THE FRACTURE TOUGHNESS OF 3 Ti ALLOYS

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This study investigates the influence of microstructural variables on the fracture toughness of the following heat treated Ti alloys in heavy sections: Ti-6Al-4V, Ti-6Al-6V-2Sn and Ti-8Mo-8V-2Fe-3Al. Compact tension and precracked Charpy specimens were obtained from thick-wall hollow extrusions. The extrusions were heat treated to provide a range of strength levels. Tensile specimens were obtained from the outside mid and inner wall locations to characterize strength parameters. For Ti-6Al-4V, a definite difference in fracture toughness exists between microstructures characterized by elongated or plate-like primary α and equiaxed primary α. It is shown that the equiaxed microstructure leads to a greater value of fracture toughness. Decreasing the oxygen level and increasing the amount of transformed beta matrix increases the value of fracture toughness. Of the alloys investigated, the largest value of fracture toughness was provided by Ti-6Al-6V-2Sn in the STOA condition. Beta flecks were present in the microstructure of modified Ti-6Al-6V-2Sn alloy and appeared to lower fracture toughness. The metastable beta alloy, Ti-8Mo-8V-2Fe-3Al is characterized by reduced tensile ductility and high fracture toughness. The reduced tensile ductility is associated with a large beta grain size. Increasing the amount of prior working decreases the grain size, increases tensile ductility and appears to lower fracture toughness as measured by W/A.

Introduction

The ability to make better utilization of high strength Ti alloys depends on a greater understanding of the effect microstructure has on important design parameters such as fracture toughness. This is especially true of heavy section geometries where hardenability and nonuniform degree of mechanical working can lead to varying microstructure across the section. For example, Broadwell and Heil(1) have evaluated the fracture toughness and strength variation of several high strength Ti alloys using a "Navaho" rib and web forging. To reveal the influence of microstructure in more detail, recent studies at AMMRC have focused on the heavy section mechanical properties of 3 Ti alloys: Ti-6Al-4V, Ti-6Al-6V-2Sn and Ti-8Mo-8V-2Fe-3Al.

Materials and Test Procedure

The materials for this investigation together with their respective composition and heat treatment are shown in Table I and II,respectively. Test specimens for mechanical property determination were taken from 11-1/2 in. long cylindrical hollows of the following dimensions: 8-3/4 in. OD and 3 in. wall. This configuration was achieved by extrusion at the following temperatures: Ti-6Al-4V (1750°), Ti-6Al-6V-2Sn (1675°F) and Ti-8Mo-8V-2Fe-3Al (1700°F). Tensile specimens (0.252 diameter) were taken from the outer, mid and inner wall locations for both the longitudinal and transverse orientation and were tested on a 120,000 hydraulic testing machine at a platen displacement of 0.005 in/min. For all alloys, fracture toughness measurements were performed with 3/4 in. thick compact tension specimens taken in a transverse orientation which allowed the crack to propagate toward the inner wall. With some alloys, additional measurements were obtained on specimens where crack propagation was toward the outer wall. Both orientations are shown in Fig. 1. The specimens were precracked in a 100,000 lb. MTS testing machine and tested to failure on a 120,000 lb. hydraulic testing machine. All precracking and fracture toughness testing procedures with the exception of the crack front profile conformed to ASTM Standard E 399-71. For all materials except the modified Ti-6Al-6V-2Sn, the crack front was thumbnail in appearance. Numerous attempts at AMMRC to produce straight crack fronts on Ti-6Al-4V, Ti-6Al-6V-2Sn and Ti-8Mo-8V-2Fe-3Al (all STA condition) also were not successful. Although it is felt that the data are valid and should be reported as K_{IC}, Para. 7.2.3 of E 399-71 specifies that if a difference between any two of the crack length measurements exceeds 5% of the average crack length, the test is invalid. For this reason, fracture toughness measurements are given in terms of K_Q.

Additional information on fracture energy was obtained by impacting precracked 0.394 x 0.394 in. standard Charpy specimens taken from the mid-wall location and noting the energy absorbed per unit area of the uncracked portion of the specimen. The value is given in terms of in-lb/in^2 and is represented by W/A. Precracking for these specimens was performed on a Manlabs fatigue precrack machine.

The amount of working accompanying the fabrication of the hollow cylinders noted above was approximately 30% and was limited by the capacity of the AMMRC press. It is the intent of this program to also examine the effect of increased mechanical working by extruding the above configuration at reduction ratios which correspond to approximately 83% reduction. At this writing, only the evaluation of the Ti-6Al-4V alloy (Heat B - Tables I and II) extruded at the larger reduction ratio has been completed. Limited tensile data are available for the Ti-8Mo-8V-2Fe-3Al alloy extruded at the larger reduction.

Results and Discussion

As shown in Table III, there is a wide range of strength levels resulting from the heat treatment of the 3 alloys. At the low end of the spectrum is the Ti-6Al-4V in both the STA and STOA condition. As expected, the large section size precluded any significant response to aging. In contrast, Heat B of Ti-6Al-6V-2Sn modified with 2.0% Zr and in the STA condition, exhibited yield strength close to 200 KSI at the outer wall, dropping to 181-187 KSI at the midwall. For the same STA condition, Heat C of Ti-6Al-6V-2Sn led to strength levels which were about 20-30 KSI lower than the modified composition. The drop in strength is attributable to pronounced effects of the added Zr and higher C, Cu and Fe levels. At all locations through the section, the Ti-8Mo-8V-2Fe-3Al alloy exhibited yield strength levels in the range of 174/182 KSI.

The K_Q values for each of the alloys are given in Table IV. The variation in K_Q with yield strength is shown in Fig. 2. The same plot is shown in Fig. 3 with each K_Q value adjusted for the density of the given alloy. For clarity, the average K_Q value corresponding to a given orientation (Fig. 1) is shown in Figs. 2 and 3. The yield strength value considered in Figs. 2 and 3 is the average of the outer and mid-wall for the K_Q specimen oriented for crack propagation toward the inner wall, and an average of the inner and mid-wall for K_Q specimens oriented for crack propagation toward the outer wall. The K_Q values obtained for each of the alloys are discussed in more detail below.

Ti-6Al-4V

While K_Q values for STOA condition of Heat A are relatively consistent between 44-51 KSI$\sqrt{\text{in}}$, the values for the STA condition of the same heat separate into two groups that depend on specimen

Table I. MATERIALS AND THEIR COMPOSITION

Alloy	Element (weight percent)									
	Al	V	Mo	Fe	Sn	Cu	C	O	H	N
Ti-6Al-4V										
Heat A	6.4	4.1	-	0.18	-	-	0.02	0.16	0.007	0.007
Heat B	6.3	4.2	-	0.20	-	-	0.02	0.13	0.004	0.009
Ti-6Al-6V-2Sn										
Heat A	5.9	5.5	-	0.81	2.0	0.78	0.020	0.16	0.005	0.015
Heat B*	6.0	5.9	-	0.99	2.0	0.97	0.12	0.07	0.004	0.010
Heat C	5.6	5.3	-	0.78	2.45	0.72	0.022	0.13	0.010	0.017
Ti-8Mo-8V-2Fe-3Al	2.3	8.0	8.2	1.8	-	0.006	0.022	0.16	0.007	0.018

*Modified with 2.0% Zr

Table II. HEAT TREATMENT OF MATERIALS

Alloy	Condition	Solutionizing Temperature & Time for WQ	Aging Temperature & Time for AC
Ti-6Al-4V			
Heat A	STOA	1750°F - 3 hr	1300°F - 6 hr
	STA	1750°F - 3 hr	1000°F - 4 hr
Heat B	STA	1750°F - 3 hr	1000°F - 4 hr
Ti-6Al-6V-2Sn			
Heat A	STOA	1600°F - 3 hr	1300°F - 6 hr
Heat B*	STA	1600°F - 3 hr	1000°F - 4 hr
Heat C	STA	1600°F - 3 hr	1000°F - 4 hr
Ti-8Mo-8V-2Fe-3Al	STA	1475°F - 1-1/2 hr	1000°F - 8 hr

*Modified with 2.0% Zr

Table III. SUMMARY OF TENSILE PROPERTIES

Alloy	Condition		0.2% Yield Strength, ksi			Tensile Strength ksi			Elongation %			Reduction of Area, %		
			OD	MW	ID	OD	MW	ID	OD	MW	ID	OD	MW	ID
Ti-6Al-4V														
Heat A	STOA	L	141.9	135.5	136.4	148.8	143.8	143.2	20.0	17.5	19.0	46.2	39.8	37.9
		T	137.2	139.8	136.5	147.8	151.6	149.8	16.3	17.5	16.8	36.5	41.7	39.0
Heat A	STA	L	135.9	130.9	136.0	144.6	145.0	147.5	19.5	21.0	20.0	48.1	41.6	33.0
		T	145.3	139.8	148.2	158.4	153.3	161.4	13.3	15.7	10.8	35.3	36.6	25.1
Heat B	STA	L	142.3	128.9	135.4	152.4	147.6	158.9	15.7	16.0	16.2	40.0	37.6	37.6
		T	139.5	137.4	148.5	156.4	148.4	151.9	13.1	12.5	11.2	33.1	26.2	20.8
Ti-6Al-6V-2Sn														
Heat A	STOA	L	143.3	143.2	144.7	153.9	151.9	154.8	14.5	15.0	16.5	33.8	37.1	43.8
		T	142.8	143.9	144.4	-	153.0	153.5	16.0	16.5	16.0	30.1	36.3	41.8
Heat B*	STA	L	201.7	180.9	195.3	208.9	185.6	199.5	2.2	3.8	3.5	5.6	9.2	8.1
		T	192.7	187.0	198.3	197.6	191.6	201.9	2.5	1.7	1.2	5.0	4.1	4.0
Heat C	STA	L	165.6	148.6	164.7	176.3	162.2	177.2	6.1	9.5	7.6	13.2	20.6	15.1
		T	160.5	157.5	162.5	179.0	170.7	176.5	4.4	7.9	6.5	8.4	14.6	12.4
Ti-8Mo-8V-2Fe-3Al														
	STA	L	177.5	181.3	174.2	178.9	182.1	181.4	1.1	1.3	2.0	2.4	2.1	5.4
		T	177.3	180.0	175.6	180.0	182.5	180.6	1.4	1.9	2.4	2.4	2.6	3.4

*Modified with 2.0% Zr

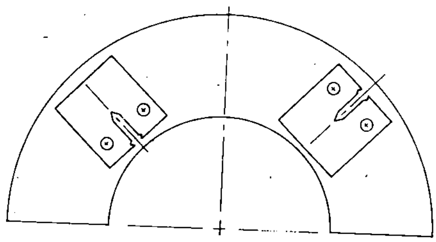


Fig. 1. Orientation of compact tension fracture toughness specimen.

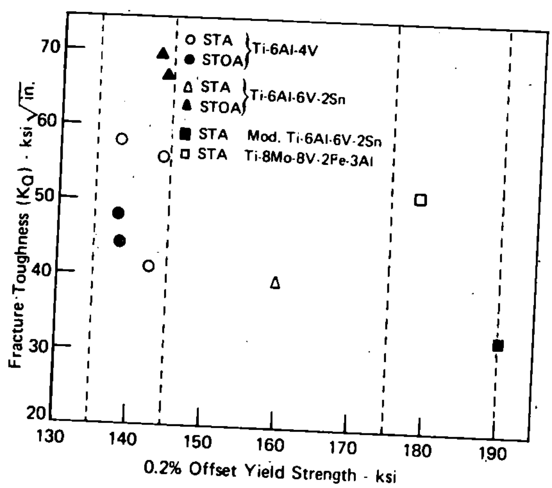


Fig. 2. Fracture toughness as a function of yield strength.

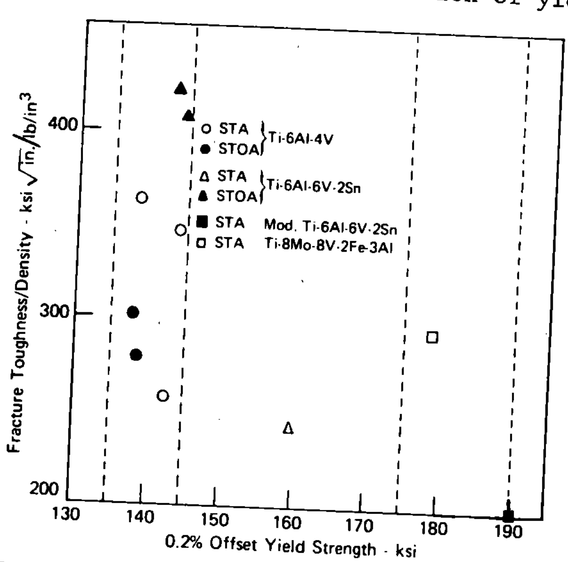


Fig. 3. Specific toughness as a function of yield strength.

orientation. The specimens with crack propagation toward the inner wall led to values in the range 41-42 KSI$\sqrt{in}$ while crack propagation in the opposite direction was characterized by significantly higher values in the range 50-56 KSI$\sqrt{in}$. Since there was a relatively small variation in tensile properties across the section, it was an opportunity to examine the possible influence of microstructure on K_Q.

Examination of the microstructure at fracture surface of the broken test specimens revealed that the higher K_Q values were associated with an equiaxed primary α (Figure 4a). The lower values of K_Q were associated with an elongated or plate-like primary α (Fig. 4b). The amount of primary α was approximately the same (32%) for both the equiaxed and plate-like microstructure as determined with a Quantimet (QTM) Image Analyzer. It is therefore evident that for this particular heat, equiaxed microstructure leads to higher values of K_Q.

Recently, Gerberich and Baker(2) have utilized relative values of crack-tip displacement and size of primary α particles to explain the fracture toughness differences between equiaxed and plate-like primary α microstructures of Ti-6Al-4V. With a duplex heat treatment, these authors were able to achieve a given plate-like microstructure that produced crack path deviation that led to increased fracture toughness values. The plate-like microstructure of the present study did not result from a duplex heat treatment and therefore could not be expected to provide the increase in K_Q noted by Gerberich and Baker. Even if it were duplicated, it is unlikely that the plate-like microstructure would produce K_Q values greater than that obtained with an equiaxed microstructure since it has been reported that an oxygen level of about 0.13% is required for plate-like α to produce increased values of fracture toughness(2). The nominal oxygen content of Heat A in the present study is listed in Table I as 0.16%, but levels averaging 0.20% were measured on the broken K_Q specimens.

As shown in Table IV, Heat B (STA condition) with a microstructure consisting of a mixture of small equiaxed and multigrained plate-like primary α (Fig. 4c) that resulted from the increased amount of working, leads to increased K_Q values when compared to Heat A (STA condition). The W/A values for Heat B (912 in-lb/in^2) are also larger than those for Heat A (835 in-lb/in^2). In addition to the equiaxed microstructure, lower oxygen content and slightly larger amount of transformed beta matrix are noted for Heat B. Chemical analyses taken on broken K_Q specimens established the oxygen level at 0.13% compared to 0.20% for Heat A as noted above. The effect of oxygen content on fracture toughness is recognized and has caused the Ti-6Al-4V material purchased for the B-1 aircraft to be controlled at maximum oxygen content of 0.13% to insure adequate fracture toughness(3). Equally as important may be the increased amount of transformed beta matrix of Heat B (75%) compared

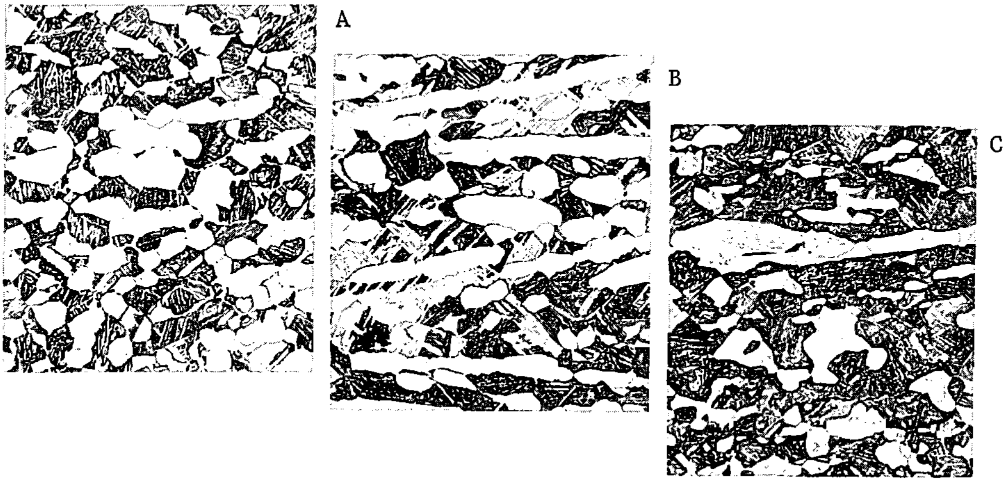


Fig. 4. Microstructure and associated fracture toughness of Ti-6Al-4V (STA). Mag. 250X.
a) Equiaxed primary α, K_Q = 55.9 ksi $\sqrt{in.}$ (Heat A).
b) Plate-like primary α, K_Q = 41.6 ksi $\sqrt{in.}$ (Heat A).
c) Equiaxed and multigrain plate-like primary α, K_Q = 59.3 ksi $\sqrt{in.}$ (Heat B).

Table IV. SUMMARY OF K_Q FRACTURE TOUGHNESS VALUES

Alloy	Condition	K_Q - ksi$\sqrt{in}$ Test 1	Test 2	Test 3	Orientation
Ti-6Al-4V					
Heat A	STOA	44.1	45.1	44.6	I*
		49.6	44.3	51.0	II+
Heat A	STA	41.3	41.0	41.6	I
		55.9	50.0		II
Heat B	STA	59.3	56.3	58.9	I
Ti-6Al-6V-2Sn					
Heat A	STOA	63.9	70.5	73.5	I
		68.0	67.0	66.2	II
Heat B†	STA	27.6	38.4	30.7	I
Heat C	STA	42.5	36.9		I
Ti-8Mo-8V-2Fe-3Al	STA	51.0	51.5	52.1	I

*Crack propagates toward ID of extrusion, see Fig. 1.
+Crack propagates toward OD of extrusion, see Fig. 1.
†Modified with 2.0% Zr.

to Heat A (68%), since the increased toughness of the fully transformed microstructure has been noted(4). All of these factors probably contributed to the increased toughness of Heat B. As shown in Fig. 5 for Heat B, the α (primary and in the matrix) appears to cause deviations in the crack path, thus increasing fracture toughness in the manner suggested by Gerberich and Baker (2,4).

Ti-6Al-6V-2Sn

Of the alloys considered in this study, it was possible to achieve the largest values of K_Q (63-74 KSI$\sqrt{in}$) with Ti-6Al-6V-2Sn (Heat A) in the STOA condition. The density is slightly greater than Ti-6Al-4V, but it is not enough to change the ranking on a K_Q/density basis (Figure 3). The consistency of the K_Q values stems from the strength and microstructural (equiaxed primary α) uniformity through the section. The combination of K_Q and strength values obtained for the STOA condition compare very favorably to the optimum combination of strength and toughness recently determined for various STOA heat treatments aimed at improving the toughness(5). However, the W/A value (549 in-lb/in^2), being lower than Ti-6Al-4V (STA condition), does not reflect the increased K_Q values, indicating a possible strain rate effect.

Increasing the strength level by employing the STA heat treatment (Heat C) reduced K_Q to 36-43 KSI$\sqrt{in}$. On the basis of yield strength, K_Q for the STA condition is compared to the other alloys in Figures 2 and 3.

A further increase in the strength level of Ti-6Al-6V-2Sn (STA condition) can be achieved through a modification in chemistry (Heat B - Table I). The addition of Zr together with higher C, Fe, and Cu contents lead to yield strengths of up to 200 KSI which are accompanied by lower ductility in the STA condition. For this material the K_Q is in the range 27-39 KSI $\sqrt{in}$ as shown in Table IV. The W/A values for this alloy (115 in-lb/in^2) were lower than values obtained for Heat A - STOA condition (549 in-lb/in^2) and Heat C - STA condition (300 in-lb/in^2). In view of the low oxygen level (0.07%), K_Q values might be expected to be somewhat higher. However, it has been shown that at strength levels comparable to those obtained for Heat B, both ELI and commercial grades to Ti-6Al-6V-2Sn exhibited K_{IC} in the range 29-33 KSI$\sqrt{in}$ (6).

It is interesting to note that this modified chemistry (Heat B) was also prone to the production of what have been termed "beta flecks". Apparently, these are regions of microsegregation of beta stabilizers that lead to a transformed structure after heat treatment due to a locally lower beta transus. The high Cu and Fe content which have been associated with "beta flecks"(7) are present in Heat B. The specimens used for K_Q determination were examined for the appearance of "beta flecks". Of the three specimens examined, the specimen which exhibited the lowest value of K_Q displayed "beta flecks" along the fracture surface as shown in Fig. 6. Hardness measurements made within the "beta fleck" reveal a higher hardness

Fig. 5. Crack propagation in Ti-6Al-4V (Heat B, STA condition). Circled regions highlight locations where α has caused crack path to deviate. Mag. 500X.

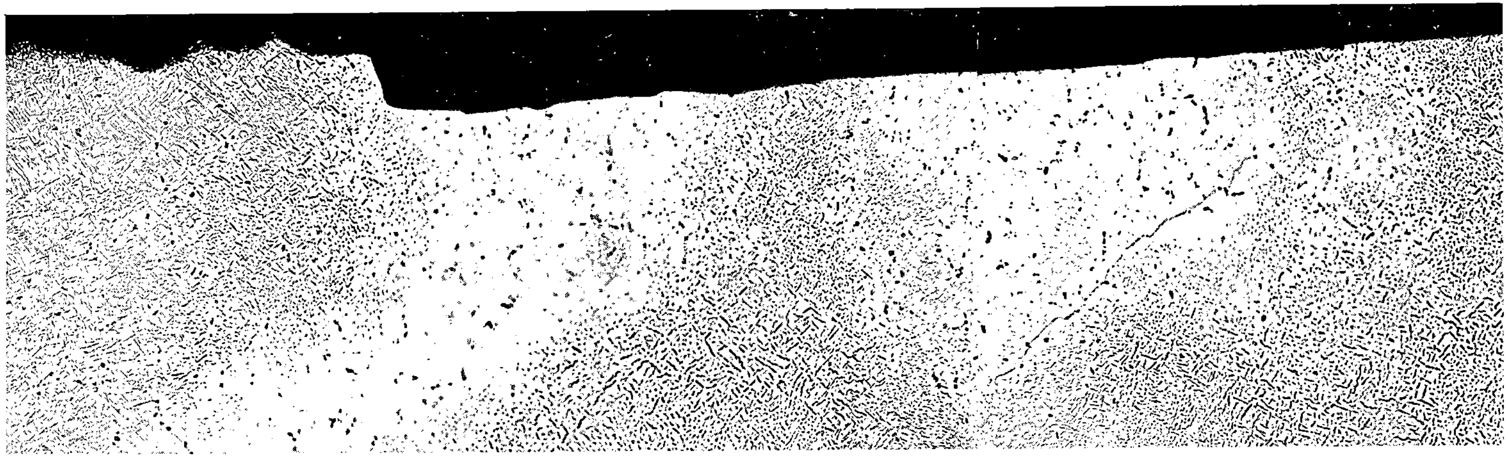


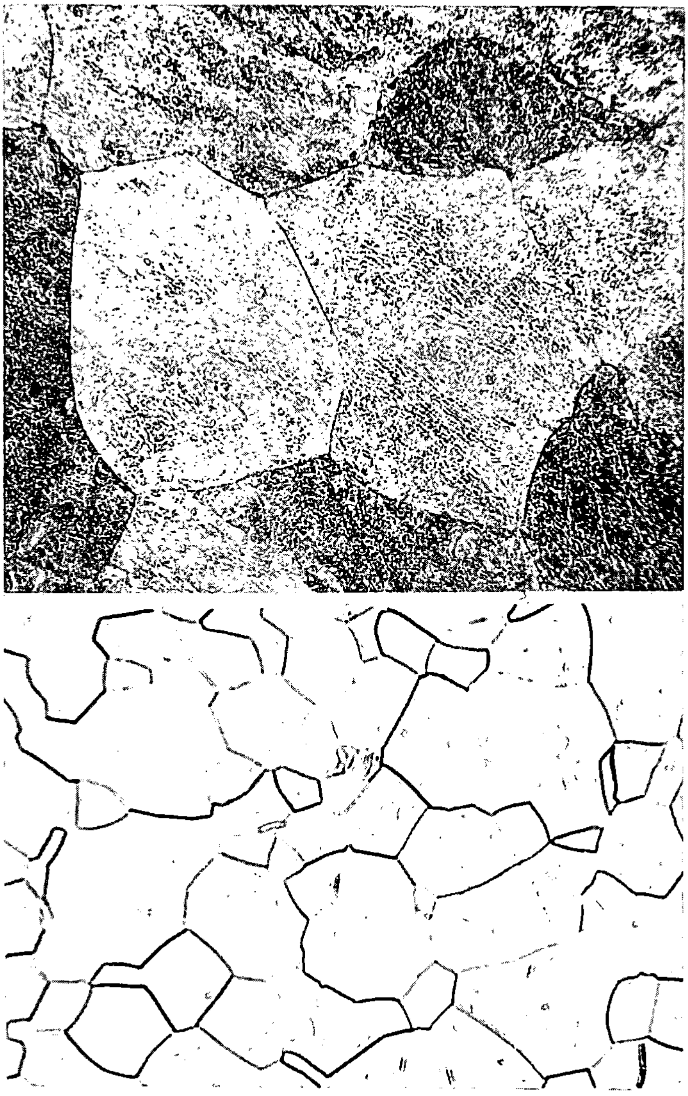
Fig. 6. The appearance in modified Ti-6Al-6V-2Sn of "Beta flecks" along fracture surface. Mag. 75X.

when compared to the hardness of the adjacent microstructure. The Knoop hardness number averaged 427 within the "beta fleck" while on either side, the average was 419. Therefore, it is not unexpected that the "beta flecks" shown detrimental to smooth specimen fatigue properties(8) also decrease fracture toughness.

Ti-8Mo-8V-3Al-2Fe

In contrast to the Ti-6Al-6V-2Sn toward the higher strength levels, Ti-8Mo-8V-3Al-2Fe provides relatively high K_Q values (Fig. 2). Its position relative to the other alloys remains essentially unchanged when density considerations are introduced (Fig. 3). The Ti-8Mo-8V-2Fe-3Al alloy possesses these values of K_Q despite rather low tensile ductilities (1-3% elongation and 2-6% RA). It has been observed that such behavior is characteristic of beta alloys with a large grain size(9). The ASTM grain size for this material is indeed coarse (Fig. 7a),being rated at approximately 0. To establish the benefits of additional working, a piece of the initial billet stock (8 in. round) was reduced approximately 78% by forging at 1900°F. The reforged material was then heat treated as before. Microstructural examination revealed a reduced ASTM grain size of 3-5. The resulting tensile properties are given in Table V. Note the increase in ductility that accompanies the reduced grain size. Limited data are also available on the tensile properties of the 3-inch wall, 11-3/4 inch O.D. hollow cylindrical extrusion that had undergone the 83% reduction at 1700°F which resulted in ASTM grain size of 3-5 (Figure 7b). As shown in Table V, the increased ductility is indicated. Therefore, as suggested by Bohanek(10) continuous hot working at sufficient reductions will reduce the grain size of large section products to a level where improved ductility is realized. However, the lower grain size does not appear to improve fracture toughness. In fact, associated with the reduced grain size obtained by the increased amount of working at 1900°F was a slightly lower fracture toughness as determined by W/A. The W/A values obtained for the larger grain size material extruded at 1700°F averaged 444 in-lb/in^2 while values averaging 330 in-lb/in^2 were obtained for the smaller grain size material processed at 1900°F. Both materials were from the same heat and were given the same aging heat treatment.

The observations emphasize the additional work that is required to detail the micromechanics of how fracture toughness of Ti-8Mo-8V-2Fe-3Al and other beta alloys is related to tensile ductility and grain size. Greenfield and Margolin(11) have shown how high fracture toughness can be associated with low tensile ductility in Ti-5.25Al-5.5V-0.9Cu-0.5Fe α/β alloy. Here, the grain boundary α that provides resistance to intergranular propagation of an existing crack also serves as a site for nucleation and growth of voids formed under tensile loading. However, in coarse grained Ti-8Mo-8V-2Fe-3Al the crack propagation is transgranular with no evidence of grain boundary α as shown in Fig. 8.



A

B

Fig. 7. Ti-8Mo-8V-2Fe-3Al grain size resulting from (a) 30% reduction shown in the aged condition and (b) 83% reduction shown in ST condition. Mag. 100X.

Table V. EFFECT OF GRAIN SIZE ON TENSILE PROPERTIES OF AGED Ti-8Mo-8V-2Fe-3Al*

ASTM Grain Size No.	Hot Working		0.2% Yield Strength, ksi	Tensile Strength, ksi	Elongation, %	RA %
	Method	Reduction				
3-5	Extrusion	83%	174.5+	182.5	4.0	9.3
3-5	Forging	78%	181.0	188.0	8.5	9.9
0	Extrusion	30%	177.7†	180.8	1.5	3.3

*1475°F (WQ) - 1000°F (8 hr).
+Transverse orientation.
†Represents average of OD, ID and MW locations given in Table III for longitudinal orientation.

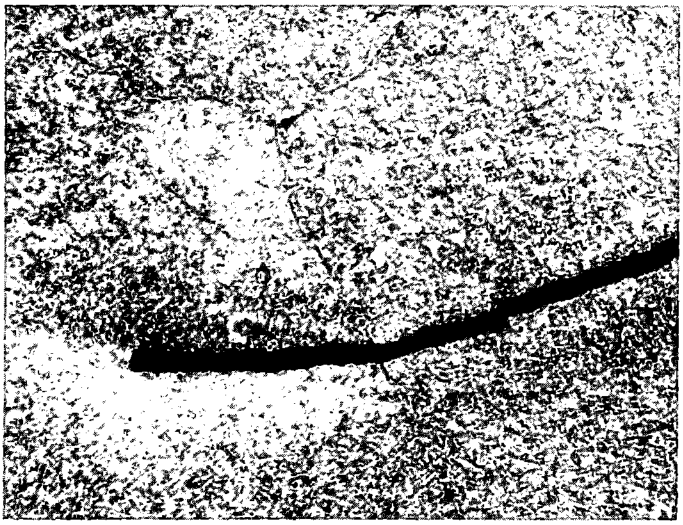


Fig. 8. Transgranular nature of crack propagation in large grain Ti-8Mo-8V-2Fe-3Al. Mag. 1000X.

Conclusions

As a result of this study which has examined the fracture toughness of three commercially available alloys (Ti-6Al-4V, Ti-6-Al-6V-2Sn and Ti-8Mo-8V-2Fe-3Al) in heavy section configuration, the following conclusions can be drawn:

1. Primary α morphology can account for the difference in fracture toughness of Ti-6Al-4V heat treated at standard solution and aging temperatures. For a given amount of primary α in Ti-6Al-4V with a commercial quantity of oxygen, equiaxed microstructure results in increased fracture toughness when compared to plate-like microstructure. Decreasing the oxygen level and increasing the amount of transformed beta matrix increase fracture toughness.

2. The Ti-6Al-6V-2Sn in the STOA conditions at approximately 143 KSI yield strength level exhibits excellent fracture toughness exceeding that of any alloy considered in the study.

3. Microsegregation in the form of "beta flecks" in Ti-6Al-6V-2Sn modified with 2.0% Zr appears to degrade fracture toughness.

4. At the high strength levels (approximately 180 KSI yield strength and above), the fracture toughness of Ti-8Mo-8V-2Fe-3Al exceeds that of modified Ti-6Al-6V-2Sn (STA condition) despite low tensile ductility. The low tensile ductility of Ti-8Mo-8V-2Fe-3Al is associated with a large beta grain size and can be improved by increasing the amount of hot work prior to heat treatment. However, decreasing beta grain size appears to lower fracture toughness as measured by W/A.

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