropic phase (HCP alpha → BCC Beta) transformation at a much lower temperature ($\sim$1675°F for C.P. titanium) increases the activity of the system sufficiently that metallurgical stability during long-time exposure to SST service temperature might be questionable.

Useful properties can easily be enhanced for these alloys through conventional heat treatment concepts. It often is desirable to control the microstructure by fast cooling the material after solutionizing near the allotropic transformation temperature, resulting in a metastable microstructure metallurgically. Transformation to more equilibrium products is then achieved by aging at lower temperatures. However, practical heat treatment and processing considerations restrict aging to conditions such that the material will not be in phasal equilibrium at service temperatures. Standard annealing procedures that incorporate air cooling to room temperature may produce even greater departure from service temperature equilibrium conditions because the beta phase present at the annealing temperature is likely to retain during cooling. Annealed material is not normally stabilized by additional aging heat treatments.

It behooves the metallurgist to exercise caution in devising heat treatments that optimize mechanical properties. Property developments must be compromised to be compatible with both acceptable processing practice and metallurgical stability requirements. Most of the heat treatment conditions tested during this study were designed to possess adequate stability for the moderate exposure environments that are included. STA treatments are overaged ensuring low driving force for continued tempering of martensite or precipitation within the beta phase. Duplex annealing treatments include stabilization at low temperature to promote equilibrium structures. It is shown that the stability of some common annealing treatments can be markedly increased by incorporating controlled slow cooling from the annealing temperature as opposed to air cooling.

Metallurgical stability for selected heat treatment conditions of Ti 8Al-1Mo-1V, Ti 6Al-6V-2Sn, Ti 4Al-3Mo-1V, and Ti 6Al-4V has been evaluated using tensile, fracture toughness, and resistance to environmental crack-growth tests. Property variations are related to metallurgical phase changes observed using thin foil transmission electron microscopy evaluations and, in some cases, monitored by X-ray diffraction measurements.

The thermal exposure conditions tested were:

a. Ti 8Al-1Mo-1V; temperatures of 400°F, 500°F, and 650°F and 40 ksi steady state applied tensile stress for times up to 30,000 hours.

b. Ti 6Al-6V-2Sn; temperatures of 250°F, 350°F, 450°F, and 650°F and zero or 25 ksi steady state tensile stress for times up to 5000 hours.

c. Ti 4Al-3Mo-1V; temperatures of 450°F and 550°F and 25 ksi steady state applied tensile stress for times up to 10,000 hours.

d. Ti 6Al-4V; temperatures of 450°F, 500°F, 550°F, and 650°F and 25 ksi or 40 ksi steady state applied tensile stress for times up to 10,000 hours.

2.0 EXPERIMENTAL PROCEDURE

The materials tested during this study are identified in Table I. Both gages of Ti 8Al-1Mo-1V were purchased in the duplex annealed (1450°F/8 hours/fce. cool + 1450°F/15 min./A.C.) condition and tested without further heat treatment. Ti 6Al-6V-2Sn, Ti 4Al-3Mo-1V, and Ti 6Al-4V plates were purchased in the mill annealed condition and heat treated prior to testing. The Ti 6Al-4V sheet was tested in the as-received mill annealed (1300°F/1 hour/A.C.) condition. Longitudinal grain direction tensile data was taken for the .200 gage Ti 8Al-1Mo-1V sheet. The other materials were all tested in the transverse grain direction. Notched specimens containing precracks were oriented such that the cracks would run parallel to the longitudinal grain direction, thereby producing a transverse fracture toughness or stress corrosion test. Most mechanical property tests were conducted at room temperature. Ti 8Al-1Mo-1V and Ti 6Al-4V sheets were also characterized at -110°F in order to satisfy fracture toughness validity criteria.

2.1 Exposure Conditions

The effect of exposure was investigated by comparing unexposed properties with data obtained from material subjected to steady state stress and temperature in creep ovens. The creep ovens were resistance heated circulating air ovens capable of maintaining a uniform temperature within ± 2.5°F over a zone up to 33 inches in length. Typically, temperature of the heated zone varied within less than 15°F of the specified temperature during the duration of exposure.

The exposure blanks were precision machined to a uniform cross-sectional dimension prior to exposure and were pinhole-loaded in series within the uniform temperature zone. Dead weight loads were applied to the exposure blanks through lever arrangements designed to magnify the stresses generated by the dead weights. Fracture toughness and stress corrosion specimens were notched and precracked following the completion of exposure. Tensile specimens were tested both in the as-exposed condition and after machining from exposure blanks with no apparent difference being evident between the two methods of specimen preparation.

2.2 Mechanical Properties Evaluation

Fracture toughness of sheet materials was determined using 8" x 24" x thickness center-notched panels. Sawcut starter notches 1/2 inch long were extended to 1.5 inches by fatigue cycling at a maximum stress of 40 ksi and then to 2.0 inches at a maximum stress of 25 ksi. Cycling frequency was 120 cpm at a stress ratio R of .20. Fracture testing was conducted at approximately 10^6 psi/sec stress rate. Cycling and fracture testing were accomplished in servovalve controlled hydraulic load cylinder jigs. Buckling restraints were used for all tests. Plane stress fracture toughness, K_c, was determined using the method described in Reference 1. ($K = \sigma\sqrt{\pi a}\ \theta$ where θ, the finite width correction factor, $= [\frac{W}{\pi a} \tan \frac{\pi a}{W}]^{1/2}$). σ is taken to be the stress associated with maximum load. Validity of the K_c determination is limited to conditions such that $\sigma_n \leq 0.8\ \sigma_{yp}$, where σ_n is the net-section stress at failure and σ_{yp} is the yield strength. Exposed K_c values were determined from testing one center-notched panel for each exposure condition. As-heat treated (baseline) K_c values were the averages of two center-notched panel tests.

Fracture toughness and stress corrosion of all plate materials were determined using .5" x 1.5" x 7.5" notched bend specimens. Some sub-length notched bend specimens were machined from failed standard-length specimens. Extension arms were pinned to these subsized notched bend specimens so that standard testing techniques could be used. The extensions were designed such that the imposed stress distribution is identical to that formed in the standard 7.5 inches long notched bend specimen. The notched bend specimens were fatigue cracked by cyclic cantilever loading in a Sonntag SF-10-U fatigue machine prior to fracture toughness testing in air or stress corrosion testing in 3.5 percent NaCl solution. The cyclic loads were selected to initiate the precrack in about 40,000 cycles at K-levels between 25 ksi $\sqrt{in.}$ and 40 ksi $\sqrt{in.}$

In the fracture toughness test, notched bend specimens were loaded to failure in four-point bending at a gross area stress rate of 1000 psi/sec. Plane-strain fracture toughness, K_{Ic}, was calculated from each load deflection curve using the method described in Reference 2. Here;

$$K_{IC} = \frac{PL}{BW^{3/2}} \left[\frac{1}{1-\mu^2} \left(34.7\right)\left(\frac{a}{w}\right) - 55.2\left(\frac{a^2}{w^2}\right) + 196\left(\frac{a^3}{w^3}\right) \right]^{1/2}$$

where P is the load corresponding to the deviation from linearity in the load-deflection curve. Validity of the K_{Ic} determination is limited to conditions where specimen thickness, t, is equal to or greater than 2.5 $(K_{Ic}/\sigma_{yp})^2$.

In the stress corrosion test, two different loading techniques were used. One method required that notched bend specimens be immersed in 3.5 percent salt solution prior to four-point loading in a hydraulic apparatus. In the other method, specimens were loaded in air and then the salt solution was added. The testing apparatus has been described elsewhere, (Reference 3). The loading sequence did markedly affect the test results, and data of Tables IV, VI, and VIII, are separated accordingly. This effect has also been reported by Curtis et al (Reference 4).

Other than the sequence of adding the salt solution, the notch bend stress corrosion testing procedure was the same for both techniques. The first specimen was loaded to an initial stress intensity level, K_{Ii}, and held at that level until failure or for a time of at least six hours. Load levels for subsequent specimens were selected to establish a curve of K_{Ii} versus time-to-failure. Visual monitoring of crack growth and examination of the fracture surface showed that the pre-existing crack propagated in salt solution at low K-levels until it reached the critical length (corresponding to K_{Ic}) necessary for rapid failure. An apparent "threshold level" for stress corrosion cracking exists in titanium alloys below which the pre-existing crack does not grow under sustained load. The threshold is taken as the K_{Ii} level at 360 minutes and is referred to as K_{Iscc} or "stress corrosion resistance".

For each exposure condition, two notched bend specimens were tested to establish the baseline K_{Ic}, and at least three notched bend specimens were tested to establish the stress corrosion threshold, K_{Iscc}. Some of the specimens that did not fail during sustained loading were re-precracked and tested a second time.

All tensile data are averaged results from duplicate tests. Two specimens were used for the tensile tests conducted in this investigation. A 9-inch long flat specimen having a reduced section 2.25 inches long and .500 inches wide was used to characterize sheet gages. A 3-inch long round specimen having a reduced section 1.25 inches long and .250 inches in diameter was used to characterize plate material.

2.3 Metallurgical Evaluation

Thin foils for transmission electron microscopy studies were prepared by grinding each specimen to .002 - .003 inches thick and then electropolishing as described by Blackburn and Williams (5). All specimens were prepared from the mid-thickness of the material. Plate was first milled to .020 inches thick prior to grinding.

The percentage beta phase present in the alloys was determined using an X-ray diffraction technique first developed by Averbach, et al. (Reference 6), and now modified by Olsen (Reference 7). Olsen compensates for preferred orientation by simultaneously tilting and rotating the specimen while the diffraction peaks are step scanned. The specimen is cut such that the surface is located in the center of a quadrant of the pole figure, so that the tilt and rotate motion averages the X-ray intensity across the quadrant with a small amount of overlap into adjacent quadrants. The $10\bar{1}2$ and $11\bar{2}0$ alpha and the 200 beta lines are measured and used to calculate the volume percentage beta as follows:

$$\text{Vol. } \% \ \beta = \frac{100}{1 + \frac{K'_\beta}{K'_\alpha} \frac{I_\alpha}{I_\beta}}$$

where $I\alpha$ = Integrated intensity of the $10\bar{1}2$ alpha peak
$I\beta$ = Integrated intensity of the 200 beta peak
K'_α, K'_β = Intensity factors involving Lorentz Polarization, absorption, phase composition, unit cell size, multiplicity, and structure factors.

The intensity values are recorded on a printed paper tape at 2θ increments of 0.1°/minute. The intensity profile is fed into a computer program which performs a numerical integration of the diffraction lines and calculates the volume percentage beta.

3.0 RESULTS AND DISCUSSION

Tensile and fracture property results are summarized in Tables II and III for Ti 8Al-1Mo-1V, Table IV for Ti 6Al-6V-2Sn, Table VI for Ti 4Al-3Mo-1V, and Tables VII and VIII for Ti 6Al-4V. The volume percentage of beta phase that is present at room temperature is tabulated for various exposure conditions of Ti 6Al-6V-2Sn in Table V. In order to permit a more exacting analysis of the stress corrosion data, fracture property results for each test condition of the Ti 6Al-6V-2Sn, Ti 4Al-3Mo-1V, and Ti 6Al-4V plate gages are tabulated in Appendices A, B, and C, respectively.

The results of the investigation will be presented and discussed separately for each alloy.

3.1 Ti 8Al-1Mo-1V

The data of Tables II and III show only small apparent change in tensile results after thermal exposure. Exposure does result in ultimate strength increases up to 5 percent and yield strength increases up to 6 percent of the as-heat treated strengths. These tensile results are not indicative of embrittlement since the associated measured elongation does not decrease and, in fact, remains very good. The fracture toughness data reported in Table II, however, are strongly affected by the exposure conditions tested indicating that the Ti 8Al-1Mo-1V has been embrittled during exposure. Exposure to 500°F and 40 ksi applied tensile stress for 20,000 hours causes approximately 20 percent decrease in the toughness measured at -110°F. Exposure to 400°F shows similar degradation but to a lesser extent. The room temperature toughness data, like the tensile results, were not a sensitive indicator of the embrittlement caused by these exposures because, with the exception of one test panel, all of the K_c calculations were invalid. The best that can be said of the R.T. data is that as the panels are progressively embrittled, the conditions for validity are gradually approached.

The metallurgical changes associated with the decreased toughness of duplex annealed Ti 8Al-1Mo-1V are conclusively established using transmission electron microscopy. Air cooling from 1450°F (the duplex annealing cycle) is sufficient to retain the beta phase in a metastable condition. Blackburn (Reference 8) showed partitioning of this metastable beta phase into two separable BCC solid solutions after aging D.A. (duplex annealed) Ti 8Al-1Mo-1V for 2000 hours at 500°F. Williams and Blackburn (Reference 9) showed that further aging for 10,000 hours at 450°F produced a dispersion of omega phase in the beta grains. No evidence that alpha had ordered to the DO_{19} superlattice could be detected by either investigator. Transmission electron microscopy analysis of material exposed for 30,000 hours at 500°F and 650°F (tensile data are reported in Table III) produced similar results. At 500°F and 40 ksi steady state applied tensile stress, a fine dispersion of omega phase precipitated within the beta phase (Figure 1) while at 650°F and 40 ksi applied stress, a fine dispersion of alpha phase formed within the beta phase (Figure 2). Selected Area Diffraction (S.A.D.) showed diffuse DO-19 superlattice reflections to be present in the primary alpha phase of the specimen exposed to 650°F/40 ksi/30,000 hrs. The reflections were too diffuse for direct imaging of the ordered α_2 - phase and, consistent with our Laboratory's experience, the ordered domains were probably less than 25 Å in diameter.

The data of Tables II and III show [illegible] properties are little affected by the embrittling second phase precipitates that have formed in both the alpha and beta phases of D.A. Ti 8Al-1Mo-1V during exposure. Table II further illustrates that valid fracture toughness data can be a sensitive indicator of beta phase embrittlement. It can be speculated that fracture toughness or stress corrosion susceptibility data would be equally sensitive to the ordering transformation apparent within the alpha phase after exposure to 650°F/40 ksi/30,000 hrs.

3.2 Ti 6Al-6V-2Sn

Mechanical property data for Ti 6Al-6V-2Sn are reported in Table IV.

Ti 6Al-6V-2Sn heat treated to the mill annealed condition (1300°F/2 hrs/A.C.) shows only slight thermal degradation after exposure to temperatures as high as 450°F, but exposure to 650°F markedly affects all of the properties tested - tensile, fracture toughness, and stress corrosion. Although exposure at temperatures up to 450°F causes increases of about 5 percent in the tensile ultimate and yield strengths and losses of about 10 to 15 percent in the fracture toughness and stress corrosion parameters, the engineering ductility, as monitored by percent elongation and reduction of area, shows no significant change. After exposure at 650°F/25 ksi/1000 hrs., the fracture toughness and stress corrosion resistance decreased greater than 35 percent with corresponding tensile property increases of 17 percent for ultimate strength and 9 percent for the yield strength. Elongation decreased about 1/3 during exposure at 650°F.

Furnace cooling improved the stability of the mill annealed condition appreciably as is shown in Table IV. Subsequent exposure at 650°F produced only negligible change in the tensile data. Attention is drawn to the strong effect that cooling rate exerts upon mill annealed tensile properties. For example, comparison of the as-heat treated properties for the two mill annealed conditions reported in Table IV shows that furnace cooling produces a 10 ksi increase in ultimate tensile strength compared to material that is air cooled. A second interesting sidelight in this data is the implication that the loading environment is important when establishing the stress corrosion threshold value. Note that two columns are used to list K_{Ii} data. This observation is further verified by data included in Table VIII which deals with the stability of Ti 6Al-4V plate.

The heat treated (E-STA-1200) material showed response to exposure similar to that described for the mill annealed condition (1300°F/2 hrs/A.C.) except that the property changes noted were smaller. One exception is for material that has been exposed to 250°F for 5000 hours which produced marked tensile strength increases, while only minimal increases occur after exposure to 350°F or 450°F. The fracture toughness was similar after exposure to 250°F, 350°F, and 450°F so no unusual microstructural changes are attributed to the exposure at 250°F, and the excessive tensile property changes for this condition must be considered anomalous.

Marked microstructural changes resulting from stressed thermal exposure were observed during transmission electron microscopy studies. Figures 3-6 illustrate changes after exposure at 650°F and 25 ksi for both the annealed and heat treated conditions of Ti 6Al-6V-2Sn. The annealed material shows a complex structure with a high density of dislocations. During exposure, the alpha phase is generally coarsened, and fine alpha particles precipitate within the beta phase. (See Figures 3 and 4). Exposure had less affect on the heat treated (STA) microstructure with a fine precipitation of alpha particles within the beta phase being the only notable change. Figures 5 and 6 show this comparison nicely. Exposure of Ti 6Al-6V-2Sn did not affect the pre-existing disorder - order condition of the alpha phase for either of the heat treatment conditions. No superlattice reflections were detectable in the 1300°F/2 hrs/A.C. condition before or after exposure. By the same token, Ti_3Al domains in the heat treated material were about the same size before and after exposure (~100 Å).

The volume percentage beta phase measurements made by X-ray diffraction (Table V) indicate that the amount of beta phase present is decreasing during exposure. This data is consistent with the more qualitative electron microscopy indications. Exposure to 650°F/25 ksi/1000 hrs. causes a decrease from about 20 vol. percent beta phase to about 6 vol. percent beta phase in both the mill annealed (air cooled) and the Beta-STA-1200 heat treatment conditions. As would be expected, the lattice parameter of the beta phase also decreased measureably between the unexposed and exposed conditions. Shrinkage of the beta phase lattice probably results from the increasing vanadium content of the beta phase during exposure. This trend is consistent with the binary phase system studies reported in DMIC Report 136A (Reference 10).

3.3 Ti 4Al-3Mo-1V

Mechanical property data for three solution treated and aged (STA) conditions and one annealed condition of Ti 4Al-3Mo-1V are reported in Table VI.

Ti 4Al-3Mo-1V in the two STA conditions, 1050°F/8 hrs/A.C. and 1150°F/8 hrs/A.C., experienced mechanical property changes after exposure similar to those reported for Ti 6Al-6V-2Sn following exposure at ≤ 450°F and 25 ksi. Material aged at 1050°F exhibited a 4 percent increase in the tensile ultimate strength, 17 percent loss in the fracture toughness and 21 percent reduction in the stress corrosion cracking threshold at exposure times ≥ 1000 hours. The tensile yield strength, plastic elongation, and reduction in area data were not affected. The 1150°F aged material shows greater change in tensile properties than the 1050°F aged material; 7 percent increase in TUS, 5.5 percent increase in TYS - but fracture properties decreased only 15 percent and 19 percent respectively for fracture toughness and stress corrosion resistance. No change was noted in the elongation and R.A. values. The duplex annealed condition experienced a slight decrease in tensile strength after exposure but did not undergo a change in the fracture toughness. As

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expected, the STA condition aged at 1175°F/8 hrs/furnace cool at 80°F/hr showed excellent stability with no mechanical property changes evident after exposure at either 450°F or 550°F.

These effects of thermal exposure on the mechanical properties of Ti 4Al-3Mo-1V are not satisfactorily understood. The fact that the STA-1050°F aged material was no more stable than the STA-1150°F aged material is not consistent with predictions based upon the phase diagram. The higher aging temperature forms more beta phase which would be expected to be more metastable and decompose faster upon exposure at 450°F or 550°F. It should be noted that both the 1050°F and 1150°F aged materials are extensively overaged; peak heat treated strength for this material would be greater than 190 ksi TUS. (Reference 11). It is considered that both of these STA conditions are unstable and that reaction kinetics at the exposure temperature is the controlling mechanism. Furnace cooling following aging did impart stability to solution treated and aged material. The duplex annealed material was air cooled following the final stabilizing soak at 1150°F., Although this final anneal is similar to the aging sequence for the heat treated conditions, the duplex annealed condition shows good stability with no degradation of either the fracture toughness or stress corrosion parameters. The 3 percent decrease in the tensile ultimate strength is not considered to be significant and the other tensile parameters were not affected. It should be noted that the duplex annealed notch bend specimens were grossly invalid. The discussion of Section 3.1 relating the inadequacy of nonvalid K_c data to detect embrittlement should be applicable to these results.

Metallurgically, changes in Ti 4Al-3Mo-1V are difficult to characterize because this material normally exhibits a very fine transformation structure. No apparent microstructural changes could be specifically linked with the exposure conditions that were tested. Based upon the results shown for Ti 8Al-1Mo-1V and Ti 6Al-6V-2Sn, it is speculated that the alpha phase grows at the expense of the beta phase during exposure at 450°F and 550°F. Electron microscopy of β-STA-1150 plate exposed at 450°F/25 ksi/10,000 hrs did show a secondary dispersion of alpha phase in the beta matrix which is considered to be a product of the exposure. X-ray diffraction measurements did not indicate significant changes in the percentage of beta phase. The amount of beta phase in the β-STA-1150 heat treatment condition after exposure at 450°F/25 ksi/10,000 hrs was 9.8 vol. percent as compared to 10.6 vol. percent before exposure.

3.4 Ti 6Al-4V

Mechanical properties for exposed Ti 6Al-4V sheet and plate are listed in Tables VII and VIII, respectively. Mill annealed, duplex annealed, high strength (β-STA-1000°F/4 hrs/A.C.) and high toughness (β-STA-1250°F/4 hrs/A.C.) heat treatment conditions were exposed and tested. Perusal of this data show Ti 6Al-4V to be a very unique alloy in that most of the mechanical properties show improvement following thermal exposure. For example, mill annealed sheet undergoes an improvement in tensile ultimate strength at -110°F of 10 ksi or 6 percent as well as a plane stress fracture toughness increase of 7 ksi $\sqrt{\text{in.}}$ or 5 percent. Similarly, room temperature test results of plate indicate ultimate tensile strength improvements of up to 8 percent for the high strength heat treatment condition, 4 percent for the high toughness heat treatment condition, and nearly 9 percent for the duplex annealed condition. Surprisingly, substantial improvement in fracture properties can accompany this strengthening. For example, increases of up to 40 percent in fracture toughness and 13 percent in stress corrosion are realized for the high toughness heat treatment following exposure. Although exposure decreases fracture toughness of the high strength condition slightly (up to 13 percent), the stress corrosion parameter is increased by up to 40 percent. Fracture toughness values of the duplex annealed conditions are little affected by the exposure conditions tested. It is uncertain if the sharp drop in the stress corrosion threshold results from exposure or if the change is partly due to refinement of test technique. It was necessary to conscientiously avoid any tendency to initially overload these specimens in order to locate the true threshold level. Increasing the plasticity at the crack tip seems to prejudice the test results toward higher stress corrosion threshold levels.

Transmission electron microscopy evaluations of exposed Ti 6Al-4V show little change in the microstructure as a result of thermal exposure. Figure 7 is an electron micrograph showing beta phase particles at the edges of lamellar alpha grains in heat treated (β-STA-1250) Ti 6Al-4V. Percentage beta phase measurements of the β-STA-1250 heat treatment condition show that exposure decreases the beta phase content slightly - 6.1 vol. percent was reported as the average content for four exposure conditions as compared to 7.8 vol. percent in the unexposed condition. Figure 7 suggests a model that can accommodate the improvement of properties noted in Tables VII and VIII. Processing history is important to development of the model and so will be described in detail. The model, as described, is discussed for heat treated (β-STA-1250) Ti 6Al-4V but is also applicable for any heat treatment that produces transformed alpha-beta phase mixtures by rapid cooling (air quench or faster). Beta processing or heat treatment destroys all equiaxed primary alpha grains. Subsequent solution treatment (water quenched) at 1725°F forms a HCP martensite which precipitates beta upon aging (Reference 9), resulting in alpha lamellae separated by interface bands comprised of a mixture of alpha and beta phases. The lamellar alpha grain boundaries are poorly defined and, in fact, are continually disrupted by the beta precipitates that extend into the alpha lamellae. Fuzzy grain boundaries are also observed in duplex annealed and mill annealed (air cooled) material. It is proposed that the lamellar alpha grain boundaries are able to migrate during exposure and reduce their surface area (and energy) by enclosing the beta phase precipitates that extended into them. At the same time, the enclosed beta phase particles appear to become spherical, thus decreasing their grain boundary energy and further lowering the free energy of the system. The beta particles are not consumed by the alpha phase during exposure because apparently the equilibrium alpha to beta phase ratio does not change appreciably between 1250°F (the aging temperature) and 450°F (the exposure temperature) as shown by the percentage beta phase data, and the fact that most of the beta phase is present at the fuzzy interface bands that separate the lamellar alpha grains.

The number of beta phase particles isolated within the alpha lamellae are increased and the beta phase particle size decreased by this model. Either occurrence can contribute to the strengthening that accompanies exposure. Consideration of the degree of strengthening achieved by affecting the beta phase distribution through heat treatment (Reference 11 and 12) lends credence to this explanation. Perhaps this presence of a beta residue within the alpha lamellae also accounts for some improvement in fracture toughness. Spurr, Curtis, et al. (Reference 11 & 12) have shown the strong influence that microstructure can exert on the fracture characteristics of Ti 6Al-4V. The ductile beta phase permits increased localized plastic deformation. Simply put, fracture toughness is primarily a measure of the dissipated energy during plastic deformation ahead of an advancing crack.

A disturbing observation of the Ti 6Al-4V results shown in Table VIII is that the duplex annealed heat treatment condition is very susceptible to stress corrosion when corrodent is present at the time the specimen is loaded. Duplicate specimens from some conditions of the β-STA-1000 material as well as the duplex annealed material were tested to determine the effects of loading environment on the threshold value established by the test. Both sets of data show that loading in the presence of the corroding environment is far more severe than loading in air and then adding the corrodent. The heat treated material retains a high threshold level of SCC, however, whereas the threshold value becomes dangerously low for the duplex annealed material.

4.0 CONCLUSIONS

It is shown that anticipated supersonic transport environmental conditions can cause metallurgical changes in a near-alpha titanium alloy (Ti 8Al-1Mo-1V) and three alpha-beta titanium alloys in many of the normal heat treatment conditions. One alloy, Ti 6Al-4V, showed improvement in both the strength and toughness properties following stressed thermal exposure, which should prove comforting to users of this material. The other three alloys normally followed the more expected tendency to increase strength and decrease toughness properties during exposure. Furnace cooling following both annealing and aging heat treatments provided an effective method for retaining heat treated properties. In general, titanium alloys show enough activity at expected SST operating temperatures to justify furnace cooling following stabilizing heat treatments. Ti 6Al-4V is the notable exception to this safety measure.

Direct evidence that exposure can trigger transformation of metastable beta phases is provided by transmission electron microscopy studies. Volume percent beta phase determinations from X-ray diffraction measurements show these transformations can be extensive. Alloys susceptible to omega phase embrittlement, Ti 8Al-1Mo-1V and Ti 4Al-3Mo-1V (Reference 9), become particularly worrisome because this transformation can occur rapidly at temperatures as low as 400°F. By comparison, the formation kinetics for alpha phase precipitation are so sluggish that temperature greater than 500°F is required for transformations to occur during the exposure times used.

Changes related to the alpha phase are less spectacular than those in the beta phase but also can affect properties. Migration of alpha grain boundaries was sometimes apparent, alpha grains growing at the expense of the beta phase in mill annealed Ti 6Al-6V-2Sn and straightening of lamellar alpha grain boundaries in heat treated (β-STA-1250) Ti 6Al-4V. Ordering to Ti_3Al domains occurred in only one instance - duplex annealed Ti 8Al-1Mo-1V exposed to 650°F/40 ksi/30,000 hrs. - and its significance was not determined. Tensile data showed no apparent change due to ordering but this condition was not characterized for fracture toughness or stress corrosion cracking changes.

This study provided an opportunity to evaluate the sensitivity of various test parameters for detecting metallurgical instability. The value of fracture mechanics is apparent from the data as good correlation between fracture toughness and microstructural changes could always be obtained. Tensile properties appear to be a less consistent indicator and the oft-used parameters of elongation and reduction of area are almost insensitive to the microstructural changes. In fact, elongation and reduction of area are affected by only advanced degradation.

The fracture toughness sensitivity - tensile property insensitivity observation is metallurgically consistent. It has been shown in the present study that "embrittling" transformations occur mostly in the beta phase, the kinetics for possible alpha phase transformations being unfavorable. Since the beta phase is only weakly stabilized for all of these alloys (ranging from about 20 volume percent in Ti 6Al-6V-2Sn to about 3.5 volume percent in Ti 8Al-1Mo-1V), tensile properties are strongly influenced by alpha-beta interactions and appear relatively little affected by incipient precipitation introduced within the beta phase particles during exposure at 400°F - 550°F; ie., the load carrying contribution of the beta phase is not significantly influenced by these changes. In this case, second phase strengthening apparently results from the matrix discontinuity produced by the dispersion of beta particles within the alpha matrix and appears relatively insensitive to the hardness of the second phase. Fracture toughness, however, is a measure of localized plastic deformation which is strongly affected by the hardness change of the beta phase.

ACKNOWLEDGEMENTS

This report summarizes the titanium alloy metallurgical stability evaluations on the subject alloys which were conducted by ST-M during the period 1964-1968. As such, the report includes data from several studies; and the author credits those individuals who actively participated in certain of the stability evaluations during this period. Dr. D. E. Piper conducted the sheet stability evaluations reported as Table II (Ti 8Al-1Mo-1V) and Table VII (Ti 6Al-4V); and W. Higby of the Structures Staff Group was responsible for the data of Table III (Ti 8Al-1Mo-1V). W. F. Spurr, R. E. Curtis, and J. P. Hutchison were each at some time associated with the Ti 4Al-3Mo-1V and Ti 6Al-4V evaluations reported in Tables VI and VIII, respectively. The data of Tables VI and VIII were earlier reported, in part, in Reference 11.

The author gratefully acknowledges contributions to this effort from Rod Boyer who conducted transmission electron microscopy experiments, Ray Olsen for the X-ray diffraction percent beta phase determinations, and Mario Schurmann who handled many of the testing details from his position in the Exposure and Stability Laboratory. Furthermore, Mr. Boyer and W. E. Quist contributed helpful critiques of the text; and Mr. Olsen generously supplied the description of his X-ray diffraction multiple-phase measurement technique that is included in the text.

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Table I - Material Identification and Chemistry (Wt. Percent)

Alloy	Gage (inches)	Heat No.	Vendor	Al (%)	Sn (%)	V (%)	Mo (%)	Fe (%)	Cu (%)	O (ppm)	N (ppm)	H (ppm)	C (%)
Ti 8Al-1Mo-1V	.050	D-3457	TMCA	7.9	---	1.0	1.0	.08	---	800	100	60	.025
Ti 8Al-1Mo-1V	.200	D-4535	TMCA	7.7	---	1.1	1.0	.09	---	900	160	60	.022
Ti 6Al-6V-2Sn	.750	D-8058	TMCA	5.6	2.1	5.6	---	.82	.75	1,500	150	50	.023
Ti 4Al-3Mo-1V	.500	D-9484	TMCA	4.5	---	1.0	3.3	.10	---	1,100	90	60	.03
Ti 6Al-4V	.040	291-279	Reactive	6.3	---	4.2	---	.17	---	1,100	200	89	.02
Ti 6Al-4V	.500	292-258	Reactive	6.2	---	4.1	---	.15	---	1,170	60	65	.02
Ti 6Al-4V	.500	292-030	Reactive	6.3	---	4.1	---	.17	---	1,142	60	66	.02

Table II - Effect of Stressed Thermal Exposure on Transverse G.D. Properties of .050 gage Duplex Annealed* Ti 8Al-1Mo-1V. (Heat D-3457)

Exposure Condition	Test Temp. -°F	Tensile TUS (ksi)	Tensile TYS (ksi)	Tensile Elong. (% in 2")	Fracture Toughness K_c (ksi $\sqrt{in}$)	Fracture Toughness $\frac{\sigma_{net}}{\sigma_{yield}}$
Exposure to 400°F & 40 ksi						
None	-110	168.1	154.2	12	159.3	.77
					162.4	.78
2,000 hrs.	-110	174.3	160.0	13	150.0	.70
5,000 hrs.	-110	166.0	153.1	12	147.0	.71
10,000 hrs.	-110	167.4	153.5	14	138.5	.66
20,000 hrs.	-110	168.2	155.0	14	138.2	.65
None	R.T.	142.2	126.0	14	164.2	.94
					168.7	.97
2,000 hrs.	R.T.	146.4	131.2	14	169	.93
5,000 hrs.	R.T.	142.8	129.4	14	163.6	.92
10,000 hrs.	R.T.	143.3	129.7	14	157.3	.89
20,000 hrs.	R.T.	143.2	131.6	15	167.2	.93
Exposure to 500°F & 40 ksi						
None	-110	168.1	154.2	12	159.3	.77
					162.4	.78
2,000 hrs.	-110	169.9	156.9	12	147.0	.67
5,000 hrs.	-110	170.6	153.7	12	134.5	.64
10,000 hrs.	-110	167.2	149.2	13	132.8	.65
20,000 hrs.	-110	168.5	156.4	12	127.8	.60
Exposure to 500°F & 40 ksi						
None	R.T.	142.2	126.0	14	164.2	.94
					168.7	.97
2,000 hrs.	R.T.	146.6	132.7	13	162.0	.90
5,000 hrs.	R.T.	145.6	129.5	14	159.1	.90
10,000 hrs.	R.T.	147.0	131.5	14	158.0	.73
20,000 hrs.	R.T.	146.5	132.2	14	150.5	.83

* 1450°F/8 hrs./Fce Cool + 1450°F/15 min./Air Cool

Table III - Effect of Stressed Thermal Exposure on the Room Temperature Longitudinal G.D. Properties of .200 Gage Duplex Annealed* Ti 8Al-1Mo-1V. (Heat D-4535)

Exposure Condition	TUS (ksi)	TYS (ksi)	Elong. (% in 2")
Exposure to 500°F & 0 ksi			
None	140.0	127.7	16
2,000 hrs.	145.0	133.5	16
5,000 hrs.	143.5	130.8	16
10,000 hrs.	147.2	133.9	16
Exposure to 500°F & 40 ksi stress:			
None	140.0	127.7	16
2,000 hrs.	144.6	131.0	16
5,000 hrs.	142.6	128.9	15
10,000 hrs.	142.9	127.8	15
30,000 hrs.	146.3	130.1	15
Exposure to 650°F & 0 ksi			
None	140.0	127.7	16
2,000 hrs.	147.5	135.3	17
Exposure to 650°F & 40 ksi			
None	140.0	127.7	16
2,000 hrs.	145.4	131.4	16
5,000 hrs.	145.0	127.9	16
10,000 hrs.	145.5	129.0	16
30,000 hrs.	144.5	131.0	16

* 1450°F/8 hrs./Fce. Cool + 1450°F/15 min./Air Cool

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Table IV - Effect of Stressed Thermal Exposure on the Room Temperature Transverse G.D. Properties of .750 Gage Ti 6Al-6V-2Sn (Heat D-8058)

Exposure Condition	TUS (ksi)	TYS (ksi)	Elong. (% in 1")	R.A. (%)	K_{Ic} (ksi$\sqrt{in}$)	K_{Iscc} (ksi$\sqrt{in}$) 1	K_{Iscc} (ksi$\sqrt{in}$) 2
MILL ANNEALED 3							
Exposure to 250°F & 25 ksi							
None	157.6	150.7	14	32	59	37	--
2,500 hrs.	1[illegible].0	[illegible]5.5	15	31	54	--	21
5,000 hrs.	160.3	153.8	17	32	56	--	21
Exposure to 350°F & 25 ksi							
None	157.6	150.7	14	32	59	37	--
1,000 hrs.	159.1	151.5	14	32	54	32	--
2,500 hrs.	162.6	157.8	15	35	51	--	22
5,000 hrs.	161.6	155.3	16	32	56	--	23
Exposure to 450°F & 25 ksi							
None	157.6	150.7	14	32	59	37	--
1,000 hrs.	160.5	153.1	13	25	53	31	--
2,500 hrs.	165.7	159.0	14	35	54	--	23
Exposure to 650°F & 25 ksi							
None	157.6	150.7	14	32	59	37	--
1,000 hrs.	1[illegible]0.[illegible]	162.9	11	22	36	22	--
Exposure to 650°F & 0 ksi							
None	157.6	150.7	14	32	59	37	--
1,000 hrs.	189.5	169.4	8	--	34	--	20
MILL ANNEALED 4							
Exposure to 650°F & 25 ksi							
None	167.0	157.8	16	27	60	20	20
1,000 hrs.	169.0	158.5	14	25	48	23	--

NOTE: TABLE IV Continued on Next Page

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Table IV (Continued)

Exposure Condition	TUS (ksi)	TYS (ksi)	Elong. (% in 1")	R.A. (%)	K_{Ic} (ksi$\sqrt{in}$)	K_{Iscc} (ksi$\sqrt{in}$) (1)	K_{Iscc} (ksi$\sqrt{in}$) (2)
Beta-STA-1200 (5)							
Exposure to 250°F & 25 ksi							
None	166.1	152.9	9	18	72	51	--
2,500 hrs.	176.2	167.7	6	12	61	--	44
5,000 hrs.	177.8	165.6	7	7	64	--	39
Exposure to 350°F & 25 ksi							
None	166.1	152.9	9	18	72	51	--
1,000 hrs.	170.2	156.2	9	12	61	44	--
2,500 hrs.	169.2	160.3	9	14	66	--	43
5,000 hrs.	170.4	160.9	7	9	69	--	42
Exposure to 450°F & 25 ksi							
None	166.1	152.9	9	18	72	51	--
1,000 hrs.	169.6	155.8	9	16	67	44	--
2,500 hrs.	170.9	161.7	9	16	66	--	45
Exposure to 650°F & 25 ksi							
None	166.1	152.9	9	18	72	51	--
1,000 hrs.	185.4	165.3	7	11	46	38	--

(1) Load applied to the notch bend specimen in air environment and then 3.5 percent salt solution was added.

(2) Load applied to the notch bend specimen in the presence of 3.5 percent salt solution environment.

(3) 1300°F/2 hrs./Air Cool

(4) 1300°F/2 hrs./Fce. Cool at 80°F/hr. to 800°F then Air Cooled

(5) 1800°F/30 min./A.C. + 1625°F/1 hr./W.Q. + 1200°F/ hrs./A.C.

Table V - Effect of Stressed Thermal Exposure on the Volume Percentage Beta Phase Present in Ti 6Al-6V-2Sn (Heat D-8058)

Exposure Condition	Volume Percent Beta	Lattice Parameters Alpha a_o	Lattice Parameters Alpha c_o	Lattice Parameters Beta a_o
Mill Annealed [1]				
Not Exposed	21.0 *	2.92	4.67	3.23
250°F/25 ksi/2,500 hrs.	20.4	2.93	4.72	3.24
250°F/25 ksi/5,000 hrs.	17.0	2.92	4.67	3.22
350°F/25 ksi/1,000 hrs.	18.2	2.92	4.69	3.22
350°F/25 ksi/2,500 hrs.	16.5	2.92	4.69	3.21
350°F/25 ksi/5,000 hrs.	22.1	2.93	4.64	3.22
450°F/25 ksi/1,000 hrs.	18.3	2.93	4.67	3.22
450°F/25 ksi/2,500 hrs.	18.3	2.93	4.70	3.23
650°F/25 ksi/1,000 hrs.	6.6 **	----	----	3.19
Beta-STA-1200 [2]				
Not Exposed	17.0 *	2.92	4.68	3.21
250°F/25 ksi/2,500 hrs.	15.1	2.92	4.68	3.21
250°F/25 ksi/5,000 hrs.	15.3	2.93	4.70	3.21
350°F/25 ksi/1,000 hrs.	19.0	2.93	4.71	3.23
350°F/25 ksi/2,500 hrs.	12.6	2.92	4.67	3.20
350°F/25 ksi/5,000 hrs.	16.6	2.92	4.69	3.22
450°F/25 ksi/1,000 hrs.	14.6	2.92	4.69	3.21
450°F/25 ksi/2,500 hrs.	13.0	2.92	4.68	3.20
650°F/25 ksi/1,000 hrs.	5.8 **	----	----	3.19

[1] 1300°F/2 hrs./Air Cool

[2] 1800°F/30 min./Air Cool
+ 1625°F/1 hr./Water Quench
+ 1200°F/4 hrs./Air Cool

* Mean result from ten determinations
** Mean result from four determinations.

Table VI - Effect of Stressed Thermal Exposure on the Room Temperature Transverse G.D. Properties of .500 Gage Ti 4Al-3Mo-1V (Heat D-9484)

Exposure Condition	TUS (ksi)	TYS (ksi)	Elong. (% in 1")	R.A. (%)	K_{Ic} (ksi $\sqrt{in.}$)	K_{Iscc} (ksi $\sqrt{in.}$)
Beta-STA-1050 1						
Exposure to 450°F & 25 ksi						
None	175.0	154.5	4	10	76	66
1,000 hrs.	181.5	156.3	4	10	64	52
2,500 hrs.	182.1	154.8	4	9	64	57
Exposure to 550°F & 25 ksi						
None	175.0	154.5	4	10	76	66
1,000 hrs.	177.9	150.3	4	10	63	58
2,500 hrs.	179.9	152.6	5	11	75	57
Beta-STA-1150 2						
Exposure to 450°F & 25 ksi						
None	154.8	137.2	7	16	96	79
1,000 hrs.	161.7	140.7	7	17	82	60
2,500 hrs.	165.6	144.9	6	14	86	66
5,000 hrs.	163.4	142.3	7	15	82	64
10,000 hrs.	162.6	144.4	7	16	85	74
Exposure to 550°F & 25 ksi						
None	154.8	137.2	7	16	96	79
1,000 hrs.	163.0	141.2	5	15	78	69
2,500 hrs.	163.0	140.1	6	15	83	65
Duplex Annealed 3						
Exposure to 450°F & 25 ksi						
None	138.0	126.2	18	54	125	120
1,000 hrs.	133.5	124.0	17	53	120	110
2,500 hrs.	134.4	124.6	17	52	121	110
Exposure to 550°F & 25 ksi						
None	138.0	126.2	18	54	125	120
1,000 hrs.	133.1	124.[illegible]	17	51	114	110
2,500 hrs.	134.4	124.9	17	51	124	110

NOTE: TABLE IV CONTINUED ON NEXT PAGE.

Table VI (Continued)

Exposure Condition	TUS (ksi)	TYS (ksi)	Elong. (% in 1")	R.A. (%)	K_{Ic} (ksi $\sqrt{in.}$)	K_{Iscc} (ksi $\sqrt{in.}$) 5
STA-1175 (F.C.) 4						
Exposure to 450°F & 25 ksi						
None	145.2	139.5	19	57	81	72
900 hrs.	145.5	141.1	15	53	84	76
2,500 hrs.	144.1	137.5	17	54	83	77
Exposure to 550°F & 25 ksi						
None	145.2	139.5	19	57	81	72
900 hrs.	146.2	140.0	15	53	94	75
2,500 hrs.	144.4	137.6	16	56	78	73

1 1875°F/30 min./A.C. + 1725°F/30 min./W.Q. + 1050/8 hrs./A.C.

2 1875°F/30 min./A.C. + 1725°F/30 min./W.Q. + 1150°F/8 hrs./A.C.

3 1725°F/1 hrs./A.C. + 1150°F/8 hrs./A.C.

4 1640°F/1 hr./W.Q. + 1175°F/8 hrs./Fce. Cool at 80°F/hr. to 800°F then Air Cooled.

5 Load applied to the notch bend specimen in air environment and then 3.5 percent salt solution was added.

Table VII - Effect of Stressed Thermal Exposure on the Room Temperature Transverse G.D. Properties of .050 Gage Mill Annealed* Ti 6Al-4V (Heat 291-279)

Exposure Condition	Test Temp. -°F	Tensile TUS (ksi)	Tensile TYS (ksi)	Tensile Elong. (% in 2")	Fracture Toughness K_c (ksi $\sqrt{in}$)	Fracture Toughness $\sigma_{net}/\sigma_{yield}$
Exposure to 500°F & 40 ksi						
None	-110	167.8	164.0	9	138.0	.62
5,000 hrs.	-110	178.2	170.2	9	143.9	.62
10,000 hrs.	-110	177.7	165.6	10	145.0	.65
None	R.T.	140.8	134.5	10	154.0	.84
5,000 hrs.	R.T.	153.7	144.6	12	170.2	.86
10,000 hrs.	R.T.	154.8	145.3	10	183.2	.92

* 1300°F/1 hr./Air Cool

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Table VIII - Effect of Stressed Thermal Exposure on the Room Temperature Transverse G.D. Properties of .500 Gage Ti 6Al-4V

Exposure Condition	TUS (ksi)	TYS (ksi)	Elong. (% in 1")	R.A. (%)	K_{Ic} ($ksi\sqrt{in}$)	K_{Iscc} ($ksi\sqrt{in}$) 1	K_{Iscc} ($ksi\sqrt{in}$) 2
Beta-STA-1000 3							
Heat 292-258							
Exposure to 450°F & 25 ksi							
None	164.6	149.9	7	11	93	56	--
900 hrs.	175.5	160.2	5	13	92	77	--
2,500 hrs.	173.9	158.9	5	7	88	78	--
Exposure to 550°F & 25 ksi							
None	164.6	149.9	7	11	93	56	--
900 hrs.	177.5	160.8	5	10	83	69	--
2,500 hrs.	172.8	154.6	5	9	86	72	--
Heat 292-030							
Exposure to 650°F & 25 ksi							
None	167.6	151.2	10	18	105	66	64
1,000 hrs.	170.1	153.9	7	14	90	65	58
2,500 hrs.	167.8	151.1	8	16	100	75	50
Beta-STA-1250 4							
Heat 292-258							
Exposure to 450°F & 25 ksi							
None	155.0	140.5	8	16	88	81	--
900 hrs.	157.7	142.6	6	17	111	88	--
2,500 hrs.	154.4	140.6	7	17	113	90	--
5,000 hrs.	161.6	144.7	7	9	93	80	--
10,000 hrs.	161.7	146.2	6	12	98	92	--
Exposure to 550°F & 25 ksi							
None	155.0	140.5	8	16	88	81	--
900 hrs.	159.9	146.0	5	14	120	85	--
2,500 hrs.	157.1	141.6	7	16	123	90	--

NOTE: TABLE VIII CONTINUED ON NEXT PAGE.

Table VIII (Continued)

Exposure Condition	TUS (ksi)	TYS (ksi)	Elong. (% in 1')	R.A. (%)	K_{Ic} (ksi$\sqrt{in}$)	K_{Iscc} (ksi$\sqrt{in}$) [1]	K_{Iscc} (ksi$\sqrt{in}$) [2]
Duplex Annealed [5] Heat 292-030							
Exposure 450°F & 25 ksi							
None	148.8	142.1	14	38	77	56	--
1,000 hrs.	151.0	142.9	15	38	80	59	--
2,500 hrs.	154.9	145.8	13	36	78	57	--
Exposure to 550°F & 25 ksi							
None	148.8	142.1	14	38	77	56	--
1,000 hrs.	156.5	145.2	12	35	80	47	--
2,500 hrs.	158.[illegible]	145.[illegible]	13	34	74	56	--
Exposure to 650°F & 25 ksi							
None	148.8	142.1	14	38	77	56	--
1,000 hrs.	157.9	147.1	14	40	71	41	26
2,500 hrs.	161.6	152.1	15	37	74	30	31
Duplex Annealed [6] Heat 292-030							
Exposure to 450°F & 25 ksi							
None	150.0	140.7	16	41	83	67	43
1,000 hrs.	157.2	148.[illegible]	18	37	90	40	21
2,500 hrs.	151.3	142.8	17	38	96	42	24

[1] Load applied to the notch bend specimen in air environment and then 3.5 percent salt solution was added.

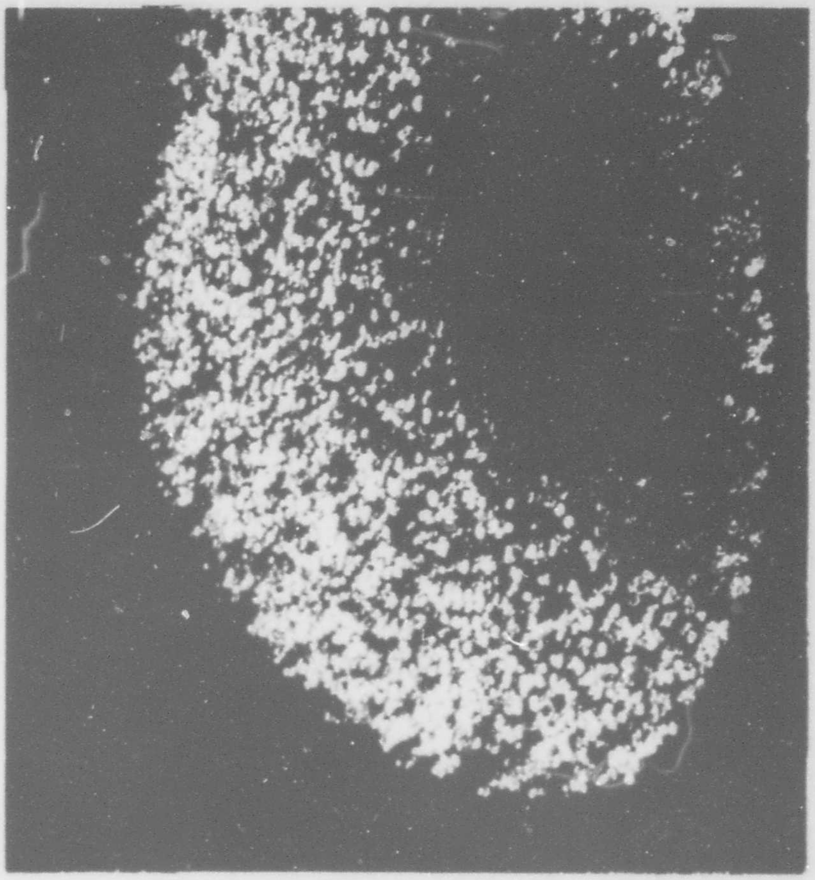
[2] Load applied to the notch bend specimen in the presence of 3.5 percent salt solution environment

[3] 1900°F/30 min./A.C. + 1725°F/30 min./W.Q. + [illegible]

[4] 1900°F/30 min./A.C. + 1725°F/30 min./W.Q. + 1250°F/4 hrs./A.C.

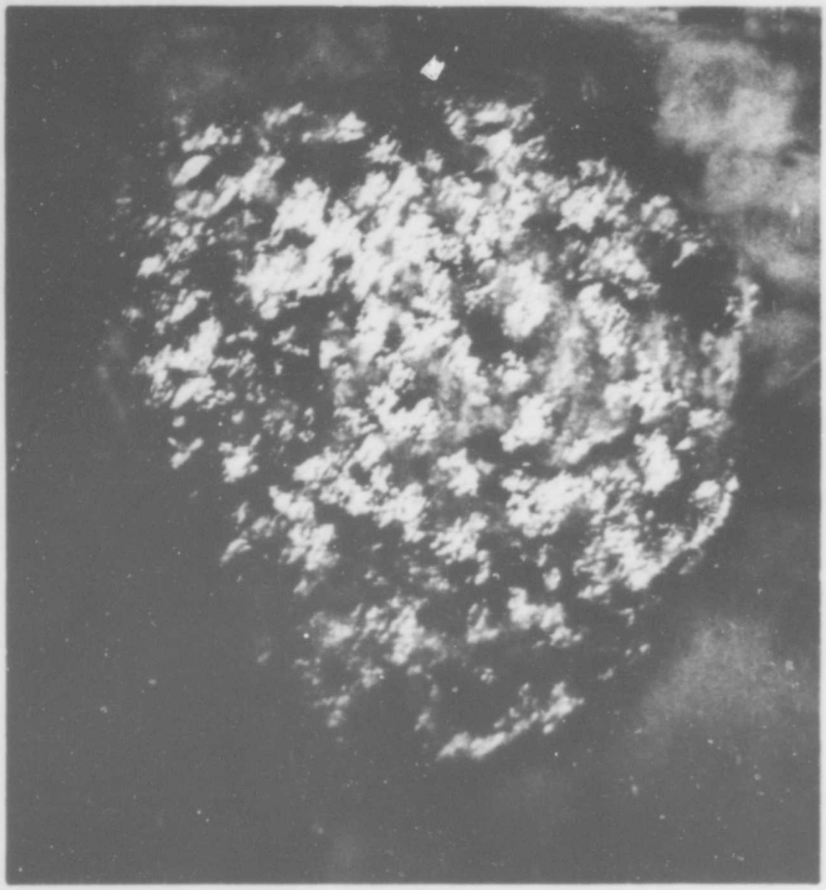
[5] 1725°F/30 min./A.C. + 1250°F/4 hrs./A.C.

[6] 1725°F/30 min./A.C. + 1250°F/4 hrs./[illegible]ce. [illegible]ool at 30°F/hr. to 500°F then air cooled.



113,500X

Figure 1. Dark field micrograph showing one varient of the ω-phase precipitation within the beta phase of Duplex Annealed Ti 8Al-1Mo-1V exposed to 500°F/40 ksi/30,000 hours.



64,200X

Figure 2. Dark field micrograph showing one varient of the α-phase precipitation within the beta phase of Duplex Annealed Ti 8Al-1Mo-1V exposed to 650°F/40 ksi/30,000 hours.

39,000X

Figure 3. Electron micrograph showing the complex (high dislocation density) structure of Mill Annealed (1300°F/Air Cooled) Ti 6Al-6V-2Sn. No exposure.

39,000X

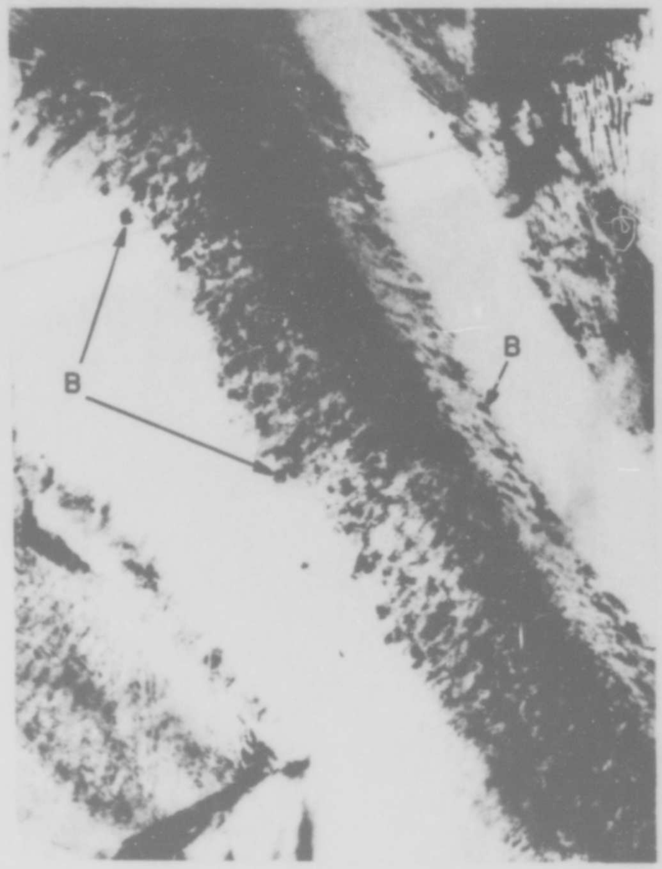
Figure 4. Electron micrograph showing precipitation of α-phase within the β-phase in Mill Annealed (1300°F/Air Cooled) Ti 6Al-6V-2Sn exposed to 650°F /25 ksi/1000 hours. Note the clear definition of the matrix alpha-beta structure.

100,000X

Figure 5. Electron micrograph showing the precipitation-free beta phase (at B) network in heat treated (β-STA-1200) Ti 6Al-6V-2Sn. No exposure.

39,000X

Figure 6. Electron micrograph showing precipitation of α-phase (at A) within beta lamellae in heat treated (β-STA-1200) Ti 6Al-6V-2Sn exposed to 650°F/25 ksi/1000 hours.



84,500X

Figure 7. Electron micrograph showing beta phase particles (at B) at the edges of lamellar alpha grains in heat treated (B-STA-1250) Ti 6Al-4V exposed to 450°F/25 ksi/5000 hours.

APPENDIX A

TABULATED FRACTURE DATA FOR Ti 6Al-6V-2Sn 0.500 INCH PLATE, HEAT D-8058

AD 1546 D

APPENDIX A

Tabulated Fracture Data - Ti 6Al-6V-2Sn Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
PFI-3	Mill Annealed 1	.37	60					Corrosion specimens were loaded in air
-4	Not Exposed	.37	56					
-5				.3[illegible]	43.[illegible]	1[illegible]	.30	
-6				.3[illegible]	43.[illegible]	1[illegible]	.17	
-7				.34	39.7	[illegible]	.46	
EA-12	Mill Annealed 1	.37	57					Corrosion specimens were loaded in salt solution.
-13	750°F/25ksi/1500 hrs.	.40	51					
-27				.30	32	1.0	.25	
-56				.33	2[illegible]	3.3	.40	
-57				.29	16.7	302 NF	trace	Fractured in air
A-14	Mill Annealed 1	.38	55					Corrosion specimens were loaded in salt solution.
-15	750 F/25ksi 5000hrs.	.32	54					
-[illegible]				.33	35.1	1.25	.20	
-72				.30	26.4	3.5	.40	
-73				.29	21.4	50	.40	
A-5	Mill Annealed 1	.35	54					Corrosion specimens were
-6	750 F/25ksi/1000hrs.	.33	54					
-34				.33	27.0	421 NF	.02	loaded in air.
-35				.35	30.7	384 NF	NA	Fractured in air
-36				.35	36.2	4	.33	
-34'				.37	33.9	3.4	.46	Reprecracked

AD 1546 D

APPENDIX A

Tabulated Fracture Data - Ti 6Al-6V-2Sn Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
EA-7	Mill Annealed [1] [illegible]°F/25ksi/2500 hrs.	.33	[illegible]					Corrosion specimens were loaded in salt solution
-8		.34	52					
-49				.3[illegible]	31.1	2.25	.40	
-50				.3[illegible]	26.7	.26	.3[illegible]	
-52				.33	[illegible].2	[illegible]	.4[illegible]	
A-[illegible]	Mill Annealed [1] 350 °F/2[illegible]ksi/[illegible] hrs.							Corrosion specimens were loaded in salt solution
-10		.35	57					
		.3[illegible]	54					
-11		.34	[illegible]					
EA-61				.31	35	[illegible]	[illegible]	
-62				[illegible]	5.8	[illegible]	[illegible]	
-6[illegible]				[illegible]	14.6	[illegible] NF	0	
-64				.30	19.6	455 NF	[illegible]	
-[illegible]				.2[illegible]	[illegible].1	[illegible]	.4[illegible]	
-6[illegible]'				.4[illegible]	[illegible].4	2.1	.2[illegible]	Reprecracked
-64'				.3[illegible]	24.	[illegible] NF	[illegible]	Reprecracked, Fractured in air.
A-1	Mill Annealed [1] [illegible]°F/[illegible]ksi [illegible] hrs.	.34	[illegible]					Corrosion specimens were loaded in air.
-[illegible]		.3[illegible]	49					
-31				.3[illegible]	[illegible].1	[illegible]	.3[illegible]	
-32				.3[illegible]	4[illegible].2	[illegible]	.2[illegible]	
-33				[illegible]	[illegible].1	3.[illegible]	[illegible]	

APPENDIX A

Tabulated Fracture Data - Ti 6Al-6V-2Sn Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
EA-3	Mill Annealed 1	.3[illegible]	[illegible]					Corrosion specimens were loaded in salt solution.
-4	650°F/25ksi/[illegible] hrs.	.30	[illegible]					
-43				.31	33.[illegible]	1.[illegible]	.20	
-44				.29	[illegible]	.25	.40	
-45				[illegible]	25	0.	.45	
A-1	Mill Annealed 1	.4[illegible]	[illegible]					Corrosion specimens were loaded in air.
-2	650°F/25ksi/1000 hrs.	.4[illegible]	[illegible]					
-3				.3[illegible]	25.[illegible]	.[illegible]	.09	
-4				.3[illegible]	22.7	1.9	.14	
-5				.30	26.[illegible]	304 NF	NA	
-5'				.3[illegible]	[illegible]1.3	41[illegible] NF	[illegible]	Reprecracked, Fractured in air.
PP-1-6	Mill Annealed 1 650°F/Zero ksi/1000 hrs.	[illegible]	[illegible]	.3[illegible]	25	[illegible]	.1[illegible]	KIc was determined from fast fracture area. Specimen was loaded in salt solution.

AD 1546 D

APPENDIX A

Tabulated Fracture Data - Ti 6Al-6V-2Sn Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
G-1	Mill Annealed	.31	[illegible]					
-[illegible]	Not Exposed	[illegible]	[illegible]					
-3				[illegible]	[illegible]	[illegible]	.11	Corrosion specimens were loaded in salt solution
-4				[illegible]	[illegible]	1.2[illegible]	[illegible]	
-5				[illegible]	[illegible]	10	[illegible]	
-1[illegible]				[illegible]	31.[illegible]	1.[illegible]	[illegible]	Corrosion specimens were loaded in air.
-181				[illegible]	21.[illegible]	[illegible]	[illegible]	
-[illegible]				[illegible]	[illegible]	[illegible] NF	NA	
-[illegible]				[illegible]	[illegible]	[illegible]	[illegible]	Not precracked
T-[illegible]	Mill Annealed	[illegible]	[illegible]					Corrosion specimens were loaded in salt solution.
-[illegible]	650°F [illegible] ksi 100 hrs.	[illegible]	[illegible]					
-[illegible]				[illegible]	[illegible]	[illegible]	[illegible]	
-[illegible]				[illegible]	[illegible]	[illegible] NF	[illegible]	
-[illegible]				[illegible]	[illegible]	-	[illegible]	
-[illegible]				[illegible]	[illegible]	[illegible]	[illegible]	Not precracked
[illegible]-1	Beta-[illegible]	[illegible]	[illegible]					Corrosion specimens were loaded in air.
-[illegible]	Not Exposed	[illegible]	[illegible]					
-[illegible]				[illegible]	[illegible]	[illegible] NF	N.A.	
-[illegible]				.37	-	-	N.A.	Overloaded during loading
-[illegible]				.32	[illegible]	[illegible]	N.A.	

REV SYM

AD [illegible]

Appendix A

Tabulated Fracture Data - Ti [illegible] Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{\text{in.}}$)	a (in.)	K_{Ii} (ksi$\sqrt{\text{in.}}$)	Time to Fail (min.)	Corr. Growth (in.)	
EB-[illegible]	Beta-STA-[illegible]	.[illegible]	[illegible]					Corrosion specimens were loaded in salt solution.
-[illegible]		.3[illegible]	[illegible]					
-[illegible]	[illegible]°F [illegible]ksi [illegible] hrs.			.[illegible]	[illegible]	[illegible] NF	N.A.	Failed in air
-[illegible]				.[illegible]	[illegible]	[illegible]	.[illegible]	
-[illegible]				.3[illegible]	[illegible]	[illegible]	N.A.	
B-[illegible]	Beta-STA-1[illegible]	.[illegible]	[illegible]					Corrosion specimens were loaded in salt solution.
-[illegible]		.33	[illegible]					
FB-[illegible]	[illegible]°F/[illegible]ksi [illegible] hrs.			.30	[illegible]	[illegible]	.[illegible]	
-7[illegible]				.31	39.[illegible]	4	.25	
-76				.3[illegible]	[illegible]	[illegible] NF	N.A.	
-[illegible]				.[illegible]	44.[illegible]	1.[illegible]	.15	Reprecracked
B-20	Beta-STA-1[illegible]	.[illegible]	[illegible]					Corrosion specimens were loaded in air
-[illegible]		.32						
-[illegible]	350°F/[illegible]ksi [illegible] hrs.			.31	[illegible].4	2441 NF	N.A.	Failed in air
-41				.31	46.6	2.5	N.A.	
-[illegible]				.34	47.4	1.5	N.A.	
EB-[illegible]	Beta-STA-[illegible]	.36	55					Corrosion specimens were loaded in salt solution.
-[illegible]3	350°F/[illegible]ksi 25[illegible] hrs.	.[illegible]	66					
-5[illegible]				.31	47.1	2	.10	Fractured in air
-53				.32	41.1	397 NF	N.A.	
-54				.32	44.4	2	.15	

REV SYM

AD 1546 D

APPENDIX A

Tabulated Fracture Data - Ti 6Al-6V-2Sn Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
B-[illegible]	Beta-STA-[illegible] 350 F [illegible] ksi [illegible] hrs.	.32	[illegible]					Corrosion specimens were loaded in salt solution
-[illegible]		[illegible]	[illegible]					
-[illegible]		.31	[illegible]					
EB-[illegible]				[illegible]	[illegible]	[illegible]	[illegible]	
-[illegible]				.32	[illegible]	[illegible] NF	[illegible]	
-[illegible]				[illegible]	[illegible]	[illegible]	.1[illegible]	
-[illegible]				[illegible]	44.1	[illegible]	[illegible]	
-[illegible]				[illegible]	[illegible]	[illegible]	[illegible]	
-[illegible]				[illegible]	[illegible]	[illegible]	[illegible]	Reprecracked
B-1[illegible]	Beta-STA-1[illegible] 450°F/[illegible] ksi [illegible] hrs.	[illegible]	[illegible]					Corrosion specimens were loaded in air
-1		[illegible]	[illegible]					
-37				[illegible]	[illegible]	[illegible]	N.A.	
-3[illegible]				[illegible]	[illegible]	[illegible] NF	N.A.	
-[illegible]				[illegible]	[illegible]	[illegible] NF	N.A.	Fractured in air
-[illegible]				[illegible]	4[illegible].2	[illegible]	N.A.	Reprecracked
EB-1[illegible]	Beta-STA-[illegible] 450°F/[illegible] ksi [illegible] hrs.	[illegible]	66					Corrosion specimens were loaded in salt solution
-1[illegible]		[illegible]	66					
-[illegible]				[illegible]	[illegible]	[illegible]	N.A.	
-[illegible]				[illegible]	[illegible]	[illegible] NF	[illegible]	
-[illegible]				[illegible]	[illegible]	[illegible] NF	[illegible]	
-[illegible]				[illegible]	[illegible]	[illegible]	[illegible]	Reprecracked
-[illegible]				[illegible]	[illegible]	[illegible]	N.A.	Reprecracked

APPENDIX A

Tabulated Fracture Data - Ti 6Al-6V-2Sn Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} ($ksi\sqrt{in.}$)	a (in.)	K_{Ii} ($ksi\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
B-[illegible]	Beta-STA-[illegible] [illegible] hrs.	.32	47					Corrosion specimens were
-	[illegible] ksi	.32	46					loaded in air
-[illegible]				.30	5[illegible].5	430 NF	N.A.	
-[illegible]				.31	37	415 NF	N.A.	
-10				.3[illegible]	42.4	.6	N.A.	
-[illegible]				.31	39.6	.5	N.A.	Reprecracked
-[illegible]				.33	30.8	1.2	N.A.	Reprecracked

APPENDIX B

TABULATED FRACTURE DATA FOR Ti 4Al-3Mo-1V 0.500 INCH PLATE, HEAT D-9484

APPENDIX B

Tabulated Fracture Data - Ti 4Al-3Mo-1V Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	All Ti 4Al-3Mo-1V Corrosion Specimens Were Loaded in Air
-3	Beta-STA-1050 (4) Not Exposed	.4[illegible]	[illegible]					
-4		.[illegible]	[illegible]					
-5				.35	65.8	360 NF	N.A.	
-6				.36	57.[illegible]	1300 NF	N.A.	Fractured in air
-7				.35	67.4	.75	N.A.	
-11	Beta-STA-1050 (4) 450°F/25ksi/1000 hrs.	.33	65					
-12		.31	6[illegible]					
-11				.33	4[illegible].0	1000 NF	N.A.	Fractured in air
-1[illegible]				.31	47.8	4[illegible] NF	N.A.	Fractured in air
-13				.31	53.8	1.25	N.A.	
-14	Beta-STA-1050 (4) 450°F/25ksi/2500 hrs.	.34	64					
-15		.34	64					
-1[illegible]				.34	54.1	2095 NF	N.A.	Fractured in air
-[illegible]				.32	61.9	.06	N.A.	
-[illegible]				.33	54.8	1.1	N.A.	
-[illegible]	Beta-STA-1050 (4) 550°F/25ksi/1000 hrs.	.32	60					
-[illegible]2		.32	66					
-21				.32	45.4	966 NF	N.A.	Fractured in air
-22				.32	53.0	4254 NF	N.A.	Fractured in air
-23				.36	61.0	1.05	N.A.	

APPENDIX B

Tabulated Fracture Data - Ti 4Al-3Mo-1V Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	All Ti 4Al-3Mo-1V Corrosion Specimens Were Loaded in Air
[illegible]-24	Beta-STA-1050	.33	72					
-25	550°F/[illegible]ksi/[illegible]500 hrs.	.34	78					
-26				.30	60.2	0	N.A.	Failed before salt solution could be added
-2[illegible]				.30	5[illegible].	1290 NF	N.A.	Fractured in air
-[illegible]				.33	5[illegible].6	.[illegible]	N.A.	
F24-3	Beta-STA-11[illegible]	.31	97					
-4	Not Exposed	.34	95					
-5				.30	[illegible]	[illegible] NF	N.A.	Fractured in air
-6				.34	7[illegible].2	2.0	N.A.	
-7				.37	70.0	1205 NF	N.A.	Fractured in air
[illegible]-1[illegible]	Beta-STA-11[illegible]	.34	[illegible]					
-1[illegible]	450°F 25ksi/1000 hrs.	.3[illegible]	[illegible]					
-11				.34	63.2	360 NF	N.A.	Fractured in air
-12				.35	69.0		N.A.	
-13				.3[illegible]	64.[illegible]	1[illegible]0 NF	N.A.	Fractured in air
[illegible]-14	Beta-STA-1150	.3[illegible]	[illegible]					
-1[illegible]	450°F/25ksi/1500 hrs.	.3[illegible]	84					
-16				.34	73.1	1.5	N.A.	
-17				.34	67.2	3.[illegible]	N.A.	
-1[illegible]				.3[illegible]	66.[illegible]	300NF	N.A.	Fractured in air

APPENDIX B

Tabulated Fracture Data - Ti 4Al-3Mo-1V Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	All Ti 4Al-3Mo-1V Corrosion Specimens Were Loaded in Air
C-5	Beta-STA-1150 5	.31	65					
-6	450°F 25ksi 1000 hrs.	.32	[illegible]					
-7				.32	65.3	1.5	N.A.	
-8				.31	57.1	1055 NF	N.A.	Fractured in air
-9				.32	65.3	500 NF	N.A.	
-9'				.3[illegible]	66.6	.5	N.A.	Not Reprecracked
C-10A	Beta-STA-1150 5	.37	90					
-11A	450°F/25ksi/10,000 hrs	.30	80					
-12				.32	60.5	4010 NF	N.A.	
-12'				.32	73.5	600 NF	N.A.	Not Reprecracked.
-13				.32	69.9	914 NF	N.A.	
-13'				.32	75.7	.5	N.A.	Not Reprecracked
-14				.32	76.5	.5	N.A.	
B-21	Beta-STA-1150 5	.31	77					
-22	550°F/25ksi/1000 hrs.	.31	80					
-2[illegible]				.31	53.6	979 NF	N.A.	Fractured in air
-2[illegible]				.31	62.6	4378 NF	N.A.	Fractured in air
-2[illegible]				.33	73.2	1.06	N.A.	

APPENDIX B

Tabulated Fracture Data - Ti 4Al-3Mo-1V Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	All Ti 4Al-3Mo-1V Corrosion Specimens were Loaded in Air
E-24	Beta-STA-115[illegible]	.34	[illegible]					
-25	550°F/25ksi/[illegible] Hrs.	.34	57					
-26				.30	66.[illegible]	3	N.A.	
-27				.32	59.4	1305 NF	N.A.	Fractured in air
-28				.32	62.4	376 NF	N.A.	
-29'				.32	66.6	957 NF	N.A.	Not Reprecracked
-20"				.[illegible]	75.[illegible]	.83	N.A.	Not Reprecracked
F2[illegible]-3	Duplex Annealed	.32	120					
-4	Not Exposed	.32	122					
-5				.31	133.0	1034 NF	N.A.	Fractured in air
-6				.31	135.2	36[illegible] NF	N.A.	Fractured in air
-7				-	-	37[illegible] NF	.06	Fractured in air
[illegible]	Duplex Annealed	.3[illegible]	[illegible]					
-11	[illegible] F/[illegible]ksi/[illegible] Hrs.	.3[illegible]	[illegible]					
-1[illegible]				.[illegible]	[illegible].5	[illegible] NF	.[illegible]	Fractured in air
-1[illegible]				.32	[illegible]	[illegible] NF	N.A.	
-1[illegible]				.[illegible]	106	[illegible] NF	N.A.	
-1[illegible]'				.[illegible]	[illegible]		N.A.	Not Reprecracked, failed before salt solution was added
-1[illegible]'				.[illegible]	[illegible]	[illegible].06	.[illegible]	Not Reprecracked

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} ($ksi\sqrt{in.}$)	a (in.)	K_{Ii} ($ksi\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	All Ti -Al- Mo-1 Corrosion Specimens were loaded in Air
[illegible]	[illegible] Annealed [illegible] hrs.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] NF	[illegible]	Fractured in air Not reprecracked, failed before salt solution was added
[illegible]	[illegible] Annealed [illegible] hrs.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] NF	[illegible] N.A. N.A.	Fractured in air Not reprecracked, both specimens failed before salt solution was added
[illegible]	[illegible] Annealed [illegible] hrs.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] NF	[illegible] N.A. N.A.	Fractured in air

APPENDIX B

Tabulated Fracture Data - Ti [illegible]Al-3Mo-1V Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} ($ksi\sqrt{in.}$)	a (in.)	K_{Ii} ($ksi\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	All Ti [illegible]Al-3Mo-1V Corrosion Specimens were Loaded in Air
[illegible]	STA-[illegible]-F[illegible]	.[illegible]	[illegible]					
-	Not Exposed	.[illegible]	[illegible]					
-				-	-	[illegible] NF	N.A.	
-				-	-	[illegible] NF	N.A.	
-				.[illegible]	[illegible]	[illegible]	N.A.	
[illegible]	STA-[illegible]	.[illegible]	[illegible]					
-[illegible]	[illegible] ksi [illegible] hrs.	.[illegible]						
-[illegible]				.[illegible]	[illegible]	[illegible] NF	N.A.	Fractured in air
-[illegible]				.[illegible]	[illegible]	[illegible]	N.A.	
-[illegible]				.[illegible]	[illegible]	[illegible]	N.A.	
[illegible]	STA-[illegible]-F[illegible]	.[illegible]	[illegible]					
-	[illegible] ksi [illegible] hrs.	.[illegible]	[illegible]					
-[illegible]				.[illegible]	[illegible]	[illegible] NF	N.A.	Fractured in air
-[illegible]				.[illegible]	[illegible]	[illegible] NF	N.A.	Fractured in air
-[illegible]				.[illegible]	[illegible]	[illegible]	N.A.	
[illegible]	STA-[illegible]	.[illegible]	[illegible]					
-	[illegible] ksi [illegible] hrs.	.[illegible]	[illegible]					
-				.[illegible]	[illegible]	[illegible] NF	[illegible]	Fractured in air
-				.[illegible]	[illegible]	[illegible]	N.A.	
-				.[illegible]	[illegible]	[illegible]	N.A.	

AD 1546 D

APPENDIX D

Tabulated Fracture Data - Ti 4Al-3Mo-1V Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	All Ti 4Al-3Mo-1V Corrosion Specimens were Loaded in Air
[illegible]	[illegible]	[illegible]	[illegible]					
[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	NF	N.A.	Fractured in air
[illegible]				[illegible]	[illegible]	NF	N.A.	Fractured in air
[illegible]				[illegible]	[illegible]	[illegible]	N.A.	
[illegible]								

APPENDIX C

TABULATED FRACTURE DATA FOR Ti 6Al-4V 0.500 INCH PLATE, HEATS 292-258 AND 292-030

AC 1586 D

APPENDIX C

Tabulated Fracture Data - Ti 6Al-4V Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
D10-3	Beta-STA-1000 ⑧ Not Exposed	.34	89					Corrosion specimens loaded in air
-4		.32	98					
-5				.32	[illegible]	1.6	N.A.	
-6				[illegible]	66.5	[illegible]	N.A.	
-7				.33	63.6	0.6	N.A.	
A-11	Beta-STA-1[illegible] ⑧ [illegible]F/25ksi/900 hrs.	.35	91					Corrosion specimens were loaded in air
-1[illegible]		.38	94					
-13				.40	70.1	360 NF	N.A.	Fractured in air
-1[illegible]				.38	[illegible]	360 NF	N.A.	Fractured in air
-93				.37	[illegible]	1.4	N.A.	
A-3[illegible]	Beta-STA-[illegible] ⑧ [illegible] hrs.	.33	[illegible]					Corrosion specimens were loaded in air
[illegible]		[illegible]	[illegible]					
[illegible]				.34	66.[illegible]	36[illegible] NF	N.A.	Fractured in air
[illegible]				.36	[illegible]	[illegible] NF	N.A.	Fractured in air
-113				.31	80.1	3	N.A.	
A-21	[illegible]ta-STA-1000 ⑧ [illegible]5ksi [illegible] hrs.	[illegible]	76					Corrosion specimens were loaded in air
-22		[illegible]	[illegible]					
[illegible]				[illegible]	[illegible]	[illegible] NF	N.A.	Fractured in air
[illegible]				.34	61.8	[illegible] NF	N.A.	Fractured in air
-103				[illegible]	67.6	360 NF	N.A.	Fractured in air

AD 1545 D

REV SYM

APPENDIX C

Tabulated Fracture Data - Ti 6Al-4V Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
A-41	Beta-STA-[illegible] [illegible]°F, [illegible] ksi, [illegible]00 hrs. ⚠	.34	87					Corrosion specimens were loaded in air
-42		.32	86					
-43				.34	64.7	360 NF	N.A.	Fractured in air
-44				.30	74.3	1.25	N.A.	
-123				.32	69.4	360 NF	N.A.	Fractured in air
-3[illegible]	Beta-STA-1000 Not Exposed ⚠	.31	104					
-3[illegible]		.2[illegible]	106					
-38				.29	74.9	.33	.[illegible]	These corrosion specimens were loaded in air*
-3[illegible]				.30	6[illegible]	989 NF	N.A.	
-40				.3[illegible]	53.6	2	.21	
-39A				.34	6[illegible].2	1	N.A.	These corrosion specimens were loaded in salt solution
-40A				.3[illegible]	[illegible].7	[illegible]60 NF	N.A.	
-4[illegible]B				.31	[illegible].5	[illegible] NF	N.A.	
-40A'				.34	4[illegible].7	1226 NF	N.A.	Reprecracked
-[illegible]B'				.35	[illegible]7.7	360 NF	N.A.	Reprecracked
-[illegible]A"				.3[illegible]	[illegible].5	411 NF	N.A.	Reprecracked

APPENDIX C
Tabulated Fracture Data - Ti 6Al-4V Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
12	Beta-STA-1000	.33	81					
13	650°F/25ksi/1000 hrs.	.36	100					
17				.32	67.8	.42	.35	These corrosion specimens were
18				.34	45.2	1220NF	N.A.	loaded in salt solution.
19				.31	54.0	360NF	N.A.	
19'				.31	59.2	1.5	.42	Not reprecracked
17A				.36	35.5	386NF	N.A.	These corrosion specimens were
12A				.42	60.2	421NF	N.A.	loaded in air
17A				.39	71.3	1	N.A.	
11	Beta-STA-1000	.32	102					These corrosion specimens were
14	650°F 25ksi [illegible]00 hrs.	.3[illegible]	[illegible]					loaded in salt solution.
1				.35	84.[illegible]	0	N.A.	Failed at load
1[illegible]				.30	61.[illegible]	.17	.09	
2[illegible]				.32	[illegible].9	360NF	N.A.	
[illegible]'				.32	54.6	1.4	.12	Not reprecracked
1[illegible]				.32	52.2	1213NF	N.A.	
[illegible]				.32	51.0	3	.40	
11				.33	50.2	433NF	N.A.	These corrosion specimens were
14				.29	59.[illegible]	563NF	N.A.	loaded in air.
16[illegible]				.34	80.4	2	.12	
11A'				.42	78.4	1	.24	Reprecracked
14A'				.36	71.3	362NF	N.A.	Reprecracked

REV SYM

APPENDIX C

Tabulated Fracture Data - Ti 6Al-4V Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
D7-3	Beta-STA-1250 ⟨9⟩ Not exposed	.35	91					These corrosion specimens were loaded in air.
-4		.31	85					
-5				.36	81.0	360NF	N.A.	
-6				.31	85.4	2.0	N.A.	
-7				.32	81.6	2.2	N.A.	
A-51	Beta-STA-1250 ⟨9⟩ 450°F/25ksi/900 hrs.	.35	115					These corrosion specimens were loaded in air.
-52		.33	109					
-53				.39	93.3	.5	N.A.	
-54				.35	77.9	360NF	N.A.	
-133				.40	94.3	1.2	N.A.	
A-71	Beta-STA-1250 ⟨9⟩ 450°F/25ksi/2500 hrs.	.33	118					These corrosion specimens were loaded in air.
-72		.32	108					
-73				.33	90.8	360NF	N.A.	
-74				.33	91.9	6	N.A.	
-153				.32	86.5	360NF	N.A.	
D-5	Beta-STA-1250 ⟨9⟩ 450°F/25ksi/5000 hrs.	.32	90					These corrosion specimens were loaded in air
-6		.32	95					
-7				.32	74.1	1046NF	N.A.	
-8				.32	83.4	7.5	N.A.	
-9				.33	81.2	3.5	N.A.	

APPENDIX C

Tabulated Fracture Data - Ti 6Al-4V Plate

IDENTIFICATION.		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
D-10A	Beta-STA-1250 9	.36	95					These corrosion specimens were
-11A	450°F/25ksi/10,000 hrs	.39	100					loaded in air.
-12				.33	76.1	4073 NF	N.A.	
-12'				.33	94.6	.63	N.A.	Not reprecracked
-13				.32	[illegible]9.1	698 NF	N.A.	
-14				.32	100.7	.25	N.A.	Not reprecracked
A-61	Beta-STA-1250 9	.39	131					These corrosion specimens were
-62	550°F/25ksi/200 hrs.	.35	109					loaded in air.
-63				.33	[illegible].2	360 NF	N.A.	
-64				.35	[illegible].0	2.2	N.A.	
-143				.35	[illegible].7	0.6	N.A.	
A-81	Beta-STA-1250	.31	124					These corrosion specimens were
-82	550°F/25ksi 2500 hrs.	.31	121					loaded in air.
-83				.30	[illegible]	360 NF	N.A.	
-84				.31	94.7	2	N.A.	
-163				.29	69.2	360 NF	N.A.	

APPENDIX C
Tabulated Fracture Data - Ti 6Al-4V Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
H-11	Duplex Annealed [10]	.31	80					These corrosion specimens
-12	Not Exposed	.30	78					were loaded in air.
-13		.31	78					
-14		.33	73					
-15		.31	80					
-11B		.34	69					
-12B		.32	81					
-13B				.34	55.5	1140NF	NR	Fractured in air.
-14B				.32	61.1	4	NR	
-15B				.32	57.[illegible]	[illegible]	NR	
H-16	Duplex Annealed [10]	.31	75					These corrosion specimens
-17	450°F/25ksi/1000 hrs.	.30	82					were loaded in air.
-18				.31	55.8	370 NF	NR	Fractured in air.
-19				.33	56.	3	NR	
-20				.31	[illegible]	1340 NF	NR	Fractured in air.
H-21	Duplex Annealed [10]	.34	78					These corrosion specimens were
-22	450°F/25ksi/2500 hrs.	.34	76					loaded in air.
-23				.32	62.5	14	.27	
-24				.32	54.8	[illegible]10 NF	N.A.	Fractured in air
-25				.34	58.7	3.1	.10	

REV SYM

APPENDIX C
Tabulated Fracture Data - Ti 6Al-4V Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
H-26	Duplex Annealed 10	.31	79					These corrosion specimens
-27	550°F 25ksi/1000 hrs.	.32	81					were loaded in air.
-28				.34	57.9	4	N.M.	
-29				.32	47.[illegible]	6	N.M.	
-30				.32	41.5	1232 NF	N.M.	Fractured in air.
H-31	Duplex Annealed 10	.31	67					These corrosion specimens were
-32	550°F 25ksi/2500 hrs.	.34	81					loaded in air.
-33				.32	59.2	5.5	.08	
-34				.33	52.6	2518 NF	N.A.	Fractured in air.
-35				.30	53.5	1324 NF	N.A.	
-35'				.30	57.0	1.75	N.A.	Not reprecracked
2	Duplex Annealed 10	.34	76					These corrosion specimens
[illegible]	550°F 25ksi 1000 hrs.	.35	66					were loaded in salt solution.
[illegible]				.36	[illegible].9	1.33	.20	
9				.35	43.7	1.66	.12	
10				.35	67.6	.25	.07	
1A				.29	26.9	14	.52	
1B				.31	20.8	1098 NF	N.A.	Fractured in air.
[illegible]A				.35	22.5	374 NF	N.A.	These corrosion specimens were
3A				.34	34.4	515 NF	N.A.	loaded in air.
10A				.35	43.5	3	.24	
2A'				.39	39.3	1127 NF	N.A.	Reprecracked.
3A'				.38	41.[illegible]	7	.2[illegible]	Reprecracked.

REV SYM

APPENDIX C

Tabulated Fracture Data - Ti 6Al-4V Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
6	Duplex Annealed 10 650°F/25ksi/2500 hrs.	.33	69					These corrosion specimens were loaded in salt solution.
7		.36	76					
4				.34	73.9	0	.06	
5				.35	53.4	.92	.15	
8				.38	46.1	1.25	.16	
4A				.32	31.[illegible]	221	.[illegible]	
4B				.3[illegible]	47.[illegible]	3.6	.36	
5A				.34	30.3	136	.4[illegible]	These corrosion specimens were loaded in air.
6A				.[illegible]	[illegible]1.6	376NF	N.A.	
7A				.[illegible]6	[illegible]7.2	466NF	N.A.	
6A'				.41	29.7	372NF	N.A.	Reprecracked
7A'				.39	3[illegible].[illegible]	491NF	N.A.	Reprecracked
7A"				.44	[illegible].4	251	.34	Reprecracked
31	Duplex Annealed 11 Not Exposed	.[illegible]	87					These corrosion specimens were loaded in air.
[illegible]		.43	79					
[illegible]				.35	64.[illegible]	[illegible] NF	.0[illegible]	Fractured in air.
[illegible]				.33	[illegible]5.6	0	N.A.	
[illegible]				.33	64.[illegible]	.[illegible]	.19	
34A				.33	[illegible]	1	.30	These corrosion specimens were loaded in salt solution.
34B				.4[illegible]	40.1	410NF	Trace	
35A				.36	[illegible].0	[illegible]	.26	
35[illegible]				.3[illegible]	46.[illegible]		.17	Reprecracked.

APPENDIX C

Tabulated Fracture Data - Ti 6Al-4V Plate

IDENTIFICATION		FRACTURE TOUGHNESS		STRESS CORROSION				REMARKS
SPEC. NO.	HEAT TREATMENT AND EXPOSURE	a (in.)	K_{Ic} (ksi$\sqrt{in.}$)	a (in.)	K_{Ii} (ksi$\sqrt{in.}$)	Time to Fail (min.)	Corr. Growth (in.)	
26	Duplex Annealed 1 450°F/25ksi/1000 hrs.	.36	95					These corrosion specimens were loaded in salt solution.
27		.33	84					
28				.38	41.7	1.66	.25	
29				.36	21.4	5.42	.60	
30				.35	13.4	1073 NF	N.A.	
30'				.40	22.8	1255 NF	N.A.	Reprecracked
26A				.34	34.2	382 NF	N.A.	These corrosion specimens
27A				.35	40.8	3	.27	were loaded in air.
28A				.36	31.5	377 NF	N.A.	
28A'				.39	36.3	362 NF	N.A.	Reprecracked
26A'				.37	34.0	360 NF	N.A.	Reprecracked
26A"				.43	38.6	462 NF	.30	Reprecracked
21	Duplex Annealed 1 450°F/25ksi/2500 hrs.	.33	96					These corrosion specimens were loaded in salt solution.
22		.34	95					
23				.32	42.9	2	.27	
24				.34	31.1	4.6	.50	
25				.37	17.5	360 NF	N.A.	
25				.39	25.7	5.25	.58	Reprecracked
21A				.33	18.6	381 NF	N.A.	These corrosion specimens
22A				.33	36.8	385 NF	N.A.	were loaded in air.
23A				.35	46.4	2	.27	
21A'				.36	35.5	376 NF	N.A.	Reprecracked
22A'				.38	42.5	10	.36	Reprecracked

REV SYM

FLAGNOTES AND SYMBOLS USED IN APPENDICES A, B, AND C

NF	No Failure
NA	None Apparent
NR	Not Recorded
1	1300°F/2Hrs/Air Cool
2	1300°F/2Hrs/Fce. Cool at 80°F/Hr to 800°F then Air Cooled
3	1800°F/30Min/Air Cool + 1625°F/1Hr/Water Quench + 1200°F/4Hrs/Air Cool
4	1875°F/30 Min/Air Cool + 1725°F/30Min/Water Quench + 1050°F/8Hrs/Air Cool
5	1875°F/30Min/Air Cool + 1725°F/30Min/Water Quench + 1150°F/8Hrs/Air Cool
6	1725°F/1Hr/Air Cool + 1150°F/8Hrs/Air Cool
7	1640°F/1Hr/Water Quench + 1175°F/8Hrs/Fce Cool at 80°F/Hr. to 800°F then Air Cooled
8	1900°F/30Min/Air Cool + 1725°F/30Min/Water Quench + 1000°F/4Hrs/Air Cool
9	1900°F/30Min/Air Cool + 1725°F/30Min/Water Quench + 1250°F/4Hrs/Air Cool
10	1725°F/30Min/Air Cool + 1250°F/4Hrs/Air Cool
11	1725°F/30Min/Air Cool + 1250°F/4Hrs/Fce Cool at 80°F/Hr. to 800°F then Air Cool