EFFECT OF BETA FLECKS ON THE FATIGUE BEHAVIOUR OF Ti-6Al-6V-2Sn

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The alpha-beta titanium alloy Ti-6Al-6V-2Sn grants higher annealed strength than Ti-6Al-4V. Due to increased additions of the beta stabilizing elements vanadium, iron and copper, the hardenability is also improved. Normally, about o,7 % iron and copper are added with common specifications limiting a range from o,35 to 1,o % (1, 2, 3, 4, 5). Alloy grades with iron and copper contents in the upper permissable range show a tendency for more frequent and greater microstructural segregations, so-called beta flecks.

The beta flecks are caused primarily by local concentration of iron and copper during dendritic solidification in slow cooling ingot zones. The beta transus is lowered in these flecks according to the degree of concentration and it may drop below the customary hot working temperatures in the $\alpha + \beta$ field. This results in flecks with Widmannstätten structure with lower or no content of primary alpha.

In spite of intense effort to reduce size and frequency of beta flecks, it is at the present state of production techniques not possible to prevent completely segragations which may cause beta flecks in Ti-6Al-6V-2Sn. This includes limiting the iron and copper additions to the lower range of the specifications (6).

No agreement was reached so far on the definition of beta flecks regarding acceptable size and primary alpha content in the annealed condition. AMS 238o (7) gives an example only for the STA condition. The effect of the inhomogeneities was also not sufficiently studied. It is already reported that mechanical properties and fracture toughness are not affected, while HCF strength of notched and LCF strength additionally of unnotched samples are reduced by beta flecks (8).

This investigation was made to obtain more data on the effect of beta flecks on the properties of annealed titanium mill products for application in airframe structures.

Materials

Two important semi-finished products were used for this investigation, forged bars of 1oo x 162 mm (Heat A) and rolled plates of 7o x 75o mm (Heat B, C). The bars and plates came from double vacuum-melted ingots of 3ooo kg. The chemical composition is given in Table 1 in comparison to AMS 4918/4978. The material was industrially converted by standard procedures. After initial rolling in the beta field, billets and slabs were forged respectively rolled at 89o °C with sufficient amount of hot work to produce the $\alpha + \beta$ microstructures. The normal heat treatment of the materials used for this study was annealing at 73o °C/AC. For some tests material was solution annealed (1/2 h, 85o °C/WQ + 2 h, 7oo °C/AC). Solution annealing reduced the amount of equiaxed primary alpha in the fine $\alpha + \beta$ matrix to about 4o %.

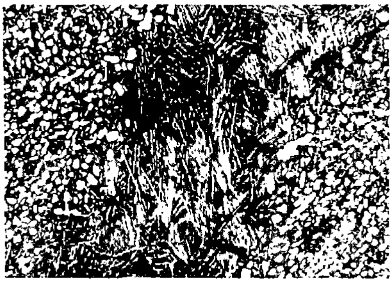
Table I Chemical Composition of Ti-6Al-6V-2Sn

Heat	Chemical Composition, wt %									
	Al	V	Sn	Cu	Fe	C	N	O	N	other elements total
A	5,2	5,2	2,o	o,67	o,64	o,olo	o,o15	o,18o	<o,oo2o	<o,4o
B	5,4	5,5	2,o	o,5o	o,53	o,o11	o,oo9	o,2oo	<o,oo2o	<o,4o
C	5,5	6,o	2,1	o,53	o,52	o,o17	o,o17	o,18o	o,oo21	<o,4o
Requirements acc. to AMS 4918 + 4978	5,o–6,o	5,o–6,o	1,5–2,5	o,35–1,oo	o,35–1,oo	≤o,o5	≤o,o4	≤o,2o	≤o,o15o	≤o,4o

From these products samples were taken for testing, in which presence or absence of beta flecks was determind by metallographic inspection. Typical micrographs of the beta flecks and their matrix are illustrated in Fig. 1a – d.

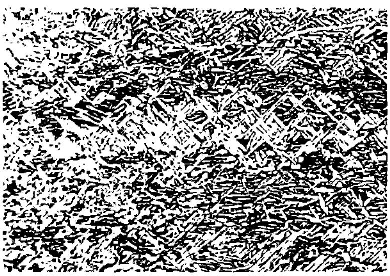
Fig. 1 Typical Microstructures of Ti-6Al-6V-2Sn with Beta Flecks

a)



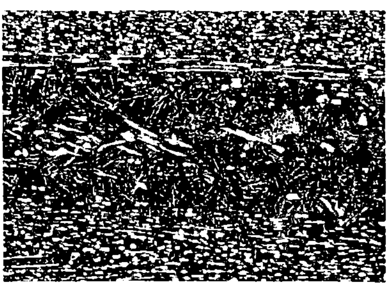
Heat A — LT-ST — Forged Bar, 100 x 162 mm, 2 h 730 °C/AC

b)



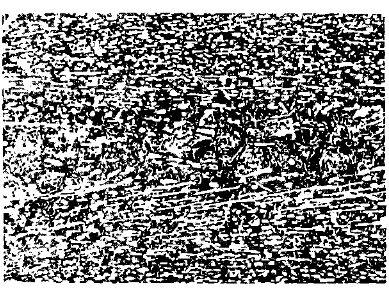
Heat B — LT-ST — Rolled Plate, 70 x 750 mm, 2 h 730 °C/AC

c)



Heat C — L-ST — Rolled Plate, 70 x 750 mm, 2 h 730 °C/AC

d)



Heat C — L-ST — Rolled Plate, 70 x 750 mm, 1/2 h 850 °C/WQ + 2 h 700 °C/AC

o, 1mm

Test Procedures

Mechanical properties were tested in longitudinal (L), transverse (LT) and short transverse (ST) directions relative to forming. Fatigue testing was carried out on L and LT samples; smooth and notched specimens were tested. While LCF tests were run with pulsating tension load (R = 0), for HCF testing rotating bend and axial tension-compression load (R = -1) was employed.

Besides the annealed condition, a limited number of tests was performed on samples in the solution annealed condition. After heat treatment, the specimens were prepared by reliable methods. For scratch-free surfaces oscillation grinding and polishing was applied. Fatigue testing was done on suitable machines and conditions. The frequency for rotating bend testing was 75 rps, for tension-compression tests 45 s^{-1} for Heat A and 1o5 s^{-1} for Heat C. LCF tests were run at 3 s^{-1}. The stress concentration factor K_t was 2,45 to 2,7 for fatigue and 3,9 for tensile test specimens (9).

The fatigue limits were determined by S-N curves based on 8 to 1o tests. All specimens were metallographically controlled after fatigue testing to verify appropriate classification.

Test Results

To evaluate the effect of beta flecks, all test results are compared to corresponding results of homogeneous samples in which no beta flecks were found.

Mechanical Properties

The mechanical properties are given in Table 2. Both microstructures, with and without beta flecks, resulted in all tested directions in conforming tensile and yield strength values. The elongation and partly the reduction of area are even higher in material with beta flecks. The ratio of notched to unnotched tensile strength is unaffected by structure and test direction.

Table 2 Effect of Beta Flecks on Mechanical Properties of Ti-6Al-6V-2Sn Annealed 2 h/730 °C/AC

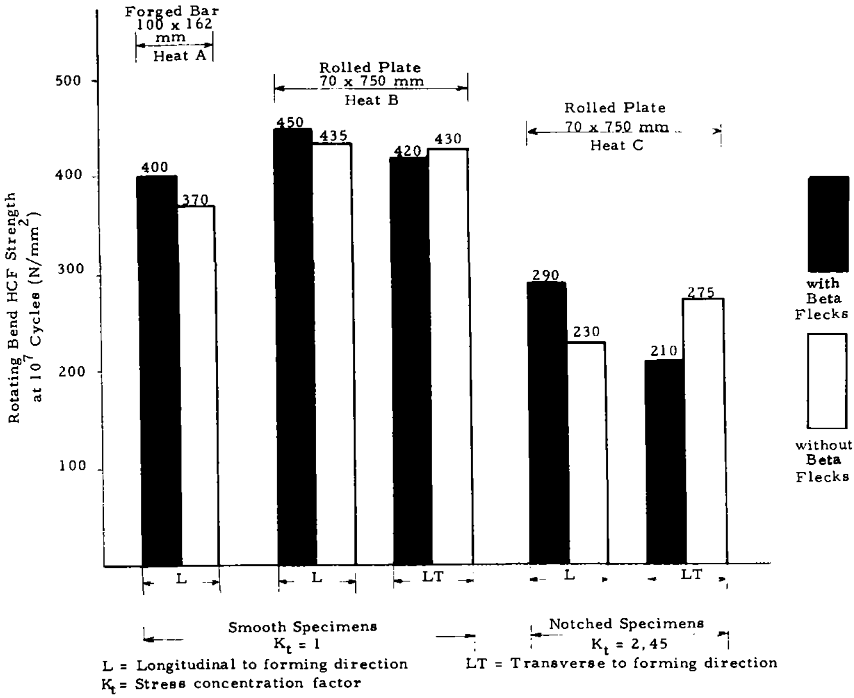
Heat	Dimension	Direction	Mechanical Properties R_m N/mm^2	$R_{p\,0,2}$ N/mm^2	A_5 %	Z %	Notch Tensile Strength K_t=3,9 $R_{m\,N}$ (Notched)	$R_{m\,N}/R_m$	Remarks
A	100 x 162	L	1030	988	18,1	43	-	-	Beta Flecks
		L	1035	1000	16,8	48	-	-	-
		LT	1049	1025	17,2	42	-	-	Beta Flecks
		LT	1050	1001	14,5	46	-	-	-
B	70 x 750	L	1086	1067	13,3	30	-	-	Beta Flecks
		LT	1126	1089	13,4	28	-	-	Beta Flecks
		ST	1055	991	13,0	33	-	-	Beta Flecks
C	70 x 750	L	1028	925	16,6	34	1646	1,60	Beta Flecks
		L	1033	956	13,4	32	1669	1,62	-
		LT	1075	993	15,7	34	1695	1,58	Beta Flecks
		LT	1048	990	13,8	37	1675	1,60	-
		ST	1009	927	13,7	35	1616	1,60	Beta Flecks
		ST	1016	937	10,3	30	1624	1,60	-
Requirements	AMS 4918	L	≥1000	931-1103	≥ 8 A_4	-	-	-	-
		LT	≥1000	931-1103	≥ 6 A_4	-	-	-	-
		ST	-	-	-	-	-	-	-
	AMS 4978	L	<1000	931-1103	≥10 A_4	≥ 15	-	-	-
		LT	<1000	931-1103	≥ 8 A_4	≥ 15	-	-	-

L = Longitudinal)
LT = Transverse) direction relative to forming
ST = Short transverse)

Rotating Bend HCF Strength

Fig. 2 illustrates the results of rotating bend HCF testing of bar and plate determined on smooth and notched specimens. Plates were tested in L and LT, bars in L direction.

Fig. 2 Effect of Beta Flecks on Rotating Bend HCF Strength (R = -1) of Ti-6Al-6V-2Sn, Annealed 2h 730 °C/AC



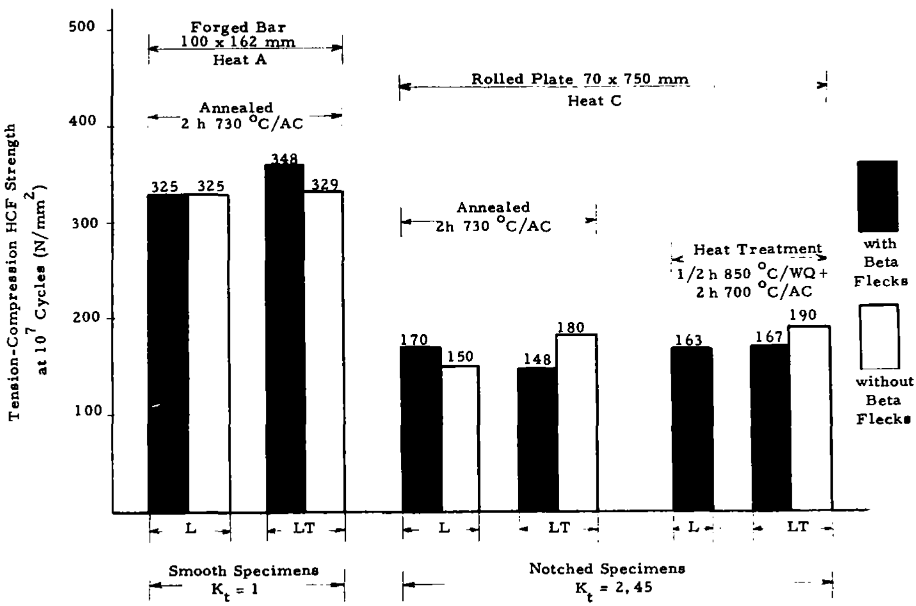
All results in L direction were for both products in the smooth and notched condition higher for the material with beta flecks. The increase is 8 % for Heat A, 3 % for Heat B, and 26 % for Heat C in the notched condition.

The results in LT direction are reverse. The fatigue strength of Heat B for smooth samples is about 2 % and of Heat C in the notched condition 23 % lower for the material with beta flecks. For notched samples with beta flecks the values are 23 % higher in the L and about the same amount lower in the LT direction.

Tension-Compression HCF Strength

The results of tension-compression HCF strength (R = -1) are presented in Fig. 3. Smooth specimens of Heat A and notched samples of Heat C in two heat treatment conditions were tested.

Fig. 3 Effect of Beta Flecks on Tension-Compression HCF Strength (R = -1) of Ti-6Al-6V-2Sn



L = Longitudinal to forming direction LT = Transverse to forming direction
K_t = Stress concentration factor

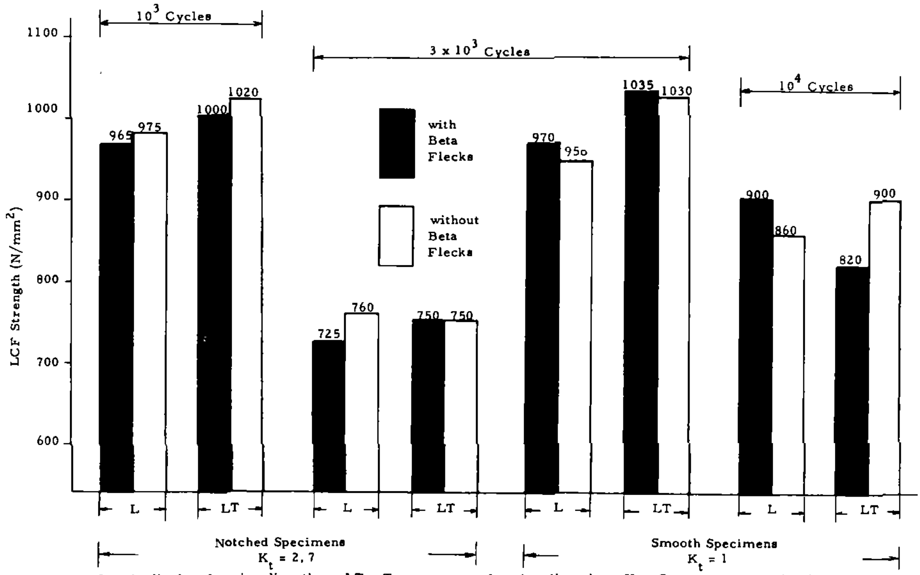
Forged bars with beta flecks show in L direction about equal and in LT direction by 5 % higher fatigue strength for the tested smooth samples.

The notched condition, in which only plates were tested (Heat C), confirms by lo % higher fatigue strength in L but by 21 % lower values in LT direction in the annealed condition. The tests also reveal that directionality can be at least partially compensated by solution annealing. While in the beta fleck material the L values remain unchanged, the LT values rise by 11 %.

LCF Strength

LCF testing was carried out in L and LT direction on plates of Heat C. In Fig. 4 the results are shown for three characteristic numbers of cycles for both microstructures. The values were taken from the average S-N curves. At 3ooo cycles the fatigue strength shows practically no difference for material with and without beta flecks for smooth and notched samples just as well as for L and LT direction. At 1ooo cycles the notched condition exhibits the same tendency.

Fig. 4 Effect of Beta Flecks on LCF Strength (R = 0) of Ti-6Al-6V-2Sn Plates, Annealed 2 h 730 °C/AC (Heat C)



L = Longitudinal to forming direction LT = Transverse to forming direction K_t = Stress concentration factor

In notched samples the material free of beta flecks seems to show a slight advantage, while for smooth samples the beta fleck material shows higher strength.

At 1o ooo cycles beta fleck material results in L direction in 5 % higher, but in LT direction in 9 % lower fatigue strength for the tested smooth samples.

Discussion and Conclusions

This investigation confirms again that mechanical properties including notched to unnotched tensile strength ratio of Ti-6Al-6V-2Sn in the annealed condition are not impaired by so-called beta flecks with reduced or no content of primary alpha phase in the microstructure. In all tested materials the minimum values of AMS specifications were exceeded.

The results of HCF testing show in the unnotched condition generally no major differences, with a tendency for higher values in material with beta flecks, especially in L direction.

The range of variation is greater in the notched condition with a tendency for a strength increase by beta flecks in L and a reduction in LT direction. An explanation for this phenomenon is possibly the fact that beta flecks are fibers which are stretched in L direction and which may have a strengthening effect under certain load conditions and a weakening effect under others.

The different effect in L and LT direction is compensated by the directionality of material, free from beta fleck also in the notched condition.

Solution annealing(1/2 h, 850 °C/WQ + 2 h, 700 °C/AC) contributes to reduction of directionality.

The LCF behaviour of Ti-6Al-6V-2Sn with beta flecks is not basically different from the HCF behaviour.

From the point of view of the material, the results of this study in the annealed condition has shown no adverse effect of beta flecks which would require direct consequences for material selection or design allowables. It would be suggested, however, to supplement this investigation by testing of components made from Ti-6Al-6V-2Sn with beta flecks to verify these results under critical service conditions.

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