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This study was undertaken to determine methods for metallurgical improvement of cyclic-crack-growth and fracture properties in Ti-6Al-6V-2Sn. Two heats of the alloy were studied: an $\alpha+\beta$-processed material containing 0.16 percent interstitial oxygen and a β-processed material containing 0.08 percent interstitial oxygen. All test specimens were given a mill anneal heat treatment; in addition some specimens from each heat were given a recrystallization anneal heat treatment. Fatigue-crack growth rates were determined using compact tension specimens, and fracture toughness was determined using 1-in. dynamic tear specimens for each combination of
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material and heat treatments. The recrystallization anneal treatment resulted in significant improvements in the fracture resistance of both materials, despite metallographic evidence that the recrystallization-annealed β-processed material did not develop a fully recrystallized structure. Improvements in cyclic-crack-growth resistance resulting from the recrystallization anneal treatment, per se, were modest for both the $\alpha+\beta$-processed and β-processed materials. However the combined effects of recrystallization anneal plus a reduction in interstitial oxygen content significantly improved the cyclic-crack-growth properties of Ti-6Al-6V-2Sn.

CONTENTS

CYCLIC-CRACK-GROWTH AND FRACTURE RESISTANCE OF Ti-6Al-6V-2Sn AS INFLUENCED BY RECRYSTALLIZATION ANNEAL AND INTERSTITIAL OXYGEN CONTENT

INTRODUCTION

Ti-6Al-6V-2Sn is a high-strength structural material used for aerospace applications requiring high strength-to-density ratios and intermediate stiffness. For many such applications resistance to cyclic crack growth and fracture are prime considerations. This study was undertaken to determine methods for metallurgical improvement of these properties in Ti-6Al-6V-2Sn.

METALLURGICAL BACKGROUND

One such method for metallurgical improvement of cyclic crack growth and fracture properties in high-strength titanium alloys is recrystallization anneal heat treatment combined with reduction of the interstitial oxygen content. It has been recognized for some time that interstitial oxygen, which promotes strengthening in titanium alloys, has a powerful effect on fracture resistance [1,2]. Harrigan, Kaplan, and Sommer [3] have recently shown that a heat-treatment process derived from diffusion bonding studies, termed recrystallization anneal (RA), significantly improved the cyclic-crack-growth and fracture properties of Ti-6Al-4V. Further, Harrigan's results indicated that the benefits of the RA treatment in improving the cyclic-crack-growth and fracture properties were enhanced by reduction of the interstitial oxygen content and thus by sacrificing some yield strength. Examples of these results for commercial-purity (CP) ($O < 0.20$ wt-%) and extra-low-interstitial (ELI) ($O < 0.13$ wt-%) Ti-6Al-4V are illustrated in Figs. 1 and 2.

High-strength titanium alloys are most commonly used for structural purposes in the mill annealed condition. In practice the mill anneal (MA) treatment can vary widely and represents no more than an attempt at stress relief. Several recent studies [3-5] of cyclic crack growth and fracture in titanium alloys have consistently shown the MA-product form to possess the least desirable values of these properties when compared to values obtained after subsequent heat treatment.

The improved fracture and cyclic-crack-growth resistance of the RA-treated material is thought to be due to the capability of absorbing greater localized deformation than the MA material. The same effect is also achieved through reduction of the interstitial oxygen

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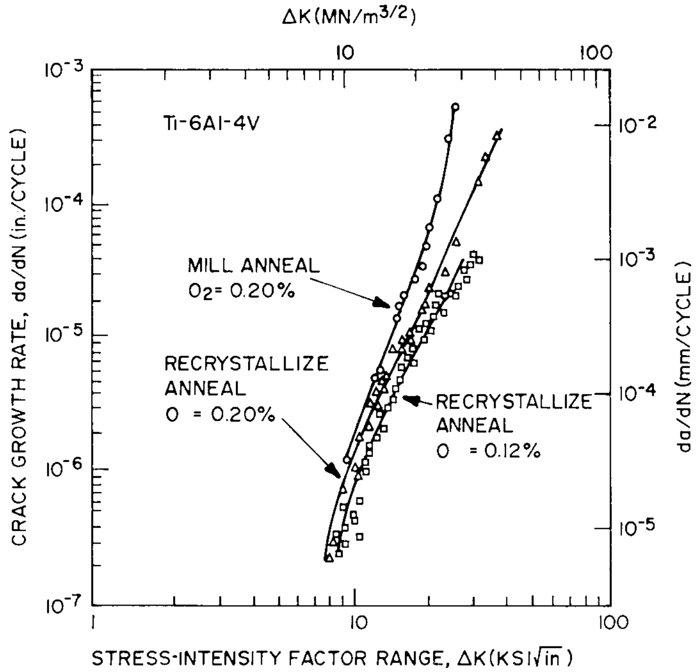

Fig. 1 — Example of the effects of recrystallization anneal and interstitial oxygen content on the cyclic-crack-growth characteristics of Ti-6Al-4V as reported by Harrigan, Kaplan, and Sommer [3]

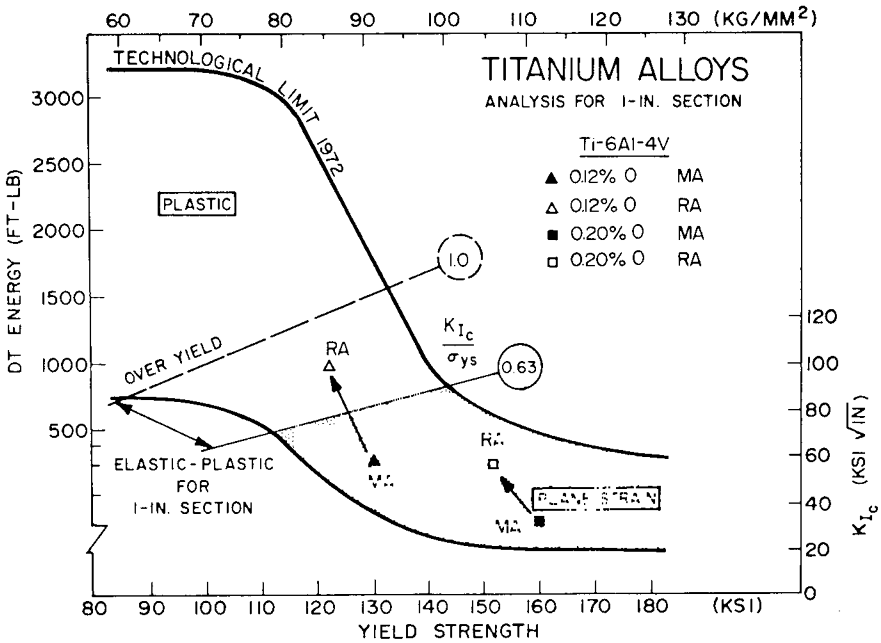

Fig. 2 — Example of the effects of recrystallization anneal (RA) and mill anneal (MA) heat treatments and of interstitial oxygen content on the fracture toughness characteristics of Ti-6Al-4V [3]

content. For MA-treated materials processed in the α+β region, sufficient stored energy remains from cold work to allow recrystallization to occur. Harrigan, Kaplan, and Sommer [3] propose that the resulting recrystallized structure is then capable of greater absorption of deformation energy accumulated under structural service loads. For titanium alloys processed in the β region, it is generally regarded that full recrystallization is not possible and the effects of the RA treatment, if any, are difficult to predict. Since a substantial amount of titanium alloys in stocks at present have been β-processed, it is important to understand the result of subsequent heat treatment on the fatigue and fracture properties of β-processed titanium alloys.

MATERIALS AND HEAT TREATMENT

Two heats of Ti-6Al-6V-2Sn were studied in this investigation: an α+β-processed CP material containing 0.165 percent interstitial oxygen and a β-processed ultra-low-interstitial (ULI) (O $<$ 0.08 wt-%) material containing 0.077 percent interstitial oxygen. Specimens of the CP material were cut from 1-in.-thick rolled plate. Chemical compositions of the materials studied are given in Table 1, the heat treatment procedures are given in Table 2, and the resulting mechanical properties are shown in Table 3.

Table 1
Alloy Compositions

Element	Content (wt -%)	
	Commercial-Purity (CP) Material	Ultra-Low-Interstitial (ULI) Material
C	0.03	0.022
N	0.012	0.010
Al	5.47	5.60
V	5.32	5.31
Sn	2.28	2.01
Cu	0.62	0.92
Fe	0.57	0.52
O	0.165	0.077
H	0.0034	—

Table 2
Heat Treatment Schedule*

Mill Anneal (MA):	Heat to 1350° F, hold for 1 hour, and then air cool to room temperature.
Recrystallization Anneal (RA):	Heat to 1640° F (±15° F), hold for 4 hours, and furnace cool to 1400° F in approximately 30 minutes. After helium purge to to 1000° F, air cool to room temperature.

*All specimens were mill annealed before further heat treatment was performed.

Table 3
Mechanical Properties of the Alloys (Table 1) after Heat Treatment (Table 2)

Material	Heat Treat.	UTS (ksi)	0.2% ys (ksi)	Elong. (%)	Red. A (%)	DTE (ft-lb)
CP	MA	162.5	153.5	14.5	26.0	215
	RA	161.5	150.2	13.2	25.0	460
ULI	MA	150.0	136.0	7.0	19.0	440
	RA	133.2	120.0	12.5	29.0	940

All heat treatments were performed on rough-cut coupons prior to machining. Special care was taken during heat treatment to avoid the development of β-fleck precipitate. This precipitate is a combination of Ti-Cu-Fe elements, all of which are characteristic of Ti-6Al-6V-2Sn. The precipitate develops at approximately 50° F below the alloy's β transus, as shown in Fig. 3. Due to a lower β-transus temperature for the precipitate relative to the matrix, the precipitate develops a Widmanstatten structure upon cooling. Thus, under fatigue cycling, crack initiation results from a strain mismatch between precipitate and matrix. Since the alloy β transus can be increased by increasing the heating rate, the alloy temperature response was closely monitored. These principles were used in determining the heat treatment schedules for the RA treatment followed in this study, as outlined in Table 2.

The microstructures developed by the heat treatments are shown in Figs. 4 through 7. The microstructure of the mill annealed CP alloy in Fig. 4 is typical of this alloy when worked high in the α+β region. The exact rolling temperature of this alloy is unknown, but it was obviously worked high in the α+β region, because the microstructure is a β matrix containing some secondary α with elongated primary α particles. The mill anneal at 1450° F for 1/2 hour is a stress relief intended to normalize all of the specimens, prior to testing or further heat treatment. The recrystallization anneal treatment produced a significant change in the microstructure of the CP alloy, as shown in Fig. 5. It appears that the elongated primary α was recrystallized into a nearly equiaxed configuration. Some of the elongated primary α appears to remain in Fig. 5; a longer time at temperature should produce a more completely recrystallized microstructure.

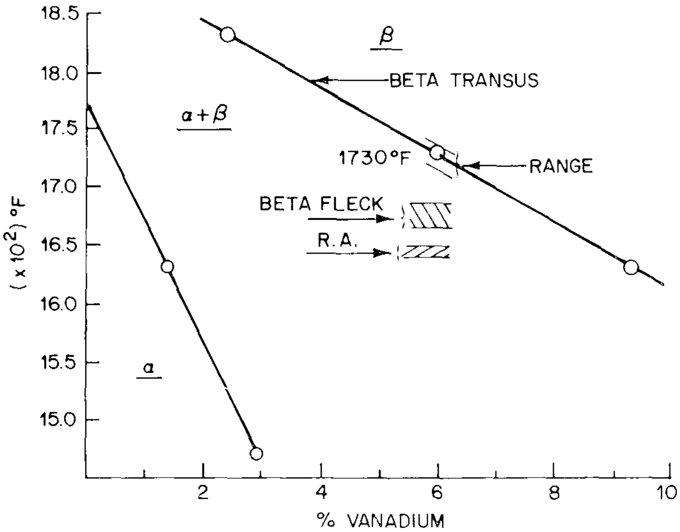

Fig. 3 — Phase diagram for Ti-V at 6 percent aluminum showing the β-fleck and recrystallization anneal regions

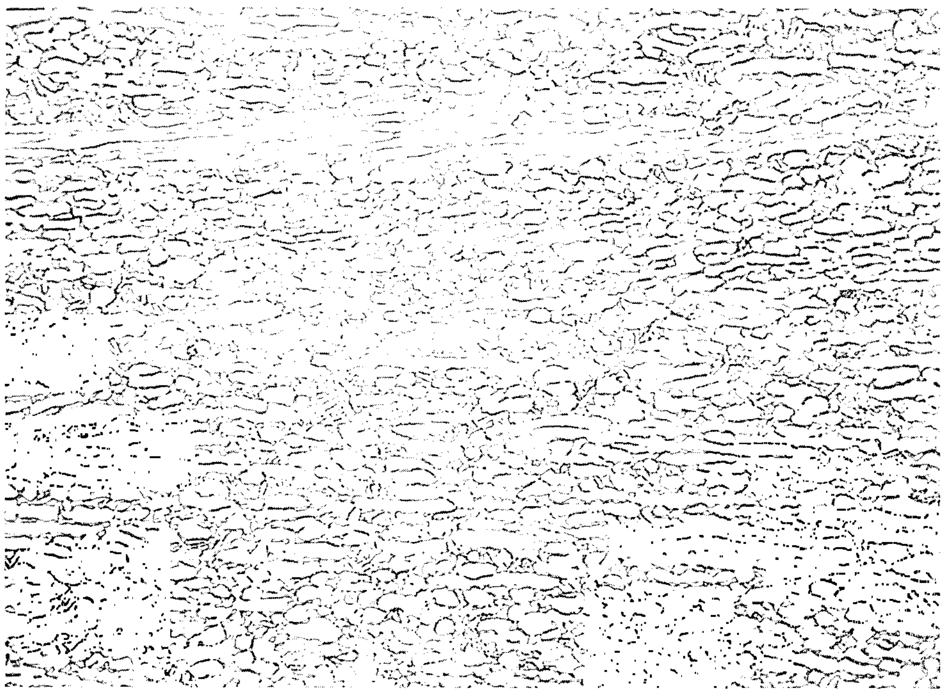

Fig. 4 — Commercial purity (CP) Ti-6Al-6V-2Sn in the mill annealed condition. The microstructure is elongated primary α (light) with secondary α in a β matrix. (500X mag. optical; Kroll's etch.)

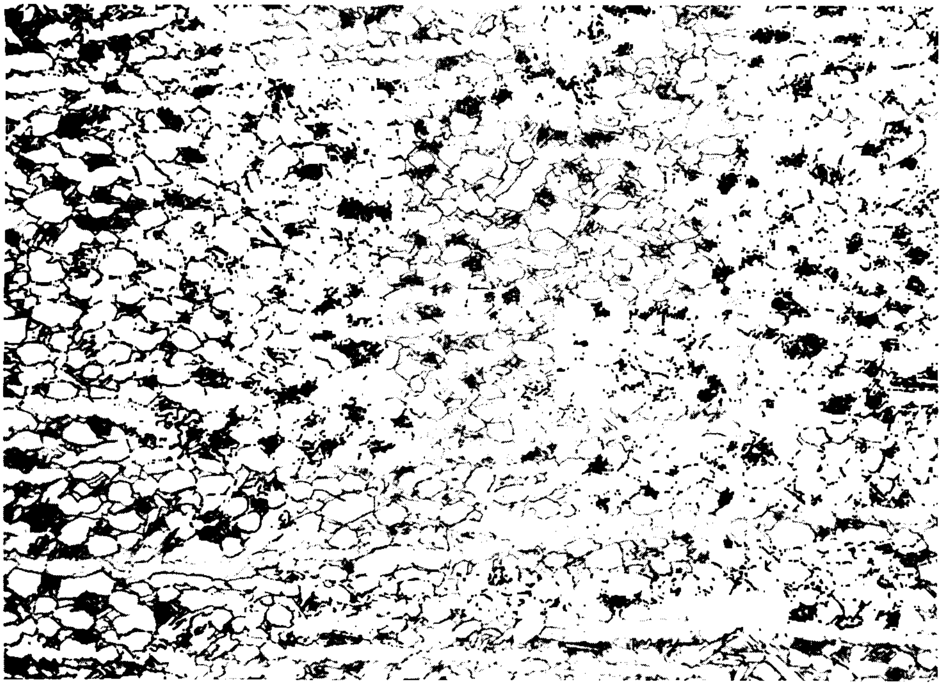

Fig. 5 — CP Ti-6Al-6V-2Sn after anneal in the recrystallized condition. The microstructure is nearly equiaxed grains of primary α (light) in a matrix of β with some secondary α. Some elongated primary α remains unrecrystallized. (500X mag. optical; Kroll's etch.)

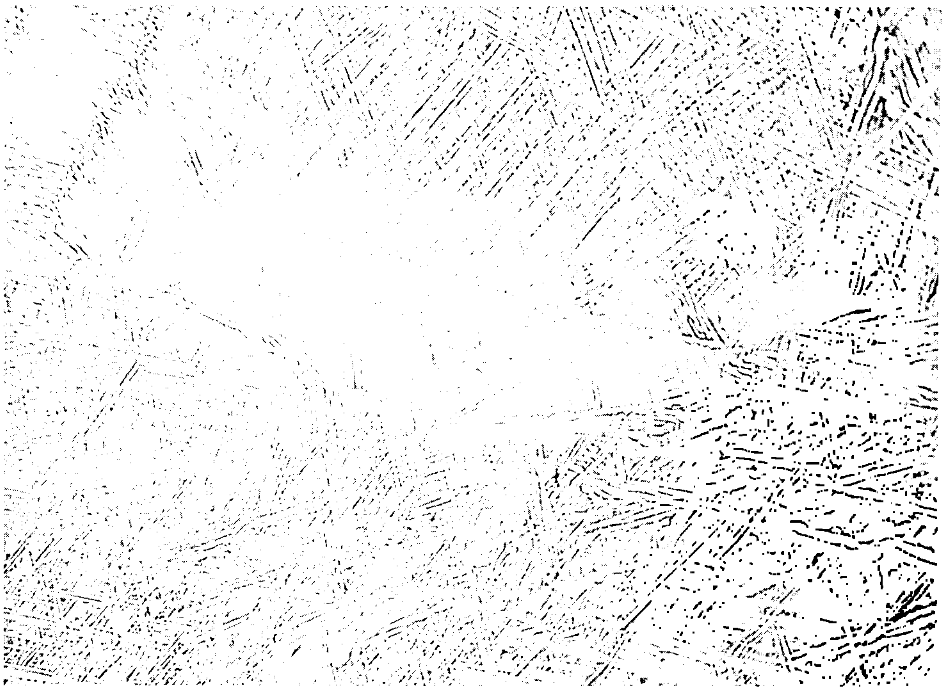

Fig. 6 — Ultra-low-interstitial (ULI) Ti-6Al-6V-2Sn after mill anneal (MA) in the β-processed condition. The microstructure is a β matrix with acicular secondary α ; continuous α is present in the prior β grain boundaries. (500X mag. optical; Kroll's etch.)

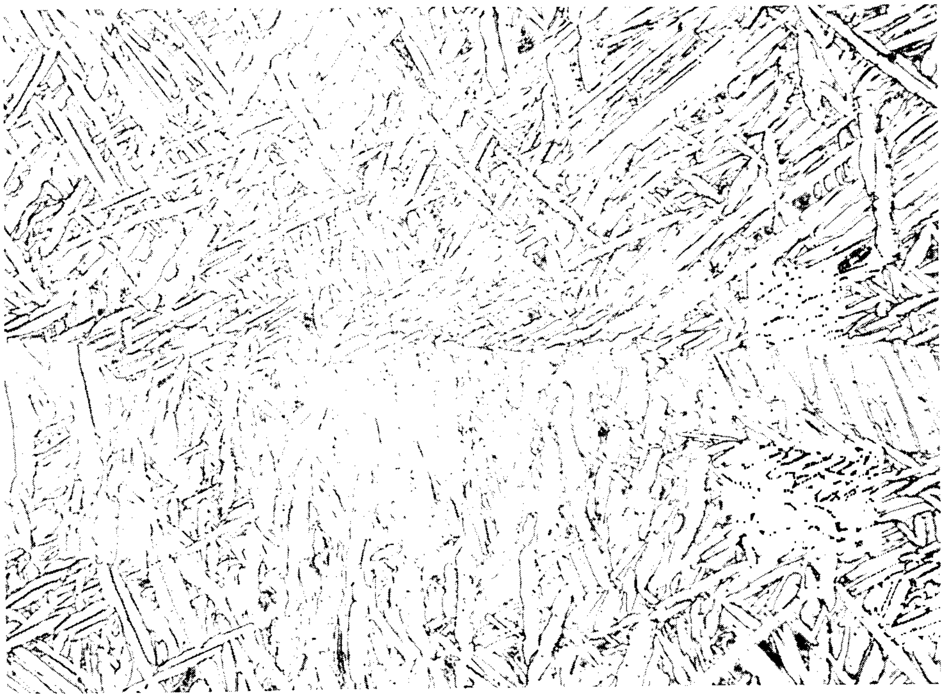

Fig. 7 — ULI Ti-6Al-6V-2Sn after RA treatment. Grain growth is evidenced by enlarged platelike α with residual β. Prior β grain boundaries are discontinuous. (500X mag. optical; Kroll's etch.)

The ULI alloy shown in Fig. 6 was obviously β-worked prior to the 1450°F mill anneal. The recrystallization treatment produced the changes shown in Fig. 7. The acicular α grains grew considerably during the RA treatment forming platelike α, but it is not clear whether the α recrystallized. The continuous α in the prior grain boundaries present in Fig. 6 was broken up by the RA treatment in Fig. 7.

TEST METHODS

Tensile data were obtained from 0.505-in.-diameter specimens tested in accordance with standard ASTM practices. Fracture tests were conducted using the NRL 1-in. dynamic tear (DT) test [6]. The 1-in. DT specimen is shown in Fig. 8. This test involves the use of a notched specimen under impact loading. A brittle electron-beam weld is placed in the root of the notch to act as a crack starter in a region ahead of the test material. Thus the test material is subjected to a natural crack under dynamic loading over a crack-run distance great enough to allow the crack to assume a natural morphology. The test has been extensively employed on titanium alloys for a decade and is well suited for the quantitative examination of metallurgically induced fracture-resistance effects in these materials.

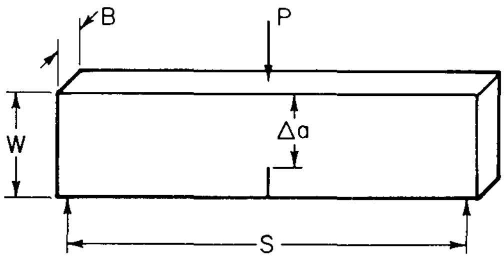

Fig. 8 — Dimensions of the 1-in. dynamic tear specimen [6]

STANDARD SPECIMEN

B		Δa		W		S	
(IN.)	(CM)	(IN.)	(CM)	(IN.)	(CM)	(IN.)	(CM)
1.0	2.5	3	7.6	4.75	12.1	16	41

The cyclic-crack-growth tests were conducted using compact tension fracture-mechanics specimens as shown in Fig. 9. Both the proportions of the specimen and the expression employed to calculate crack-tip stress intensities were obtained from ASTM E399 [7]. Fatigue-crack growth rates were measured in ambient air at 10 Hz on a closed-loop electrohydraulic materials testing system. A stress ratio (minimum load/maximum load) of R = 0.05 was employed in all tests, and crack length observations were made optically at 33X magnification using a Gaertner traveling microscope. The fatigue specimens were precracked 0.20 in. prior to the beginning of data accumulation. In most instances duplicate specimens were tested for each of the mechanical properties reported.

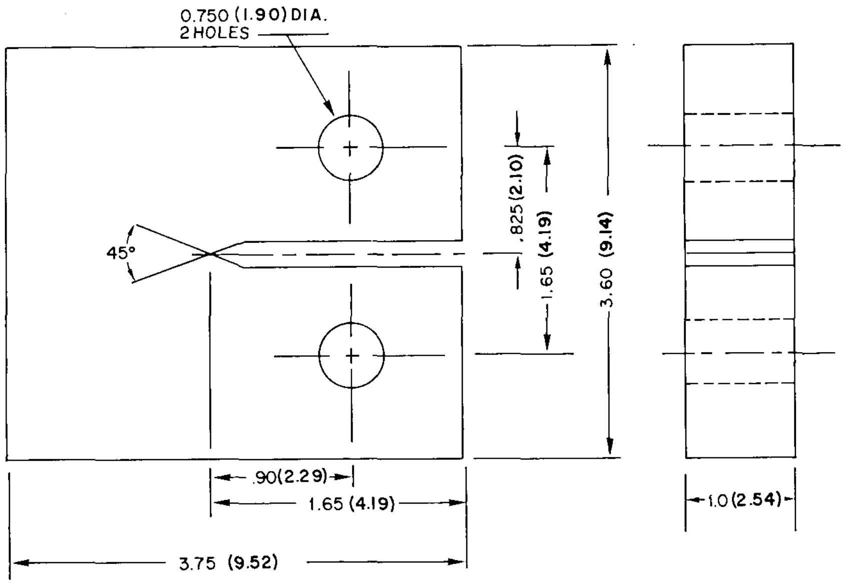

Fig. 9 — Details of the compact tension specimen [7]. Dimensions are in inches (and centimeters).

RESULTS AND DISCUSSION

The cyclic-crack-growth results are shown in Fig. 10, which is a logarithmic plot of crack growth rate per cycle of repeated load (da/dN) vs the crack-tip stress-intensity factor range (ΔK). The fracture results are illustrated in Fig. 11, where the data are plotted on the NRL Ratio Analysis Diagram (RAD) for high-strength titanium alloys [2].

The RAD on which data are presented in Fig. 11 (and in Fig. 1) is a cumulative plot, by alloy family, of fracture toughness vs yield strength for the full spectrum of high and intermediate yield-strength levels. The low-yield-strength portion of the diagram has been compiled from dynamic tear (DT) [6] tests, and the high-yield-strength portion of the diagram from valid plane strain fracture toughness (K_{Ic}) tests. However the entire diagram can be developed by conducting two simple engineering tests, a DT test and an ordinary tensile test. For alloys of sufficiently low toughness-to-strength ratios, a correlation is available between DT energy and K_{Ic} [2], thus enabling graphical fracture mechanics solutions for brittle fracture problems.

Limiting values for the upper and lower extremes of fracture toughness are indicated on the RAD, and within this overall region of observed fracture behavior further subregions are categorized on the basis of significant plane strain fracture toughness-to-yield strength (K_{Ic}/σ_{ys}) ratios. For 1-in.-thick alloys the two significant ratio lines are $K_{Ic}/\sigma_{ys} = 0.63$ and 1.0. The ratio value of 0.63 is derived from the thickness requirement for plane strain fracture toughness measurements [7]. Alloys which possess fracture toughness characteristics within the subregion bounded below the 0.63 ratio line are susceptible to plane strain elastic instability fracture. The ratio value of 1.0 has evolved as a reasonable estimate of a sufficient level of toughness to attain fracture over the yield stress for 1.0-in.-thick plates containing a through-thickness flaw several inches long. Alloys possessing fracture toughness characteristics above this ratio can be expected to be immune from brittle elastic fracture and will require some degree of gross plastic deformation before fracture will occur. The subregion between these two significant ratio lines is termed elastic-plastic fracture. Alloys which have fracture toughness characteristics between ratios 0.63 and 1.0 require some degree of large-scale localized plastic deformation in the vicinity of the crack before fracturing, even though net section stresses away from the crack remain below yield. However the degree of localized deformation involved is sufficient to render a plane-strain fracture mechanics analysis invalid. The net effect of this localized deformation is to relieve constraint around crack tips and thus permit substantially larger flaws to develop in service than would be predicted from a plane strain analysis.

It can be seen from the data presented in Figs. 10 and 11 that the RA treatment and the reduction in interstitial oxygen content had a consistently beneficial effect on the cyclic-crack-growth and fracture properties of Ti-6Al-6V-2Sn. From the data on cyclic-crack-growth resistance (Fig. 10) it appears that interstitial oxygen exerted a greater effect than the RA treatment. In fact the RA treatment, per se, resulted in only a modest reduction in da/dN values in each of the two materials studied, except for the significant effect at high values of ΔK in the CP alloy (0.16 percent oxygen). However the combined effects of reducing the interstitial oxygen content and of the RA treatment had a significant beneficial effect on cyclic-crack-growth resistance in Ti-6Al-6V-2Sn, with da/dN

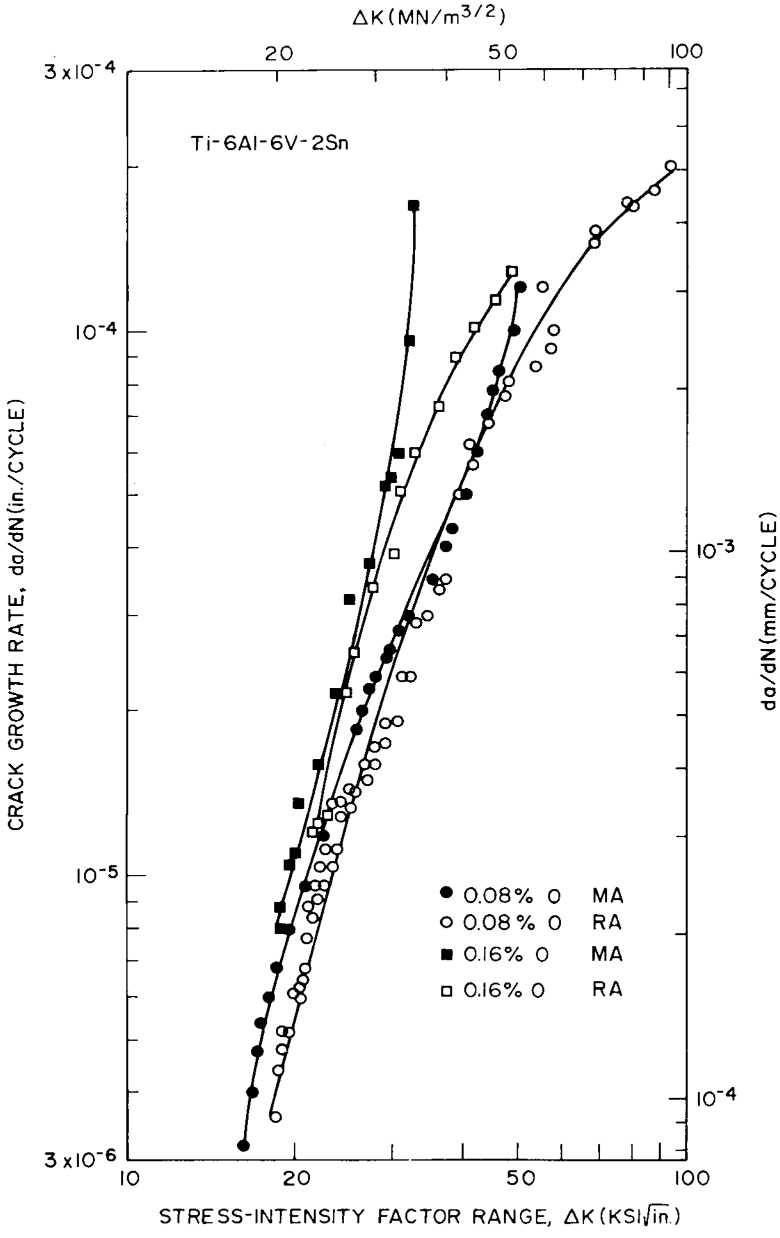

Fig. 10 — Cyclic-crack-growth properties of Ti-6Al-6V-2Sn alloys of differing interstitial oxygen contents heat treated to the mill anneal (MA) and recrystallization (RA) conditions, as determined in this investigation.

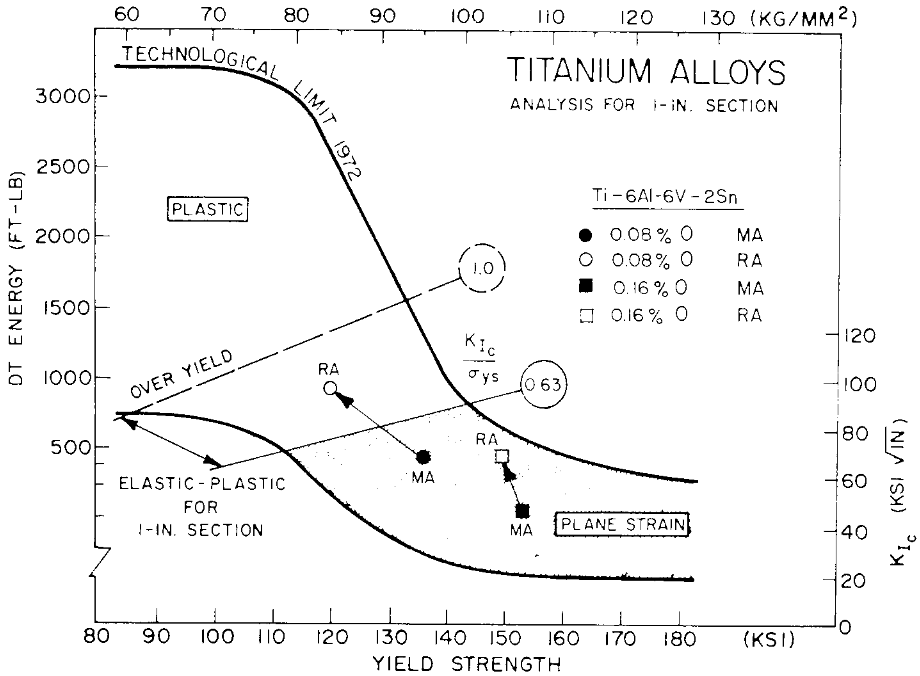

Fig. 11 — Fracture characteristics of 1-in.-thick Ti-6Al-6V-2Sn as influenced by heat treatment and chemistry in this investigation.

values being reduced by as much as a factor of 5 due to these combined influences. The cyclic crack growth results shown in Fig. 10 for Ti-6Al-6V-2Sn are in general agreement with the results of Harrigan, Kaplan, and Sommer on Ti-6Al-4V shown in Fig. 1.

An examination of the fracture test results (Fig. 11) reveals that interstitial oxygen content and the RA treatment also exerted significant beneficial effects on the fracture resistance of Ti-6Al-6V-2Sn. In this instance the RA treatment, per se, was of significant value in improving the fracture toughness levels of both materials studied. Overall there is a high degree of similarity between the findings of this study and the data on Ti-6Al-4V reported by Harrigan, Kaplan, and Sommer [3] illustrated in Fig. 2. In both studies the RA treatment significantly improved fracture toughness values for each level of oxygen chemistry examined. In both studies the maximum attainable fracture toughness value increased with reductions in interstitial oxygen content. However, concomitantly in both studies, the penalty for higher fracture toughness through control of interstitial oxygen was loss of yield strength.

In the present study two facets stand out for special note: the α+β-processed CP material exhibited substantial improvement in fracture toughness through RA treatment with only a very minor loss of yield strength, and the β-processed ULI material exhibited a significant improvement in fracture resistance even though a fully recrystallized structure did not develop after the RA treatment.

CONCLUSIONS

- Ti-6Al-6V-2Sn alloys are susceptible to improvement of cyclic-crack-growth and fracture properties through control of interstitial oxygen content and heat treatment.

- The recrystallization anneal (RA) treatment of the CP alloy (0.165 percent oxygen) improved the fatigue and fracture properties relative to the mill anneal (MA) treatment with no significant loss in yield strength. The dynamic tear energy increased from 215 to 460 ft-lb, whereas the yield strength dropped only from 154 to 150. The crack propagation rate was significantly reduced by the RA treatment of the CP alloy, but little improvement was observed for low values of ΔK.

- The RA treatment of the ULI material (0.077 percent oxygen) improved the fracture resistance by more than a factor of 2, but only a small improvement was observed in fatigue crack propagation rate; however a 12-percent loss in yield strength resulted.

- Reduction of the interstitial oxygen content from 0.165 to 0.077 percent significantly enhanced both fracture and cyclic-crack-growth properties but also resulted in a significant loss of yield strength.

- The greatest benefits to cyclic-crack-growth and fracture properties were achieved through the combined effects of reduction in interstitial oxygen content plus application of the RA treatment.

- The same ranking order was observed for both cyclic-crack-growth and fracture properties in both materials studied.

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