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Fatigue and Fracture Behavior of the High Hardenability Martensitic Transage Titanium Alloys

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Smooth bar fatigue, crack growth rate and fracture toughness data are reported for 25-mm (1-in.) plates of the martensitic Transage titanium alloys: T-129 (Ti-2A1-11V-2Sn-11Zr) and T-134 (Ti-2A1-12V-2Sn-6Zr). The axial fatigue ($R=0$), 10^5-cycle, runout stress of T-134 was found to be 980 MPa (142 ksi)—92% of yield strength. Rotating bend fatigue ($R=-1.0$) 10^7-cycle runout stresses of T-129 and T-134 were found to be 600 and 610 MPa (87 and 88.5 ksi), respectively. Crack growth rates for 0.25 Hz and 5-min hold testing were found to be similar to those of typical Ti-6A1-4V engine forgings. Unusual resistance to fracture resulted from the occurrence of stress-induced phase transformation in the alloys.

Introduction

A NEW type of titanium alloy, called "Transage" offers exceptional promise for improving structural efficiency in fatigue critical parts, and for reducing costs through their capability for achieving net shape or near net shape by isothermal or near isothermal forging in the 650-760°C (1200-1400°F) temperature range.[1] The alloys have exceptionally high hardenability, with ideal round sizes estimated to be in the range from 120 to 200 mm (5.5 to 8 in.).[2]

The Transage alloys transform partially to a submicroscopic hexagon-close-packed martensite (alpha prime) on air cooling from the beta phase field. Heating into the age hardening range of 455-565°C (850-1050°F) causes the submicroscopic martensite to grow very rapidly and results in a very fine and uniform Widmanstatten distribution of alpha in a beta matrix. The residual beta undergoes stress-induced transformation that contributes to fracture resistance. The primary purpose of this paper is to present fatigue results obtained for 25-mm (1-in.) plates of Transage 129 and 134 alloys, and to describe their unusual fracture behavior. Compositions of the alloys in weight percent are: Ti-2A1-11V-2Sn-11Zr and Ti-2A1-12V-2Sn-6Zr, respectively. The Transage 129 plate was produced from a 820-kg (1800-lb) heat, and the Transage 134 plate from a 45-kg (100-lb) heat. Transage 129 has a density of 4816 kg/m^3 (0.174 lb/in.^{3}) and a beta transus temperature of approximately 720°C (1325°F). Transage 134 has a density of 4733 kg/m^3 (0.171 lb/in.^{3}) and a beta transus of approximately 746°C (1375°F).

Results and Discussion

Tension Test Results

Mechanical properties of the test materials are given in Table 1. A double aging treatment was selected for fatigue evaluation because earlier testing of Transage 129 in sheet form showed substantially better fatigue resistance than for single temperature aging.[3] Rolls-Royce employed air cooling from a solution heat treatment temperature of 815°C (1500°F) while Lockheed employed fan air cooling. This is believed to have caused the 115 MPa (16 ksi) lower yield strength obtained by Rolls-Royce for Transage 134 compared to Lockheed results. The smaller difference of only 28 MPa (4 ksi) for Transage 129 is believed to be due to its greater hardenability compared to Transage 134. Tension test properties for single temperature aging treatments are included for comparison. [The gage section of the tension test specimens was 6.4 mm (0.25 in.) in diameter.]

Microstructures of the fully heat-treated materials evaluated in fatigue are shown in Figs. 1 and 2 for Transage 129 and 134, respectively. The extraordinary fineness of structure, especially for Transage 134, should be noted.

Fatigue Test Results

Axial fatigue data for smooth bar specimens of Transage 129 and 134 alloys are compared with data for forgings of Ti-6A1-4V and Ti-10V-2Fe-3A1 in Fig. 3. Only forged Ti-l0V-2Fe-3A1 at a 1240 MPa (180 ksi) minimum ultimate strength level is competitive.[4] The TIMET data for Ti-10V-2Fe-3A1 forgings is for a 1034 MPa (150 ksi) level of ultimate strength.[5]

Rotating bend data for smooth bar specimens of the Transage alloys are compared with Ti-6A1-4V forgings in Fig. 4. The very limited scatter in the data for the Transage alloys is remarkable. The two alloys differ in heat size, heat treatment, and yield strength [by 62 MPa (9 ksi)]. They have in common only that they are 25-mm (1-in.) plates and possess the fine Widmanstatten microstructure characteristic of Transage alloys. Axial fatigue data for center hole notched sheet specimens of Transage 129 alloys showed similar lack of scatter.[3] The lack of scatter is less evident in Fig. 3 because of the limited number of specimens.

Transage 134 was observed to be slightly more fatigue resistant than Transage 129 under both axial and rotating bend loading conditions, although it was lower in yield strength by 62 MPa (9 ksi). This is attributed to its finer microstructure (compare Figs. 1 and 2).

Transage 134 is compared in strength-to-density with selected high-strength structural materials in axial and rotating bend fatigue in Figs. 5 and 6, respectively. It is clearly evident that significant weight reductions in fatigue critical structures can be had by using it in place of high-strength aluminum, steel, and other titanium alloys.

Crack Growth Rate

Crack growth data for Transage 129 and 134 alloys are shown in comparison with Ti-6A1-4V forgings in Fig. 7.

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Table 1 Mechanical properties of 25-mm (1-in.) plates of Transage 129 and 134 alloys[a]

Data origin	Aging treatment Temperature °C	°F	Time h	Yield strength (0.2% offset) MPa	ksi	Ultimate tensile strength MPa	ksi	Elong.,%[c]	RA,%[d]	0°C (32°F) Charpy V-notch impact J	ft-lb	Fracture toughness ASTM E399 MPa-m½	ksi-in.½
Transage 129 (Ti-2Al-11V-2Sn-11Zr)													
LMSC[b]	538	1000	4	1207	175	1276	185	7.5	22	—	—	—	—
LMSC	620/455	1150/850	2/48	1151	167	1234	179	10.0	21	—	—	—	—
RR[b]	620/455	1150/850	1/24	1124	163	1255	182	9.8	24	—	—	41	38
Transage 134 (Ti-2Al-12V-2Sn-6Zr)													
LMSC	510	950	3	1313	190	1380	200	5.0	10	—	—	—	—
LMSC	538	1000	3	1202	174	1267	184	7.5	14	9.5	7.0	48	44
LMSC	566	1050	2	1097	159	1167	169	9.5	34	11.5	8.5	55	50
LMSC	595/480	1100/900	1/4	1175	170	1240	180	9.0	26	11.9	8.8	55	50
RR[b]	595/480	1100/900	1/4	1060	154	1138	165	14.0	45	—	—	59	54

[a] All materials were solution heat treated at 815°C (1500°F) for 1 h followed by air cooling for the Rolls-Royce tests and fan air cooling for the Lockheed tests. [b] Average for two tensile and fracture tests, all other data for single specimens. [c] Tensile elongation. [d] Reduction of area.

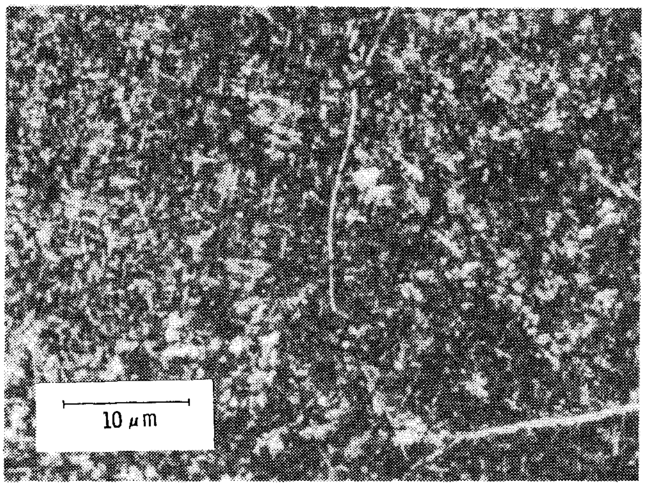

Fig. 1 Photomicrograph of Transage 129 alloy (Ti-2Al-11V-2Sn-11Zr), 25-mm (1-in.) plate, 815°C (1500°F), 620°C (1150°F)-1h-AC, 455°C (850°F)-24h-AC.

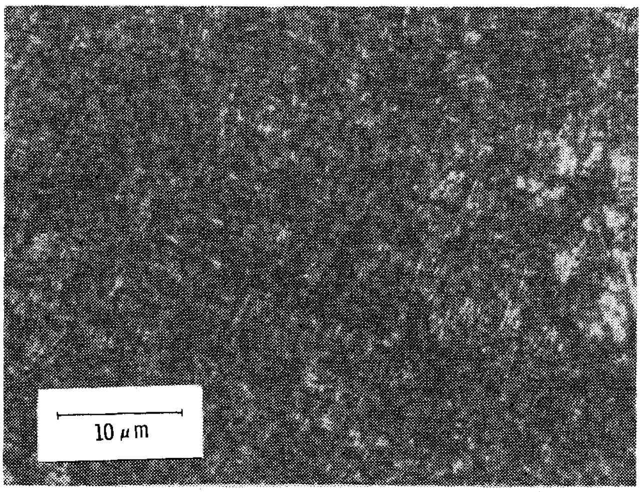

Fig. 2 Photomicrograph of Transage 134 alloy (Ti-2Al-12V-2Sn-6Zr), 25-mm (1-in.) plate, 815°C (1500°F)-1h-AC, 595°C (1100° F)-1h-AC, 482°C (900°F)-4h-AC.

Transage 134 exhibited significantly greater resistance to crack propagation than Transage 129 and approximates the behavior of the Ti-6Al-4V forgings.

Crack growth rate of Transage 134 is compared to Ti-6Al-4V for 5-min hold at maximum load in Fig. 8. As in the case

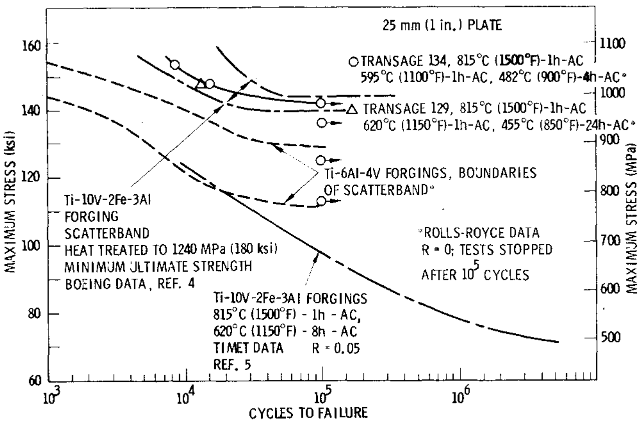

Fig. 3 Smooth specimen axial fatigue data for heavy section titanium alloys.

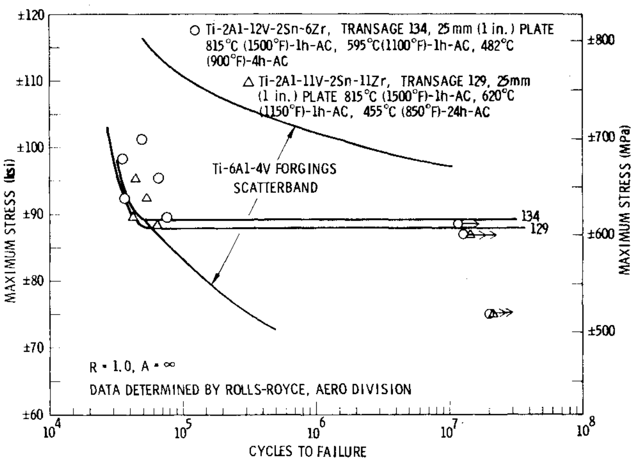

Fig. 4 Smooth specimen rotating bend fatigue comparison of Transage alloys with Ti-6Al-4V.

of the 0.25 Hz data shown in Fig. 7, the Transage 134 data lies within the scatterband of Ti-6Al-4V. Like Ti-6Al-4V, it is not sensitive to this loading condition.

Fracture Behavior

The Transage alloys, especially 134, have respectable values of fracture toughness at high strength levels (see Table 1). However, the nature of the load vs crack-opening-displacement (COD) curves of Transage alloys in fracture toughness testing may have far reaching significance in terms

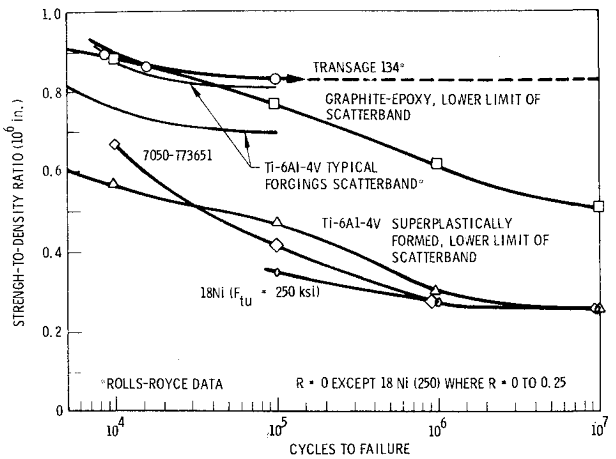

Fig. 5 Smooth specimen axial fatigue strength-to-density comparison of Transage 134 alloy with high-strength structural materials.

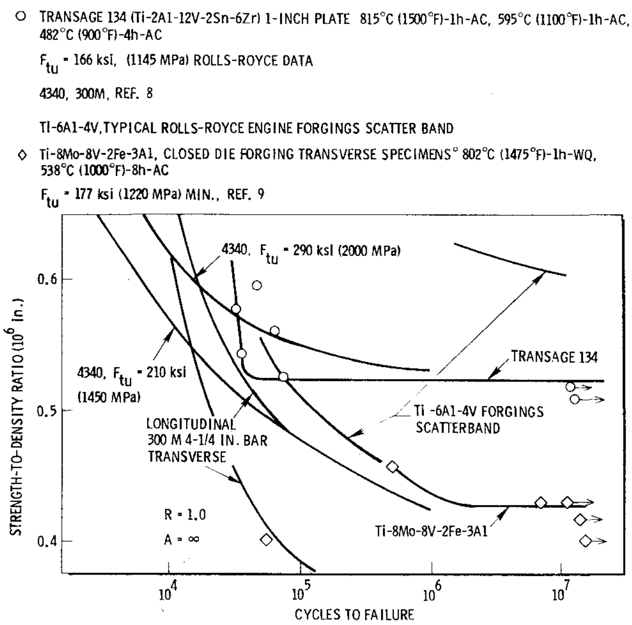

Fig. 6 Smooth specimen rotating bend fatigue strength-to-density comparison of Transage 134 with high strength structural alloys.

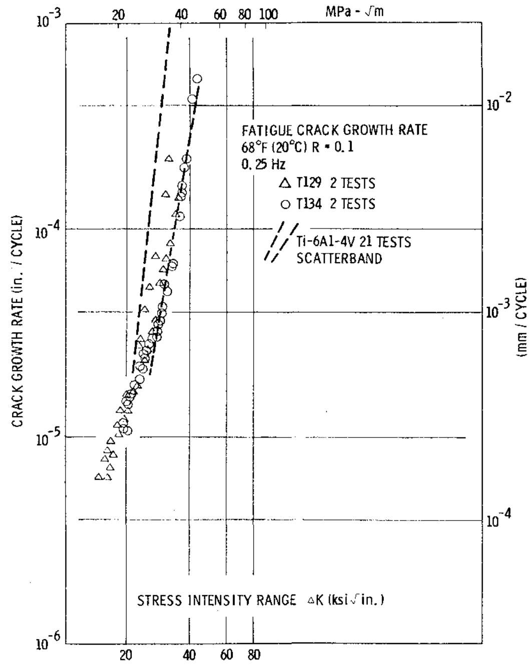

Fig. 7 Crack growth rates of Transage alloys compared with Ti-6Al-4V.

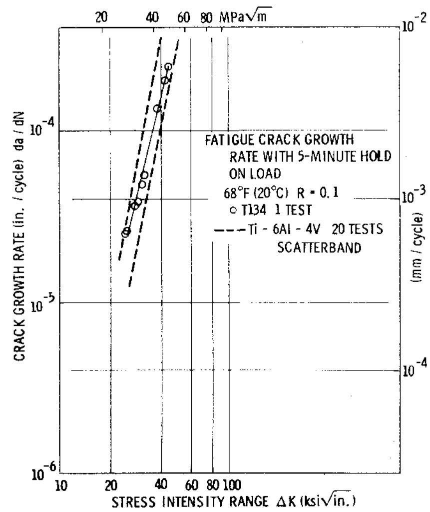

Fig. 8 Crack growth rates under 5-min hold condition of Transage 134 and Ti-6A1-4V alloys.

of real structures. In Fig. 9 curves for two 25-mm (1-in.) compact tension (CT) specimens of Transage 129 alloy are shown with a curve for Ti-6A1-4V plate. The conventional wisdom of the ASTM E 399 standard determination is that Ti-6A1-4V at 64 MPa-$\sqrt{m}$ (58 ksi-$\sqrt{in.}$) has a three times longer critical crack length than the Transage specimens at 38 MPa -$\sqrt{m}$ (35 ksi-$\sqrt{in.}$). However, at a COD of 2.8 mm (110 mils) the Ti-6A1-4V specimen has lost all of its load carrying capability, while the Transage specimens sustain more than 50% of their maximum loads. This stable crack growth is due to stress-induced phase transformation ahead of the crack tip.[6] The phase transformation is from residual beta to alpha. The stress-induced transformation, in turn, results in transformation-induced plasticity, or TRIP, as defined by Zackay et al.[7]

Another means for evaluating the resistance to fracture is the area under the load vs COD curve, which is proportional to the energy absorbed by the specimen during fracture. Qualitatively, it is apparent from Fig. 9 that the Transage 129 specimens absorbed more energy to fracture than the Ti-6A1-4V specimen. The Transage 134 alloy offers exceptional promise in this regard due to the character of its load vs COD curves for slow bend precracked Charpy (SBPC) test specimens. While fracture toughness determinations by the ASTM E 399 standard were carried out on 25-mm (1-in.) CT specimens of Transage 134 alloy; unfortunately the load vs COD curves were not recorded beyond the 95% secant intercept. However, it is possible to project the likely behavior of 25-mm (1-in.) CT specimens based upon a correlation between SBPC and CT specimens made for Transage 129 alloy.

A tensile test specimen and SBPC and CT test specimens were machined from a fully heat-treated piece of Transage 129 25-mm (1-in.) plate. The load vs COD curves for the fracture toughness tests were superimposed in Fig. 10 employing different scales. The two curves for the Transage 129 specimens illustrate a general finding that the plateau following elastic instability was more pronounced for CT specimens than for SBPC specimens. It is believed that this was primarily because the 25-mm CT specimens had about ten times greater area in front of the crack tip at the start of testing than the SBPC specimens. Also, there was greater triaxial constraint in the CT specimens. For these reasons, the contribution of stress-induced transformation to fracture

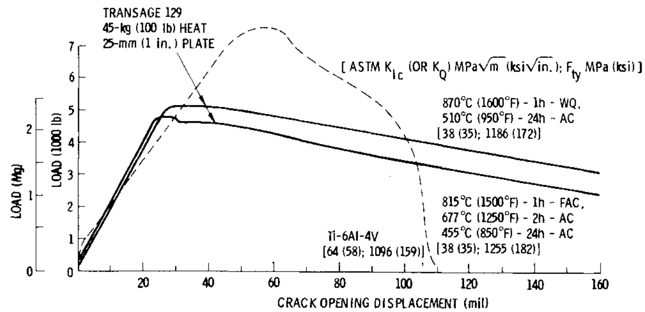

Fig. 9 Load vs crack-opening-displacement curves for 25-mm (1-in.) compact tension specimens of Transage 129 and Ti-6A1-4V alloys.

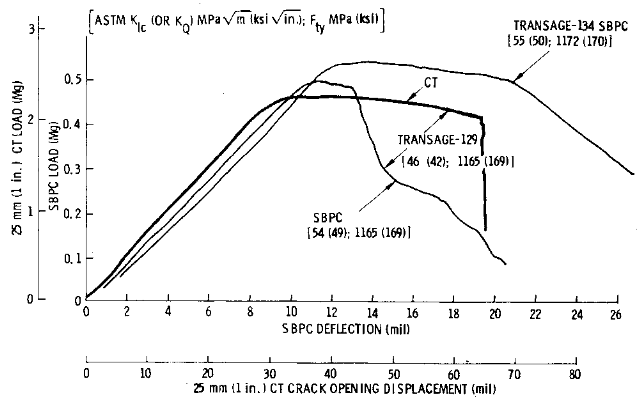

Fig. 10 Significance of material volume available for stress-induced transformation relative to fracture resistance, as reflected in the more pronounced plateau following elastic instability of the 25-mm (1-in.) compact tension specimen of Transage 129 alloy, compared to its slow bend precracked Charpy counterpart.

resistance was greater in CT specimens compared with SBPC specimens. Given these considerations, the load vs COD curve for the Transage 134 SBPC specimen shown in Fig. 10 suggests that stress-induced transformation makes a much larger contribution to its fracture resistance than it does to Transage 129. Note that the two alloys were of the same yield strength—about 1170 MPa (170 ksi)—and had virtually the same fracture toughness value as determined by ASTM E 399 [about 55 MPa$\sqrt{m}$ (50 ksi$\sqrt{in.}$)].

This size effect relative to the contribution of stress-induced transformation to fracture resistance is possibly of great significance in structural components, particularly large ones. Fracture toughness test specimens have a very large precrack in relation to their size. Thus, they provide little opportunity for demonstration of the effectiveness of a stress-induced transformation mechanism in resisting fracture. Nonetheless, the implication of the load vs COD curves of properly processed Transage alloys, especially Transage 134, is that structural component crack propagation rate would be controlled by phase transformation ahead of the crack tip until the remaining ligament is unable to support the load. That is, it would appear that catastrophic crack propagation would be delayed, permitting considerably more stable crack growth than is the case for other high-strength materials, and perhaps would be impossible.

Conclusions

The martensitic Transage 134 titanium alloys exhibits exceptional structural efficiency, durability, and reliability, because of its fatigue and fracture behavior, and its exceptional forgeability promises reduced costs.

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