New Alloys for Advanced Metallic Fighter-Wing Structures

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This paper summarizes the materials test portion of a program sponsored by the U.S. Air Force Flight Dynamics Laboratory (AFFDL) to develop lightweight/low-cost fighter-wing structures. Fatigue-crack propagation-rate curves are presented which compare aluminum alloys 7475-T7651, 7050-T73651, 7050-T7651 plates and 7050-T736 forgings, and titanum alloys Ti-6-4 βMA, Ti-6-2-1-1 A plates, Ti-6-4 A and STA castings, and Ti-6-22-22 STA forgings. Standard mechanical properties are also reported. For most aircraft applications, these new aluminum alloys appear better than 7075. Except for Ti-6-2-1-1 A plate and Ti-6-4 STA castings, the titanium alloys tested are better than conventional, wrought Ti-6-4 and Ti-6-6-2.

I. Introduction

THIS alloy evaluation program was undertaken as a portion of an Advanced Development Program sponsored by the Air Force Flight Dynamics Laboratory under Contract F33615-72-C-1891 (Project 486U) with the Northrop Corporation for the design of advanced metallic fighter-wing structures. Part of the objective was to design an F-5E fighter-wing using new structural concepts and new alloys which would meet specific damage tolerance criteria.

The materials evaluation portion of the program concentrated on the mechanical properties needed for a thin, lightweight fighter-wing structure.[1] Figure 1 shows that for a wing of this type, the upper wing skin is usually loaded in compression so that compression yield and compression modulus values are of primary importance. The lower wing skin is subjected to tensile forces; therefore, the design is based on the criteria of tension yield, tension modulus, *S-N*-fatigue, corrosion behavior, plus new design criteria based on stress corrosion (K_{Iscc}), fracture toughness (K_{Ic} and K_c), and fatigue-crack propagation (FCP) rates. Ribs and spars need properties which are compatible with both skins.

Several new alloys and heat treatments emphasizing improved fracture toughness have been developed in the last few years. The objective for the materials program was to select and evaluate pertinent alloys, heat treatments, and product forms which could become useful for fighter aircraft in the near future.

Wing skins of thin-wing fighters are structural members carrying a large portion of the loads. To do this with minimum weight, tapering or sculpturing of the wing skins is required. Aluminum wing skins are normally machined from plate material. Therefore, important mechanical properties were measured as a function of thickness and orientation within the plate material. In this program, 1-in. to 1¼ in. aluminum plates were machined to produce specimens typical of the center 1-in., 0.5-in., and 0.125-in. thicknesses of the plate. Titanium wing skins would be thinner and, in many designs, separate pieces would be spliced together rather than machined from thick plate. For these reasons, the titanium specimens were made from 0.5-in., 0.3-in., and 0.125 in. rolled products.

Besides determining the strength, *S-N* fatigue, and fatigue-crack growth-rate behavior across the above range of thicknesses, it was also necessary to determine the effect of a corrosive environment and the significance of the product form (i.e., plate, forging, and casting) on properties.

The preceding criteria were used to judge the potential usefulness of alloys, heat treatments, and product forms for this program. Materials were selected for possible use as upper or lower wing skins, ribs, and spars. However, after the test results were compiled, the materials were evaluated for all of the possible applications.

Designers and structures engineers want allowables for designing advanced structures. However, this test program developed average properties which were used to predict design allowables for comparing the new alloys with present production materials. In this paper, the average test values from the program were adjusted to estimated MIL-HDBK-5 "S" values for comparison with established "S" values. These adjusted values are shown in the figures and tables presenting tensile, compression, and bearing data; all other data are actual test values or average test values.

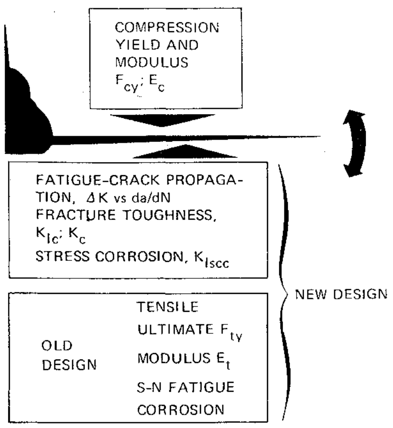

Fig. 1 Important mechanical properties for design of a lightweight fighter-wing.

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Index categories: Aircraft Structural Materials; Materials, Properties of.

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Table 1 Test plan[a]

MATERIAL	GAGE	TENSILE TEST (F_{tu}, F_{ty}, E, %e)		COMP. TEST (F_{cy}, E_c, PL)		BEARING (e/D=2) (F_{by}, F_{bu})	S-N FATIGUE (R=*) F = 30 Hz K_t = 3	STRESS CORROSION K_{ISCC}	FRACTURE TOUGHNESS K_{IC} OR K_C	R = 0.1 ΔK AIR	R = 0.1 VS. da/dN 3.5% NaCl	R = 0.3 ΔK AIR	R = 0.3 VS. da/dN 3.5% NaCl
ALUMINUM													
SHEET AND PLATE													
7475-T7651	1.0	3L	3T	3L	3T	3L	12L	3TL	3LW	2LW	2LW	2LW	2LW
7475-T7651	0.5 CENTER CUTS	3L	3T	3L	3T	3L			(1LW)	(2LW)	(2LW)		
7475-T7651	0.125 FROM 1" PLATE	3L	3T			3L	12L		(2LW)	(2LW)	(2LW)		
7475-T651	1.0	3L	3T	3L	3T	3L		3TL	3LW				
7050-T73651	1.0	3L	3T	3L	3T	3L	12L	3TL	3LW	2LW	2LW	2LW	2LW
7050-T73651	0.125" CENTER CUT FROM 1.0" PLATE	3L	3T			3L	12L			(2LW)	(2LW)		
7050-T7651	1.0	3L	3T	3L	3T	3L	12L	3TL	3LW	2LW	2LW		
FORGINGS													
7050-T736	~1.0	3L	3T	3L	3T	3L	12L	3TL	3LW	2LW	2LW		
TITANIUM													
SHEET AND PLATE													
Ti-6-22-22 STA	0.5	3L	3T	3L	3T	3L		3LW	3LW				
Ti-6Al-4V βMA	0.5	3L					12L	3LW		2LW	2LW	2LW	2LW
Ti-6Al-2Cb-1Ta-1Mo A	0.5	3L	3T	3L	3T	3L	12L	3LW		2LW	2LW		
Ti-6Al-4V βMA	0.3	3L				3L		(3LW)		(2LW)	(2LW)		
Ti-6Al-4V βMA	0.125	3L				3L	12L	(3LW)		(2LW)	(2LW)		
Ti-6-22-22A (EVALUATIONS)	1.0	6L							6LW				
FORGINGS													
Ti-6-22-22 STA	1.0	3L	3T	3L	3T	3L	12L	2LW	3LW	(2LW)	(2LW)		
CASTINGS													
Ti-6Al-4V STA	0.5	8		8		8	15	4	4	2	2		
Ti-6Al-4V A	0.5	8		8		8	15	4	4	2	2		

[a] L = rolling direction; W = long transverse direction; T = short transverse direction; *R values to be selected for each alloy; ( ) = thin specimens.

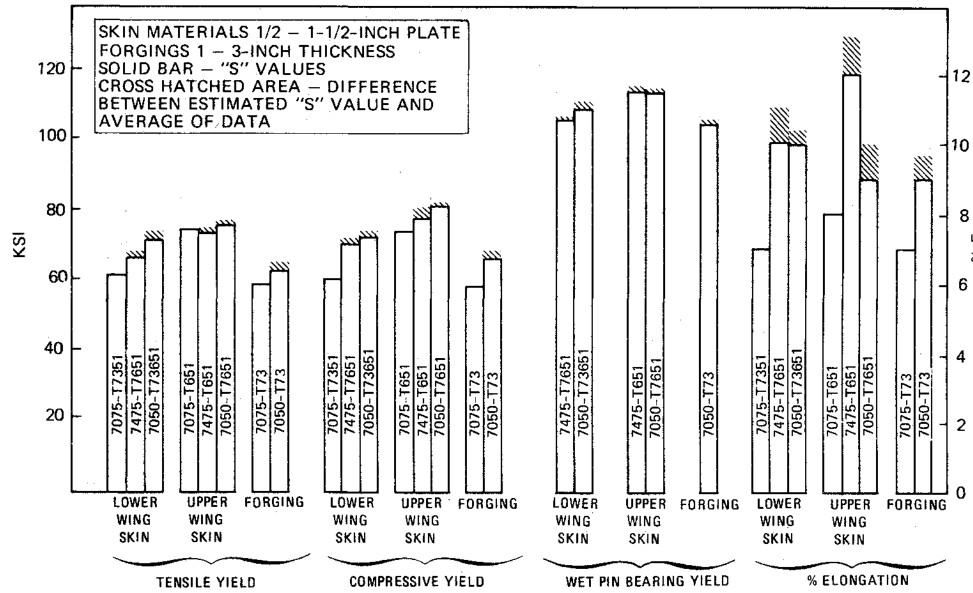

Fig. 2 Comparative yield strengths and elongations for the aluminum alloys.

II. Test Specimens and Procedures

Most of the mechanical property data were generated with standard specimens as follows: 1) Tension tests were conducted with 2-in. gage length, ⅛-in. thick, flat specimens according to ASTM E-8. 2) Compression tests were conducted with strain gaged, ½-in. and 1-in. diam cylinders according to ASTM E-9. 3) Bearing tests were conducted using ⅛-in. flat specimens with an edge distance of two times the pin diameter of 0.250-in., according to ASTM E-238, except that lubricated pins rather than dry pins were used to obtain conservative design values. 4) Fatigue tests were conducted on a ⅛-in. thick, flat, double-edge notched specimens with a stress concentration factor of 3.0, following ASTM STP Nos. 91 and 91A. 5) Stress corrosion tests were conducted using three different specimens: the aluminum specimens were 1-in. by 1-in. by 5-in. double cantilever beams (DCB) oriented in the TL direction and loaded by constant displacement; the titanium

Table 2 Materials comparison

MATERIAL ALLOY	FORM	STATIC PROPERTIES F_{tu} KSI	F_{ty} KSI	E_t 10^6 PSI	%	F_{cpl} KSI	F_{cy} KSI	E_c 10^6 PSI	F_{bu} KSI WET PIN	F_{by} KSI WET PIN	S-N FATIGUE, MAXIMUM FATIGUE STRESS KSI: CYCLES/10^4	10^5	10^6	K_t	R	FATIGUE CRACK GROWTH (DRY AIR) ΔK KSI$\sqrt{IN}$: CRACK GROWTH RATE/10^{-6} IN/CYCLE	10^{-5}	10^{-4}	FATIGUE CRACK GROWTH 3.5% NaCl ΔK KSI$\sqrt{IN}$: CRACK GROWTH RATE/10^{-6} IN/CYCLE	10^{-5}	10^{-4}	FRACTURE TOUGHNESS K_{Ic} KSI$\sqrt{IN}$ LW	STRESS CORROSION 3.5% NaCl K_{Iscc} KSI$\sqrt{IN}$
ALUMINUM																							
7075-T7351 [a]	1/4"-1/2" PLATE	78	63	10.3	7	–	62	10.6	–	–	30	18	14	3.0	0.1	5	10	20	–	–	–	35	24TL [c]
7475-T7651	1" PLATE	78	68	10.2	10	60	72	10.6	145	107	38	20	18	3.0	0.2	5.5	10	25	5.5	7	15	40	24 TL
7050-T73651	1" PLATE	82	73	10.2	10	62	74	10.7	150	110	30	14	11	3.0	0.2	5	10	25	5	7.5	18	33	25 TL
7075-T651 [a]	1/4"-1/2" PLATE	85	76	10.3	8	–	75	10.5	–	–	33	21	15.5	3.0	0.1	5	9	18	–	–	–	26	7 TL
7475-T651	1" PLATE	86	75	10.3	12	67	79	10.6	156	115	–	–	15.3	–	–	–	–	–	–	–	–	35	7 TL
7050-T7651	1" PLATE	84	77	10.0	9	69	83	10.6	158	115	34	17	—	3.0	0.2	6	10	25	5.5	7	16	31	< 20 TL
7075-T73 [a]	3" FORGING	71	60	10.3	7	–	60	10.5	–	–	–	–	–	–	–	4	10	22	–	–	–	34	
7050-T73	1-1/2" FORGING	73	64	10.1	9	61	68	10.6	140	106	34	18	15	3.0	0.2	11	16	27	–	8	19	35	23 TL
TITANIUM																							
Ti-6-4A [b]	0.18"-4" PLATE	137	126	16.0	10	–	132	16.4	245	198	80	60	54	3.0	0.1	10	19	37	–	–	–	55	35
Ti-6-6-2A [b]	0.18"-2" PLATE	158	147	17.0	10	–	158	17.5	–	–	82	50	35	3.0	–	8	19	35	–	–	–	40	30
Ti-6-2-1-1A	1/2" PLATE	130	115	16.5	13	90	130	17.5	255	196	52	39	34	3.0	0.1	12	22	48	12	20	29	REPORTED* TO BE 90	>93 LW
Ti-6-4 βMA	1/2" PLATE	137	126	16.0	13	–	–	–	–	–	55	37	33	3.0	0.1	13	25	48	13	20	28	REPORTED TO BE >95	34 LW
Ti-6-4 βMA	0.3" PLATE	145	136	16.5	11	–	–	–	295	225	–	–	–	–	–	15	28	60	–	15	26	REPORTED TO BE >95	38 LW
Ti-6-4 βMA	1/8" SHEET	159	153	17.5	15	–	–	–	302	234	60	40	39	3.0	0.1	15	28	65	–	23	–		66 LW
Ti-6-4A	1/8" & 1/2" CASTING	140	136	16.0	2.0	117	148	16.4	290	235	<43	31	28	3.0	0.1	15	24	50	–	20	–	75	>30 LW
Ti-6-4 STA [b]	0.18"-0.75" PLATE	168	152	16.0	8	–	162	16.4	–	–	87	50	40	3.0	0.1	–	–	–	–	–	–	41	28
Ti-6-6-2 STA [b]	0.18"-1.5" PLATE	178	168	17.0	8	–	168	17.5	–	–	72	48	39	3.0	0.1	11	22	37	–	–	–	34	–
Ti-6-22-22 STA	1/2" PLATE	173	159	17.2	13	145	177	18.1	315	260	–	–	–	–	–	–	–	–	–	–	–	50	36 LW
Ti-6-22-22 STA	1-1/2" FORGING	161	151	16.0	13	128	162	17.3	–	–	47	39	37	3.0	0.1	15	26	60	15	24	–	42	–
Ti-6-4 STA	1/8" & 1/2" CASTING	128	128	17.1	1.5	122	155	17.8	295	240	< 38	23	21	3.0	0.1	13	22	47	10	15	30	70	>44 LW

[a] C. ROSENKRANZ, ET AL, ADVANCED LIGHTWEIGHT FIGHTER STRUCTURAL CONCEPT STUDY, AFFDL-TR-72-98, JULY 1972
[b] C. ROSENKRANZ, ET AL, ADVANCED LIGHTWEIGHT FIGHTER STRUCTURAL CONCEPT STUDY, AFFDL-TR-72-98, JULY 1972 AND MIL-HDBK-5, "S" VALUES
[c] D.O. SPROWLS, ET AL, EVALUATION OF STRESS-CORROSION CRACKING SUSCEPTIBILITY USING FRACTURE MECHANICS TECHNIQUES, NAS 8-21487, MAY 1973

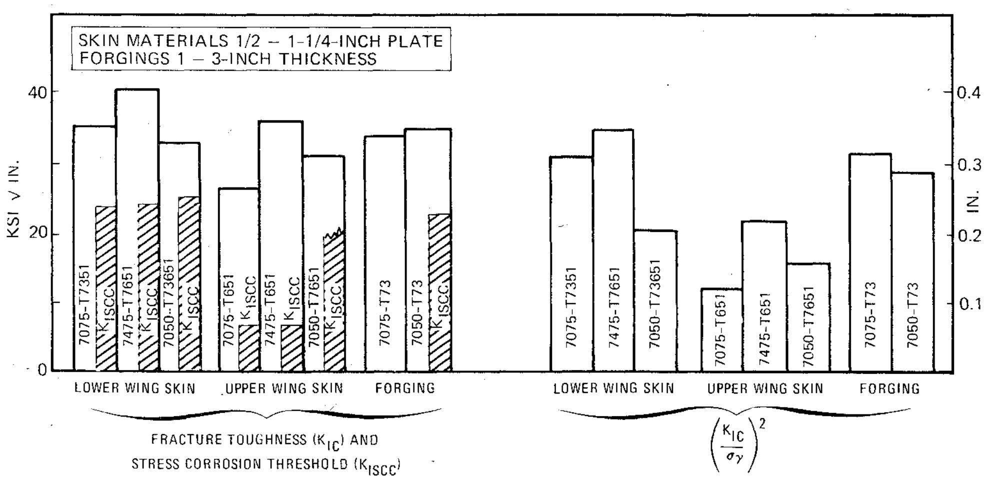

Fig. 3 Comparative toughness, stress corrosion resistance, and $(K_{Ic}/\sigma y)^2$ for the aluminum alloys.

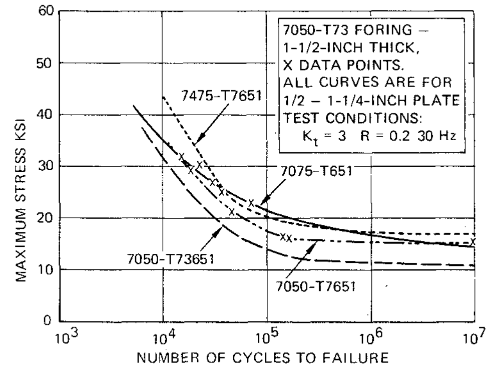

Fig. 4 Comparison of S-N fatigue behavior between new aluminum alloys and 7075-T651.

specimens were oriented in the LW direction and were either ½-in. by 2-in. by 5-in. DCB type, loaded by constant displacement, or ⅛-in. by 2.4-in. by 3-in. compact tension type stressed under constant load. 6) Fracture toughness tests (LW orientation) were conducted with ½-in. to 1-in. thick, standard compact tension specimens tested according to ASTM E-399-72T. 7) Fatigue-crack propagation (FCP) rates were measured using compact tension specimens (LW orientation) with an h/W of 0.486 rather than the standard h/W of 0.6 used for fracture toughness tests.

III. Test Results

Aluminum Test Results

Table I includes the aluminum portion of the test program. The aluminum alloys evaluated were 7475-T651 and 7050-T7651 (candidates for upper wing skins), 7475-T7651 and

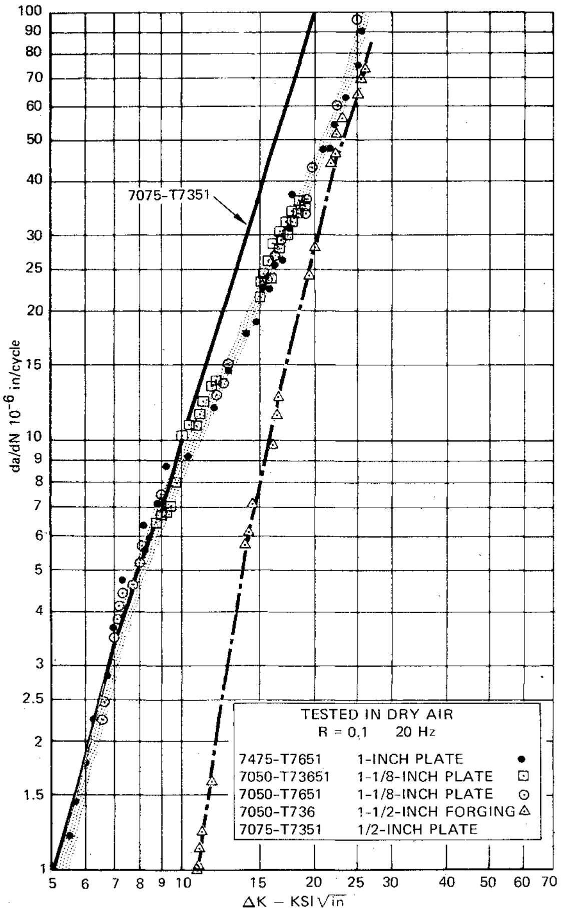

Fig. 5 Comparison between the FCP rates for new aluminum alloys and 7075-T7351 in dry air.

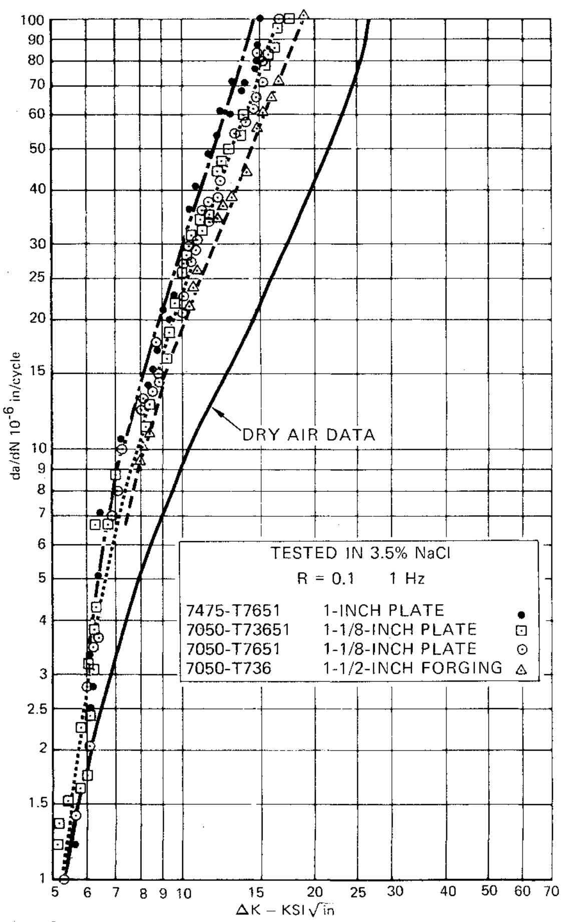

Fig. 6 Comparison between the FCP rates in dry air and 3.5% NaCl solution for aluminum alloys.

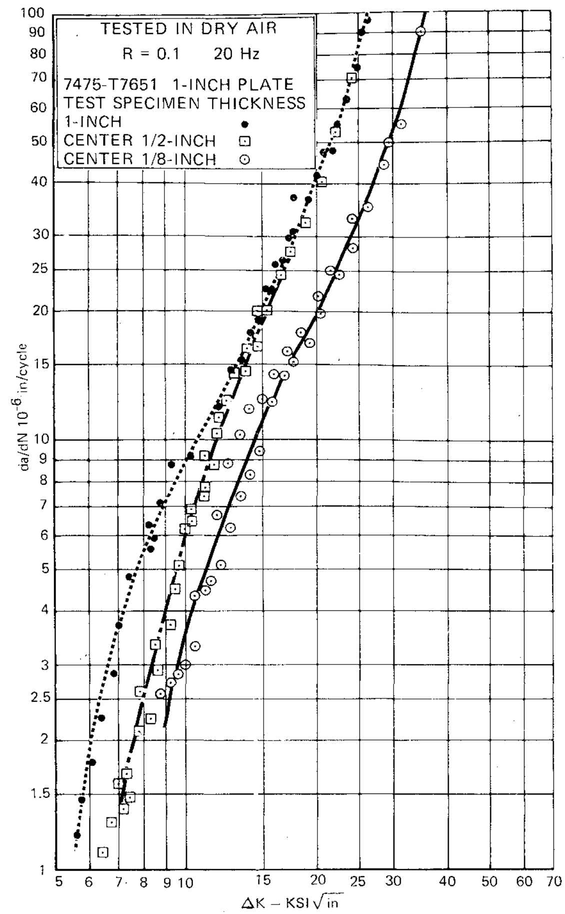

Fig. 7 Effect of thickness on FCP behavior of 7475-T7651—machines from 1 in. plate and tested in dry air.

7050-T73651 (for lower wing skins), and 7075-T736 forgings (for ribs and spars). The 7050 alloy is useful over a wide thickness range (up to 5-6 in.) and for forged parts; whereas, the 7475 alloy is usually produced as sheet or plate (up to 2 in.). All of the aluminum alloy chemistries were certified by the vendor.

Figure 2 compares the mechanical strength properties of tension yield, compression yield, bearing yield, and percent elongation of these new alloys with the 7075-T7351 baseline alloy. A complete listing of properties is given in Table 2. Figure 3 shows fracture toughness values (K_{Ic}), the stress corrosion threshold values (K_{Iscc}), and the ratio (K_{Ic}/σ_y). This ratio is useful for comparing alloys and heat treatments as it is proportional to the critical crack size at limit stress as well as to the plastic zone size. Thus, the larger the ratio, the more desirable the alloy, assuming other properties remain equal.

Figures 2 and 3 show that 7475-T7651 alloy is tougher, stronger in tension, tolerates a longer crack, and forms a larger plastic zone than 7075-T7351, thus offering the best combination of strength and toughness for lower wing skins.

Figure 4 compares the *S-N* fatigue data. These data show the 7475-T7651 alloy as a good choice for most fatigue applications. Interestingly, the 7050-T73651 plate material used in this program did not compare favorably with either the 7475-T7651 or the 7075-T651. However, the fatigue strength of this heat of 7050 appears to be typical when compared to data recently generated by J.G. Kaufman.[2]

FCP comparisons were made between the program alloys and 7075-T7351 as shown in Fig. 5. It should be emphasized at this time that small shifts of the FCP rate curves can be very significant when the data are used in calculations predicting the damage tolerant service life of an aircraft. As seen in Fig. 5, the new alloys are essentially equal to the 7075-T7351 up to an FCP rate of 10×10^{-6} in./cycle. At faster growth rates,

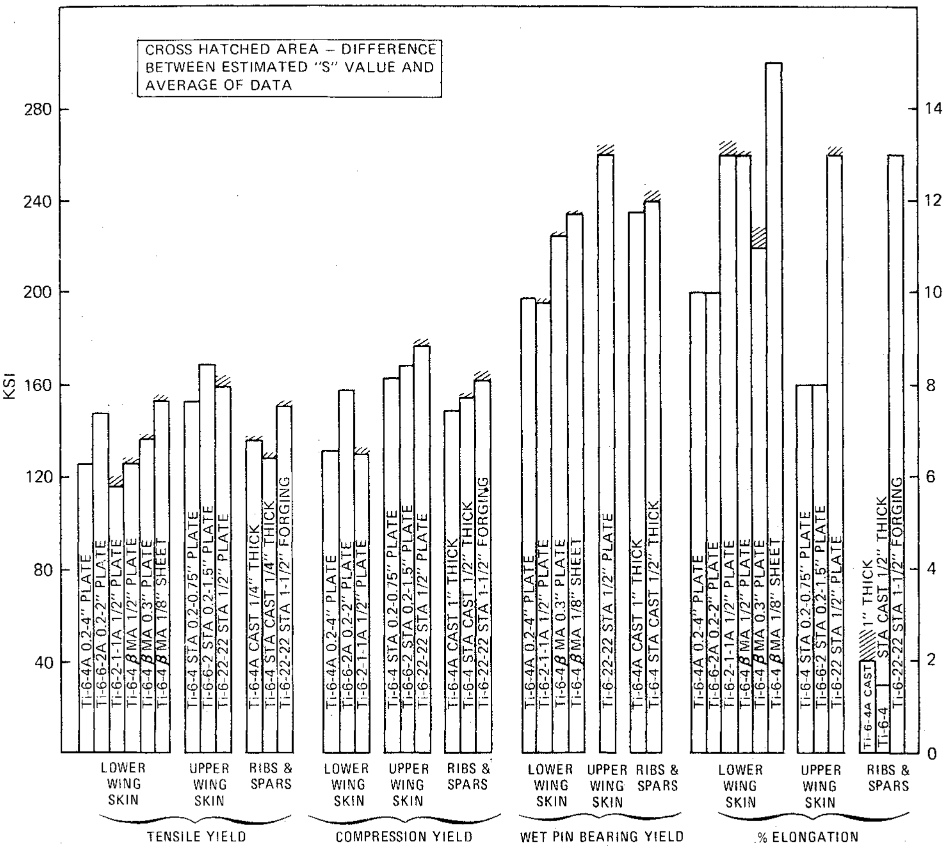

Fig. 8 Yield strengths and elongations for titanium alloys.

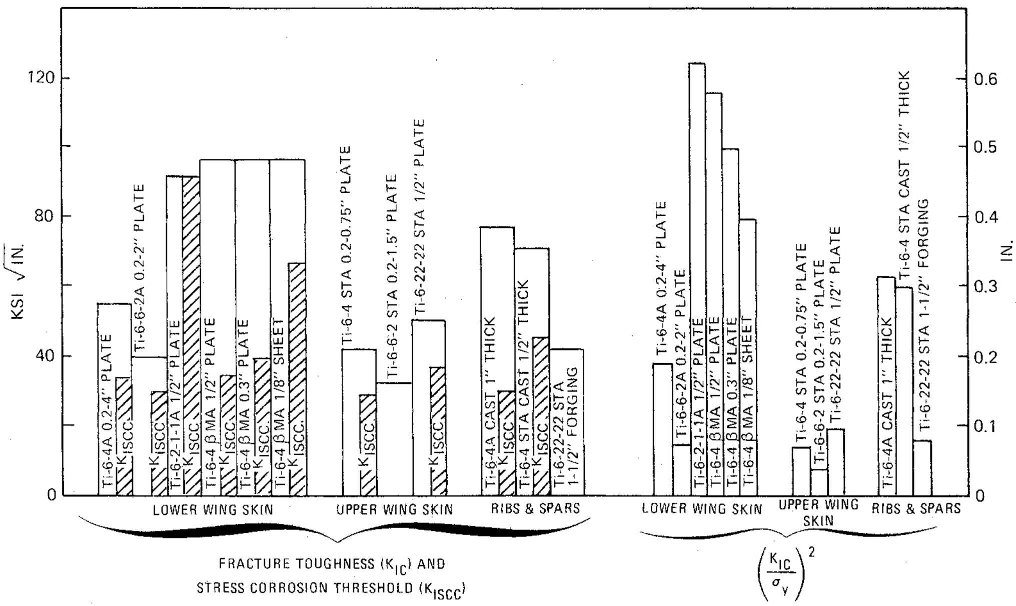

Fig. 9 Toughness, stress corrosion resistance, and $(K_{Ic}/\sigma y)^2$ for titanium alloys.

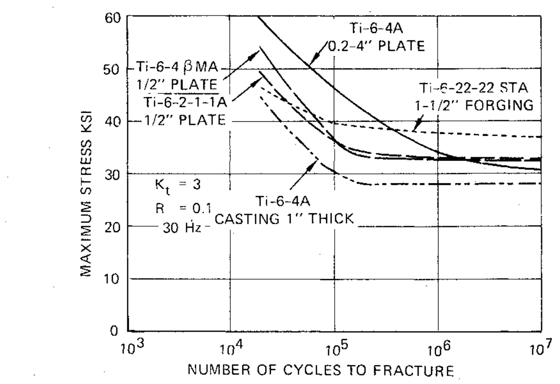

Fig. 10 Comparative S-N fatigue behavior for the titanium alloys.

the new alloys are better than the 7075-T7351. The 7050-T736 forging shows a remarkable improvement at the low crack-propagation rates. It is believed that this improvement is due to the forged grain orientation in the test area, and a similar trend was seen in the recent work by Kaufman.[2]

The next set of FCP curves, Fig. 6, compares the composite, dry-air FCP rate curve of Fig. 5 with data generated in a 3-½% NaCl solution. At a low stress-intensity factor (approximately 5 ksi in.$^{1/2}$), all of the data are essentially within the same band, indicating an insignificant environment effect. At higher stress-intensity factors, the saltwater increased the FCP rate significantly. At a stress-intensity factor of 15 ksi in.$^{1/2}$, the 7050-T736 forging is superior to the 7050-T7651 and T73651 plates which, in turn, are better than the 7475-T7651 plate. The final comparison of aluminum FCP rates,

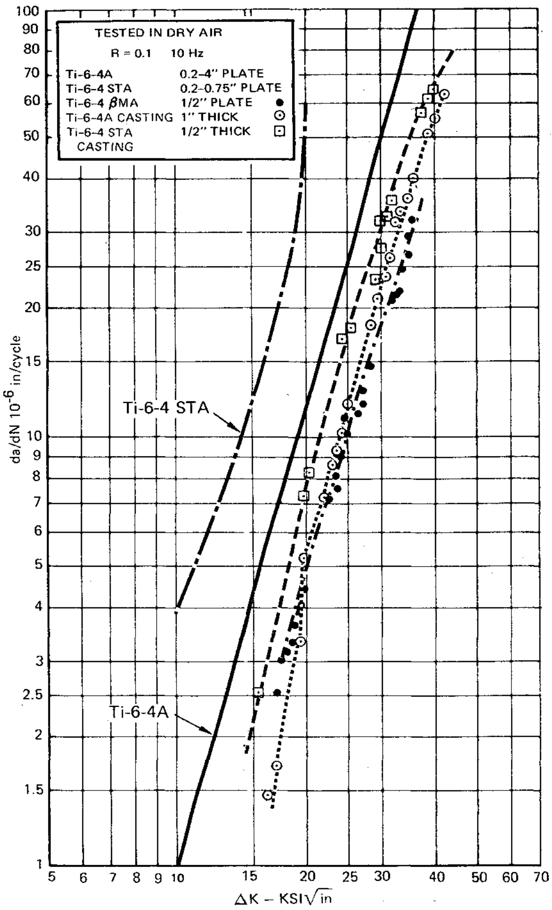

Fig. 11 Comparison of FCP rates for various forms and heat treatments of Ti-6-4 tested in dry air.

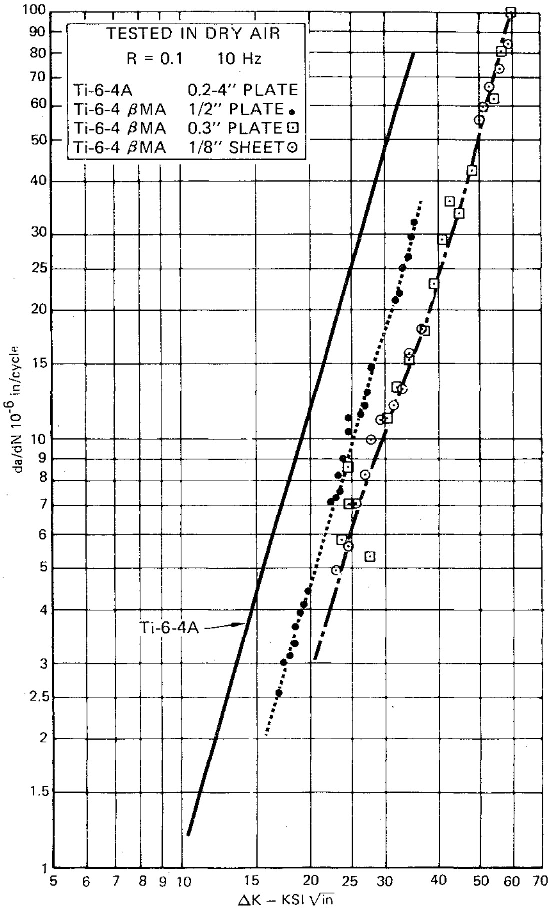

Fig. 12 Effect of product thickness on FCP behavior of Ti-6-4 beta mill annealed in dry air.

Fig. 7, shows the effect of reducing the thickness of a 1-inch thick 7475-T7651 plate on the FCP rate. Here is is seen that, as the plate is sculptured down to the center ½-in. and finally to the center ⅛-in. in thickness, the FCP rate tends to be reduced. However, at stress-intensity factors of 17 ksi in.$^{1/2}$ and above, the FCP rate for the ½-in. thickness equals the FCP rate at the 1-in. thickness. Notice, however, that this is the combined effect of specimen thickness and metallurgical differences through the 1-in. plate thickness. However, the FCP rate changes indicate that wing skins can be designed conservatively if the thick-plate FCP rates are used, or the designer may take advantage of the lower FCP rates in thinner sections cut from the plate.

Titanium Test Results

The titanium portion of the program (Table I) included evaluating a new heat treatment for Ti-6Al-4V, cast Ti-6Al-4V alloy, and two alloys which are new to aerospace applications. The chemistries of these alloys were certified by the vendors. The conventional Ti-64-4 alloy was evaluated, in three thicknesses of the beta mill annealed condition (βMA), for improved fracture toughness properties. Step castings were made to evaluate cast Ti-6-4 in both the annealed and STA conditions. The Ti-6Al-2Cb-1Ta-1Mo is new to aerospace, but it was developed for marine applications requiring high toughness, stress-corrosion resistance, and weldability. The Ti-6Al-2Sn-2Mo-2Cr-2Zr-0.25Si was recently developed on a U.S. Air Force contract[3] for rolled plate and forgings. This alloy is air hardenable (up to approximately 1 in. thick) to high strength levels which minimizes distortion.

Figure 8 compares the mechanical strength properties of tensile yield, compression yield, bearing yield, and percent elongation of the alloys with those of conventional Ti-6-4 A and STA and Ti-6-6-2 A and STA plates. Figure 9 compares the fracture toughness values (K_{Ic}), the stress-corrosion threshold values (K_{Iscc}), and the ratio $(K_{Ic}/\sigma_y)^2$ of these same alloys. Several interesting comparisons can be made from these figures: 1) the K_{Iscc} for Ti-6-2-1-1 is essentially equal to the K_{Ic} of the alloy; 2) Ti-6-4 βMA material has a high K_{Ic} value but the K_{Iscc} of the thick plate is essentially the same as for Ti-6-4 A plate; 3) the Ti-6-22-22 STA plate has a K_{Ic} and K_{Iscc} nearly equal to that of Ti-6-4 A, while offering a 30-40 ksi higher yield strength; 4) the cast Ti-6-4 offers excellent fracture toughness but low elongation; and 5) based upon the ratio $(K_{Ic}/\sigma_y)^2$, a comparison of the relative critical crack size at limit stress shows that Ti-6-4 STA, Ti-6-6-2 A, Ti-6-6-2 STA, and Ti-6-22-22 STA all have low values. This means that these alloys should be used for all applications which do not require high toughness characteristics such as upper wing skins.

The S-N fatigue data for the various alloys are compared in Fig. 10. Only representative curves are shown, but interestingly, the alloys rank significantly different in *S-N*-fatigue than they do in strength and fracture toughness.

Figure 11 compares the FCP rates of various forms of Ti-6-4 alloy. This figure shows that Ti-6-4 A castings and Ti-6-4 β-MA plate, which have similar microstructures, also have similar FCP rates. It also shows that both castings (A and STA) and the Ti-6-4 βMA plate are better than Ti-6-4 A plate. Figure 12 shows the effect of rolled product thickness on the FCP behavior of beta mill-annealed material. Here, the ½-in. thick rolled plate is compared to the 0.3 in. thick and 0.1-in. products; there is a substantial decrease in the FCP rate as the thickness of the mill product decreased from 0.5-in. to 0.3-in. However, no further FCP rate reduction took plate in going from 0.3-in. to 0.1-in.

Figure 13 compares FCP behavior of Ti-6-4 A and STA plates with the 0.5-in. Ti-6-4 β MA plate, the Ti-6-2-1-1 A

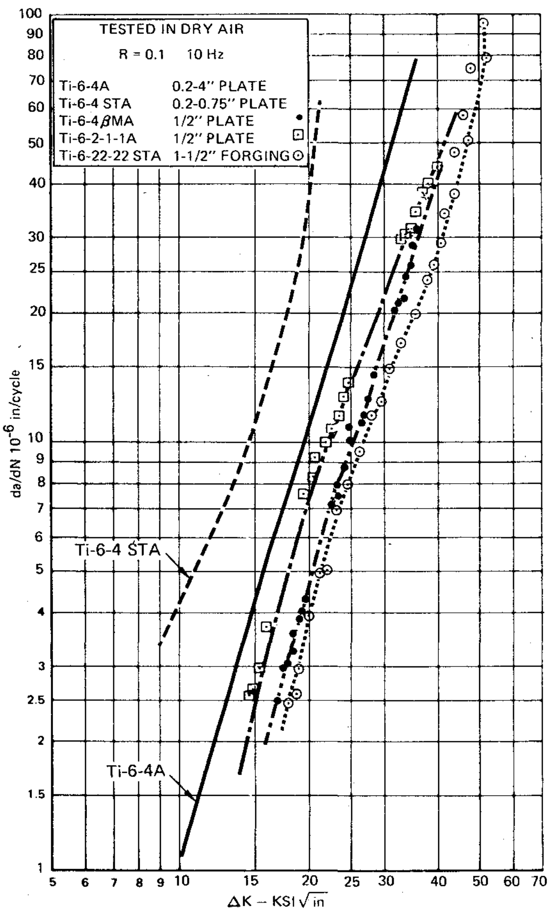

Fig. 13 Comparison between the FCP rates for the titanium test alloys and Ti-6-4A and STA in dry air.

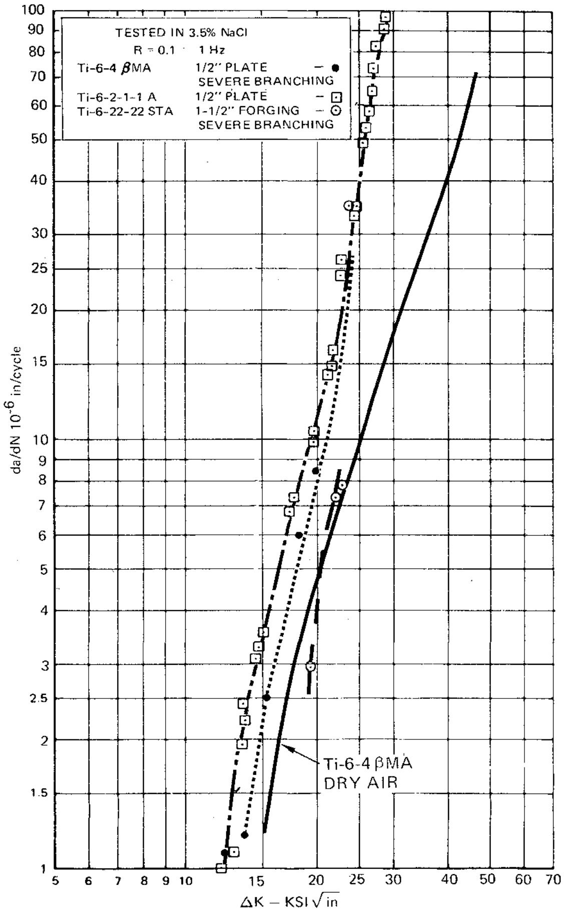

Fig. 14 Comparison between titanium FCP rates in 3.5% NaCl solution and Ti-6-4 beta mill annealed in dry air.

plate, and the Ti-6-22-22 STA forging. In this comparison, the forged material appears quite resistant to fatigue-crack growth; whereas, the Ti-6-2-1-1 A alloy does not compare as favorably as the other new materials. However, it is still better than Ti-6-4 A plate material. These same materials were tested in a 3-½% NaCl solution, the results of which are shown compared to the Ti-6-4 A dry-air curve in Fig. 14. Both the Ti-6-2-1-1 A and the Ti-6-4 βMA plates show an increase in FCP rate while maintaining their positions relative to each other. The Ti-6-22-22 STA forging showed little change in its FCP rate due to the 3-½% NaCl solution. Only limited test data were obtained for the Ti-6-4 βMA plate and the Ti-6-22-22 STA forging as the cracks tended to branch severely, thus reducing the usable crack length for testing.

IV. Conclusions

As stated earlier, some of the test data were averaged and adjusted for comparison with MIL-HDBK-5 "S" values for standard production materials in the published data. Based upon these adjusted figures, the following conclusions were made: 1)7475-T7651 is superior in *S-N* fatigue, FCP resistance, and fracture toughness and, therefore,is the best alloy for use in the fatigue-critical lower wing skin application when an aluminum skin is desired. 2) The 7050-T7651 had the best compression strength and stress-corrosion resistance and is the best aluminum upper wing skin material. 3) The 7050-T73 aluminum forgings were selected for many rib and spar applications in the wing. 4) The Ti-6-4 beta mill annealed material has the best balance of strength and fracture properties for use as a titanium lower wing skin. 5) The Ti-6-4 beta mill annealed material is best for use in formed or forged spars. 6) The Ti-6-4 A castings exhibit good properties for several specific rib applications. 7) The Ti-6-22-22 STA plate has a promising future for use in forged ribs and as an upper wing skin material. However, further evaluation of the best heat treatments must be performed before this alloy can reach its full potential for these applications. 8) Of the Ti-6-4 castings, the annealed heat treatment is preferred over the STA due to the more consistent data and higher percent elongation. 9) The Ti-6-2-1-1 A alloy does not appear to have sufficient strength for use in small fighter wing structures unless stress corrosion is a severe problem. 10) An environment of 3-½% NaCl increased the FCP rate of every alloy tested.

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