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FRACTURE AND FATIGUE OF DIFFUSION, EXPLOSIVE, AND ROLL BONDED Al/Al AND Ti/Al LAMINATES

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The fracture and fatigue crack propagation characteristics of Al and Ti/Al laminates were evaluated. Seven laminate panels of approxim y 12.7 mm (0.50 in.) thickness were fabricated using diffusion, explosive, and roll bonding procedures. Specific alloy systems investigated included: diffusion bonded and roll bonded 7475 Al/1100 Al, explosive bonded and roll bonded 7075 Al/7072 Al, and diffusion bonded Ti-6Al-4V/6061 Al. A typical laminate consisted of five 2.3 mm (0.090 in.) 7475 Al primary layers

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20. Abstract

interleaved with four 0.13 mm (0.005 in.) 1100 Al secondary layers. It was found that all laminates exhibited substantially higher critical fracture toughness in the crack divider orientation than corresponding baseline, monolithic plate alloys. For example, the Al/Al laminates possessed average toughness values that ranged from 33% to 56% higher than those values for monolithic 7475 Al and 7075 Al plates. The Ti-6Al-4V/6061 Al panel had a toughness 117% higher than the baseline Ti-6Al-4V plate. Crack divider fatigue crack propagation rates were found to be similar to those rates for the baseline alloy plates. Crack arrest orientation fracture and fatigue propagation tests confirmed these laminates had significant crack arrest capacity. Criteria were outlined for efficient metal/metal laminate design for achieving highly damage tolerant structural materials.

PREFACE

This report describes the work performed at Vought Advanced Technology Center during the period 17 February 1976 to 17 February 1977 on a metals laminate development for structures program. This program was conducted for the Naval Air Systems Command under Contract No. N00019-76-C-0288. The project monitor was Mr. W. T. Highberger, Code AIR-52031D, Naval Air Systems Command, Washington, D. C.

The program was conducted under the supervision of Dr. D. H. Petersen. The principal investigator for this investigation was Dr. R. D. Goolsby. Technical support was provided by Messrs. B. K. Austin, T. E. Mackie, J. H. Thomas, and W. M. Willis. Support for laminate fabrication was provided by: Mr. P. L. Mehr and Mr. A. N. Anderson, Alcoa Technical Center; Mr. R. E. Pattee and Mr. V. D. Linse, Battelle Columbus Laboratories; and Mr. J. F. Dolowy, Jr., DWA Composite Specialties, Inc.

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1.0 INTRODUCTION

The application of metal laminates in structural design has seen an increased interest in the past few years, particularly in the aerospace field. Metal laminates are attractive as structural elements because they potentially offer greater reliability, increased life expectancy, and lower cost than conventionally forged and machined components. In particular, the high fracture and fatigue resistance and the crack arrest properties of metal laminates have been the subject of intense investigation.[1-21] These studies have included evaluations of metal/epoxy and metal/metal laminate panels, as well as structural component fabrications using laminated materials. Most of the studies related to aerospace applications have concerned metal/epoxy systems. These metal/epoxy systems have been concentrated on primarily because of the potential fabrication cost savings associated with these materials. However, metal/epoxy systems have been limited in primary aerospace structural applications because of uncertainties regarding their use in the presence of hostile environments (e.g. salt water) and their use at elevated temperatures. Thus, totally metallic laminate systems would be useful for structures operating under these more severe service conditions.

The present investigation is concerned with development of totally metallic laminates for aerospace structural application. In spite of the numerous studies that have been conducted in the past on both metal/epoxy and metal/metal laminates, insufficient information regarding material, configurational, and processing variables is available for efficient structural design using metal/metal laminates. This study is directed toward determining the effects of these various parameters on the fracture and fatigue properties of Al/Al and Ti/Al laminates. Seven different laminate configurations were fabricated by three distinctive processing methods: diffusion bonding, roll bonding, and explosive bonding. The materials systems were 7475 Al/1100 Al, 7075 Al/7072 Al, and Ti-6Al-4V/6061 Al. The specific experimental program conducted under this study was designed to isolate the following parameters affecting metal/metal laminate properties.

> <u>Laminate Properties vs. Sheet and Monolithic Plate Properties</u>. For each of the seven metal/metal laminate configurations documented similar documentation was obtained for monolithic primary alloy

plate of the same thickness as the laminate panel. Also, properties were determined of primary alloy sheet of the same thickness as that of the primary layers in the metal/metal laminates.

Process Method. Diffusion bonding, roll bonding, and explosive bonding laminate fabrication methods were employed on identical Al/Al laminate configurations. This enabled direct comparisons to be made between the three fabrication methods regarding their effects on: metallurgical structure, tensile properties, fracture properties, and fatigue crack propagation properties of the processed laminates.

Alloy Type. 7075 Al and 7475 Al (both having very similar chemical compositions) were used as primary metals so that direct comparisons could be made regarding the use of these two aluminum alloys in laminate materials. Titanium was also used as a primary laminate metal to evaluate its utility in laminate design.

Interleaf Thickness Effects. Three different interleaf thicknesses were employed in the fabrication of three laminates processed by the same method (diffusion bonding) and having the same metal/metal constitution (7475 Al/1100 Al). Test results from these three laminates allowed for comparison of metallurgical, tensile, fracture, and fatigue crack propagation properties as a function of interleaf thickness.

The fracture and fatigue crack propagation behavior of these materials were characterized in both crack divider and crack arrest orientations. The metallurgical properties and failure mechanisms were documented using optical metallography, electron probe microanalysis, and scanning electron microscopy.

2.0 EXPERIMENTAL PROCEDURE

2.1 MATERIAL SELECTION

The essential first step in an experimental investigation of metal/metal laminates is the selection of primary and secondary laminae materials and thicknesses. From the numerous investigations that have been conducted on all types of laminar composite systems, it has been noted that the principal factors which affect the fracture resistance of laminates are:

(1) Primary metal properties - strength, toughness, ductility, etc.
(2) Secondary (bonding or interleaf) metal - strength, ductility bonding properties.
(3) Primary metal lamina thickness
(4) Secondary metal (interleaf) thickness

The selections of these metals are described below.

Primary Metal Selection. In the present investigation only aluminum and titanium alloys were considered for application as primary metals, because of the advantageous strength-to-weight ratios of these alloys. Selections of the exact aluminum and titanium alloys were based on fracture toughness vs. thickness characteristics, strength, fatigue resistance, corrosion resistance, and stress corrosion resistance. The alloys selected on this basis were 7075-T76, -T7651 Al; 7475-T761, -T7651 Al; and mill annealed Ti-6Al-4V titanium alloy. The baseline sheets and plates that were used in this investigation are given in Table 1.

Secondary (Bonding or Interleaf) Metal Selection. The secondary metal is considered important primarily because of its effect on bondline strength, and therefore on the tendency of the primary laminae to fail in a plane stress manner. Failure of the primary laminae under plate stress conditions is necessary to achieve maximum fracture toughness. For all three processing methods used in laminate preparation, a soft interleaf metal was employed as the secondary or bonding metal. 1100 Al was used as the interleaf metal in all Al/Al diffusion bonded panels and in one of the Al/Al roll bonded panels. 7072 Al was used as the secondary metal in the Al/Al explosive bonded panel and in one of the Al/Al roll bonded panels. 6061 Al was used as the secondary metal in the diffusion bonded Ti/Al panel. Specific secondary metal thicknesses and laminate configurations are described in Section 2.2

TABLE 1. BASELINE ALUMINUM AND TITANIUM ALLOY SHEETS AND PLATES INVESTIGATED

ALLOY	HEAT TREATMENT CONDITION	NOMINAL THICKNESS mm	(in.)	LOT OR HEAT NUMBER
7475 Al	-T761	2.3	(0.090)	108 - 369
7475 Al	-T7651	13.2	(0.520)	---
7075 Al	-T76	2.3	(0.090)	212251
7075 Al	-T7651	12.7	(0.500)	---
Ti-6Al-4V Titanium	Mill Annealed	3.2	(0.125)	N6721
Ti-6Al-4V Titanium	Mill Annealed	13.7	(0.540)	N4555

2.2 LAMINATE SELECTION AND FABRICATION

Diffusion bonding, roll bonding, and explosive bonding were used to fabricate the Al/Al and Ti/Al laminate panels. Seven laminate panels were evaluated during this study: three diffusion bonded Al/Al laminates, two Al/Al roll bonded laminates, one Al/Al explosive bonded laminate, and one diffusion bonded Ti/Al laminate. The specific laminate configurations assessed (illustrated schematically in Figure 1) are detailed in Table 2 and are discussed in the following paragraphs.

Diffusion Bonded Laminate Panels. The diffusion bonded laminate panels were fabricated by DWA Composite Specialties, Inc. The Al/Al panels consisted of five layers of 2.3 mm (0.090 in.) thick 7475-T761 Al sheet interleaved with four layers of 1100 Al. The only differences among the three panels were the 1100 Al interleaf sheet thicknesses [0.05 mm (0.002 in.), 0.13 mm (0.005 in.), and 0.25 mm (0.010 in.)]. These panels were processed under vacuum for 1/2 hour at 477°C (890°F) at 20.7 MPa (3000 psi) pressure. The Ti/Al laminate consisted of four layers of 3.2 mm (0.125 in.) thick mill annealed Ti-6Al-4V titanium alloy sheet interleaved with three layers of 0.10 mm (0.004 in.) 6061 Al foil. This panel was processed under vacuum for 1/2 hour at 524°C (975°F) at 27.6 MPa (4000 psi) pressure. The area of all diffusion bonded panels fabricated was approximately 406 mm x 711 mm (16 in. x 28 in.).

Roll Bonded Laminate Panels. The roll bonded Al/Al laminate panels were fabricated and heat treated by Alcoa Technical Center. One laminate configuration (RA1) consisted of five layers of 2.3 mm (0.090 in.) 7075 Al sheet interleaved with four layers of 0.13 mm (0.005 in.) 7072 Al sheet. The other laminate configuration (RA4) consisted of five layers of 2.3 mm (0.090 in.) 7475 Al sheet interleaved with four layers of 0.13 mm (0.005 in.) 1100 Al sheet. Total size of laminate RA1 was 11.9 mm x 305 mm x 1370 mm (0.47 in. x 12 in. x 54 in.). Total size of laminate RA4 was 11.9 mm x 305 mm x 1120 mm (0.47 in. x 12 in. x 44 in.). The final laminate panel was fabricated by initially processing three subpanels and warm rolling these three subpanels into the final configuration. After roll bonding the panels to final dimensions the laminates were heat treated to give -T7651 properties to the primary metal phase (7075 or 7475).

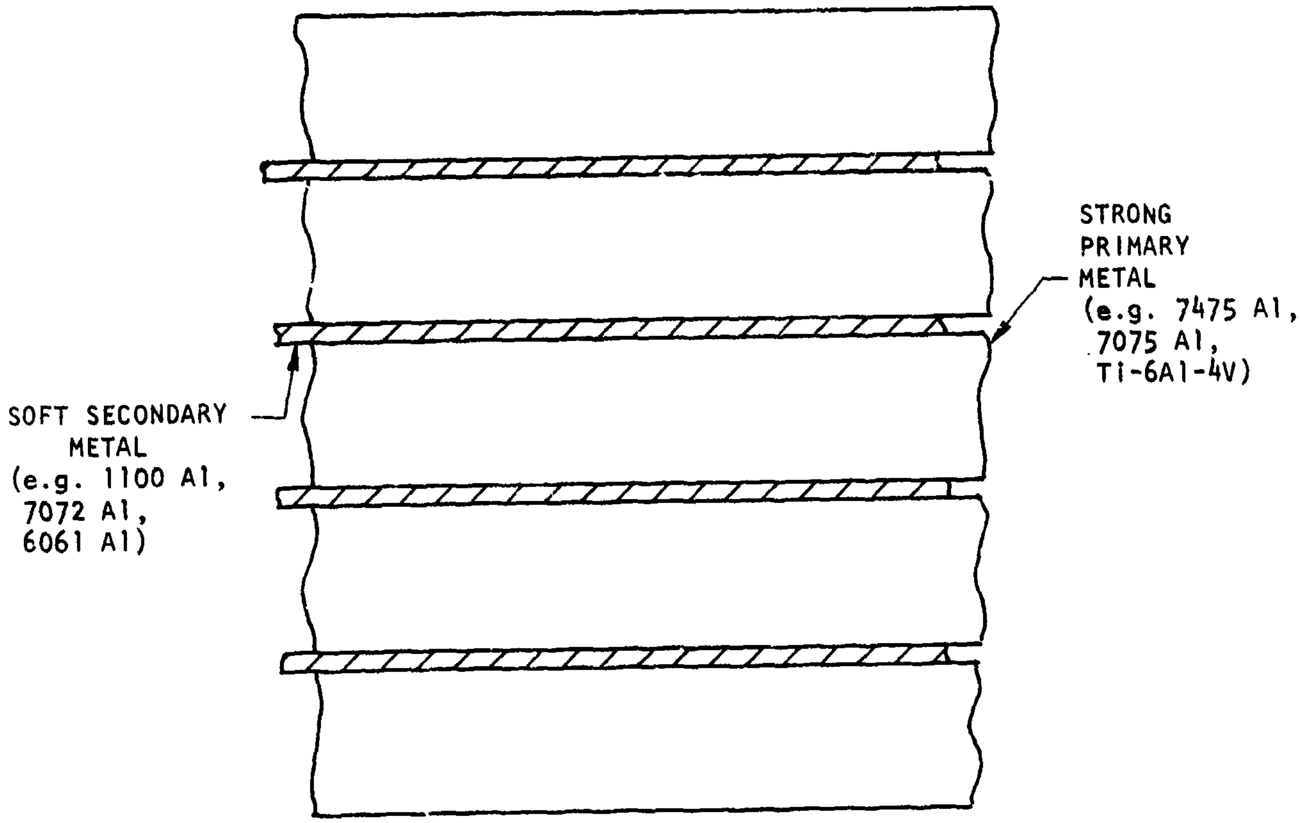


FIGURE 1. SCHEMATIC OF METAL/METAL LAMINATE INVESTIGATED.

TABLE 2. DIFFUSION BONDED, ROLL BONDED, AND EXPLOSIVE BONDED Al/Al AND Ti/Al LAMINATE PANELS INVESTIGATED

LAMINATE PANEL DESIGNATION	BONDING PROCESS	PRIMARY METAL			Secondary Metal			NOMINAL LAMINATE PANEL SIZE mm (in.)
		ALLOY	NUMBER OF LAYERS	LAYER THICKNESS mm (in.)	ALLOY	NUMBER OR LAYERS	LAYER THICKNESS mm (in.)	
DA1	Diffusion	7475 Al	5	2.3 (0.090)	1100 Al	4	0.13 (0.005)	11.9 x 406 x 711 (0.47 x 16 x 28)
DA2	Diffusion	7475 Al	5	2.3 (0.090)	1100 Al	4	0.25 (0.010)	12.4 x 406 x 711 (0.49 x 16 x 28)
DA3	Diffusion	7475 Al	5	2.3 (0.090)	1100 Al	4	0.05 (0.002)	11.7 x 406 x 711 (0.46 x 16 x 28)
DT1	Diffusion	Ti-6Al-4V	4	3.2 (0.125)	6061 Al	3	0.10 (0.004)	13.2 x 406 x 711 (0.52 x 16 x 28)
RA1	Roll	7075 Al	5	2.3 (0.090)	7072 Al	4	0.13 (0.005)	11.9 x 305 x 1370 (0.47 x 12 x 54)
RA4	Roll	7475 Al	5	2.3 (0.090)	1100 Al	4	0.13 (0.005)	11.9 x 305 x 1120 (0.47 x 12 x 44)
EA1	Explosive	7075 Al	5	2.4 (0.095)	7072 Al	4	0.13 (0.005)	12.4 x 279 x 381 (0.49 x 11 x 15)

Explosive Bonded Laminate Panel. The explosive bonded 7075 Al/7072 Al laminate panel EA1 was fabricated by Battelle Columbus Laboratories. This laminate was fabricated from five layers of 2.5 mm (0.099 in.) 7075-T6 Alclad Al sheet. Thus, the as-bonded laminate consisted of five layers of 2.4 mm (0.095 in.) 7075 Al interleaved with four layers of 0.13 mm (0.005 in.) 7072 Al sheet. Total area of the explosive bonded laminate was approximately 12.4 mm x 279 mm x 381 mm (0.49 in. x 11 in. x 15 in.). The laminate was fabricated using a single-sided welding procedure as illustrated in Figure 2. The standoff distances between the upper four sheets were all 1.52 mm (0.060 in.). The standoff distance between the lower two sheets was reduced to 1.02 mm (0.040 in.) to minimize any tendency toward overwelding. The panel was welded using SWP-1 explosive at a charge density of 1.65 g/cm^2. [SWP-1 explosive is a nitrostarch-sensitized ammonium nitrate powder explosive that detonates at a nominal velocity of 3000 m/sec (9850 ft/sec)]. Subsequent to fabrication the laminate was tempered at Vought Advanced Technology Center to give -T76 tensile properties to the 7075 Al.

2.3 CHEMICAL ANALYSIS, MICROSTRUCTURAL EVALUATION, AND NONDESTRUCTIVE INSPECTION

Chemical Analysis. All primary metal sheets and plates used in this program were analyzed to determine chemical compositions employing emission spectroscopy.

Microstructural Evaluation. Baseline metal sheets and plates and laminated panels were examined using a Leitz Ortholux metallograph. Electron probe microanalysis was performed on all laminated panels using a Cameca MF 46 analyzer.

Nondestructive Inspection. All laminated panels were inspected using ultrasonic C-scan.

2.4 MECHANICAL TESTING

2.4.1 Tension Tests

The tension tests were performed using the 25.4 mm (1.00 in.) and 50.8 mm (2.00 in.) gage length specimens shown in Figure 3. All materials were evaluated using the 50.8 mm specimen with the exception only of the explosive bonded laminate EA1. Triplicate tests were performed on all

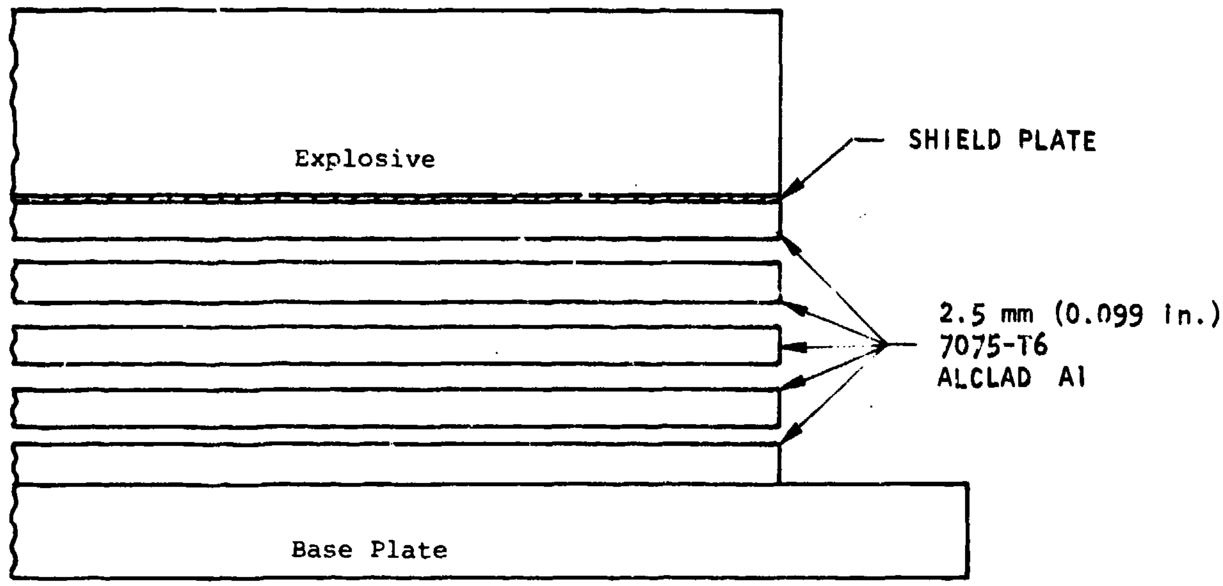
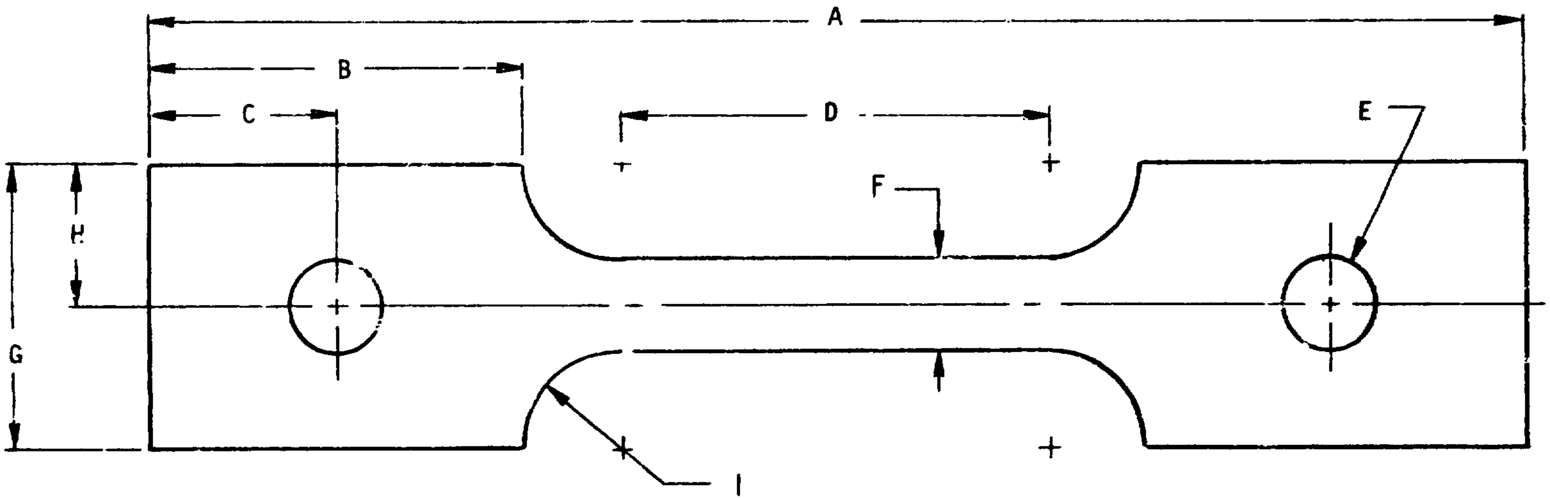


FIGURE 2. SCHEMATIC OF SINGLE-SIDED EXPLOSIVE BONDING PROCEDURE FOR FABRICATION OF LAMINATE EA1.



SPECIMEN GAGE LENGTH mm (in.)	DIMENSION mm (in.)								
	A	B	C	D	E	F	G	H	I
25.4 (1.00)	82.6 (3.25)	19.0 (0.75)	9.5 (0.38)	31.8 (1.25)	6.4 (0.25)	3.2 (0.12)	19.0 (0.75)	9.5 (0.38)	6.4 (0.25)
50.8 (2.00)	184 (7.25)	50.8 (2.00)	25.4 (1.00)	57.2 (2.25)	12.7 (0.50)	12.7 (0.50)	38.1 (1.50)	19.0 (0.75)	12.7 (0.50)

FIGURE 3. 25.4 mm (1.00 in.) AND 50.8 mm (2.00 in.) GAGE LENGTH TENSILE SPECIMENS

materials in the longitudinal orientation. These tests were run at 1.27 mm/min (0.05 in./min) at room temperature. Testing was accomplished on either a 90 kN (20 kip) capacity CGS or 450 kN (100 kip) capacity MTS servo-hydraulic closed-loop testing system under stroke control. Elongation was monitored using an MTS 632.12 strain gage extensometer.

2.4.2 Fracture Tests

Fracture toughness tests were performed using the compact tension (CT), single-edge-notched (SEN), and three point bend (TPB) specimens shown in Figures 4, 5, and 6. The SEN and CT specimens were used for all of L-T, crack divider orientation tests (Figure 7). The TPB specimen was used for L-S, crack arrest tests (Figure 7). Testing was performed in a manner similar to the ASTM E 399 test method for compact tension and three point bend specimens,[22] and to the procedures outlined in the Damage Tolerant Design Handbook.[23] The specimens were fatigue precracked at 10 Hz and subsequently tested to failure using a loading rate within the ASTM recommended range. A double cantilever crack-opening-displacement (COD) gage similar to that developed by Fisher, et al.[24] was used to monitor crack length during testing. Load and crack-opening-displacement were recorded on an X-Y recorder for all tests. These tests were run in triplicate at room temperature on either the CGS or MTS system described earlier.

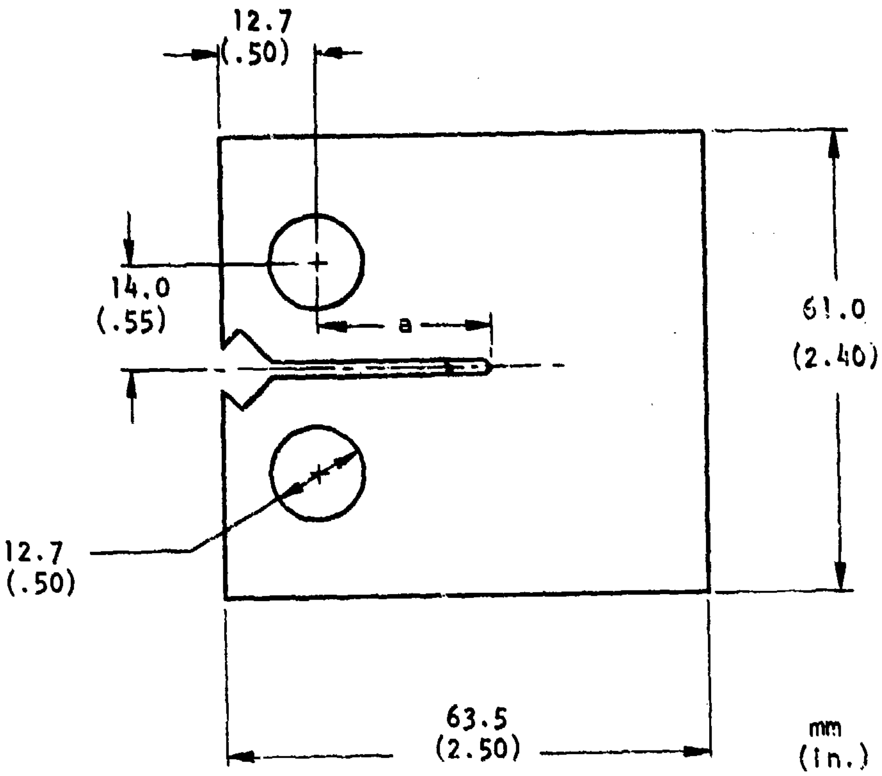
Pertinent crack lengths relative to the load/crack-opening-displacement failure curves were determined using experimentally derived COD compliance calibrations. These COD compliance calibrations were determined for each specimen configuration (CT, SEN, and TPB, including a calibration for three different values of W for the TPB specimen).

The following fracture toughness parameters were determined for specimens tested in this study:

K_Q - conditional fracture toughness, determined by the 5% offset method described in ASTM E 399-74

K_{app} - apparent fracture toughness, evaluated using maximum failure load and the original crack length

K_c - critical fracture toughness, evaluated using maximum failure load and the crack length at failure

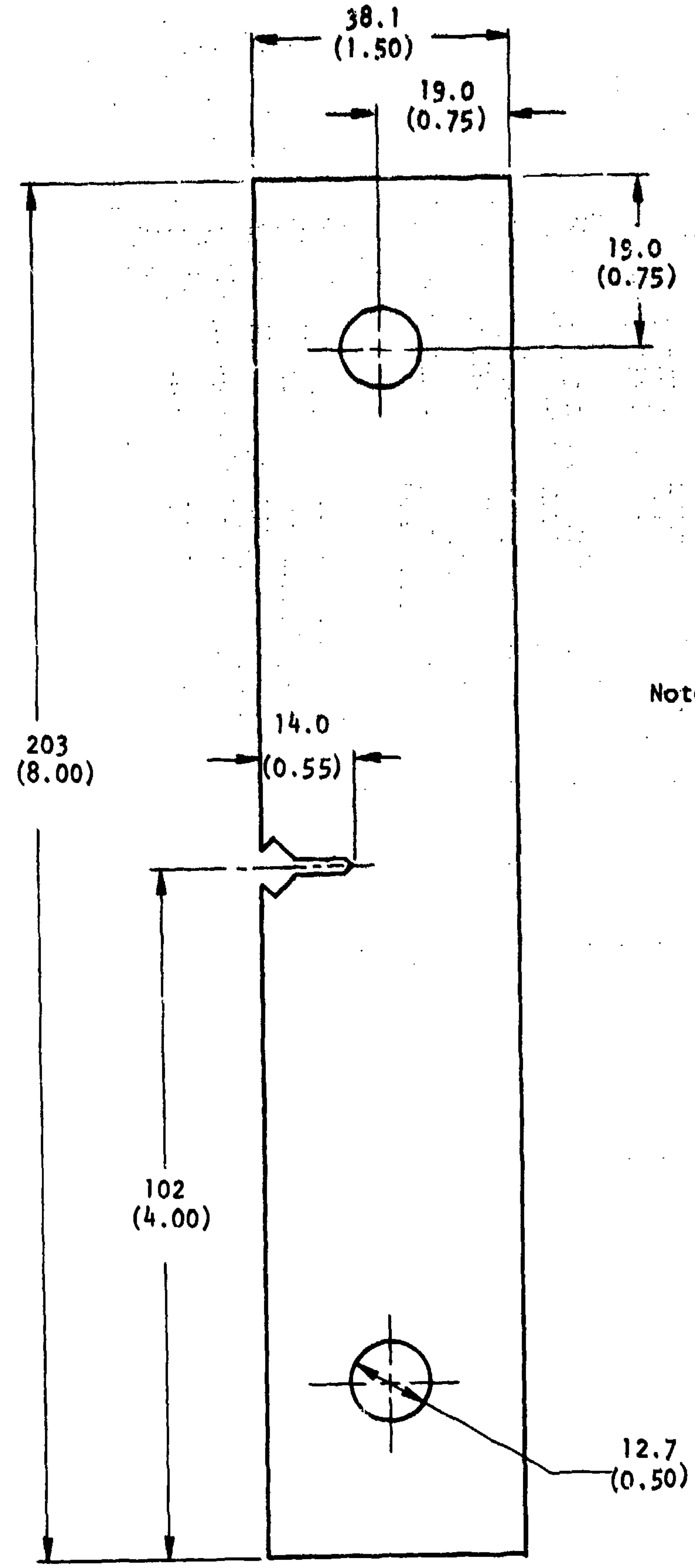


Notes: (1) Knife edges at notch opening are 5.1 mm (0.20 in.) apart.

(2) Notch is chevron shaped at tip and is 1.6 mm (0.063 in.) wide.

(3) a = 22.9 mm (0.90 in.) for fracture toughness test specimens.
a = 10.2 mm (0.40 in.) for fatigue crack propagation test specimens.

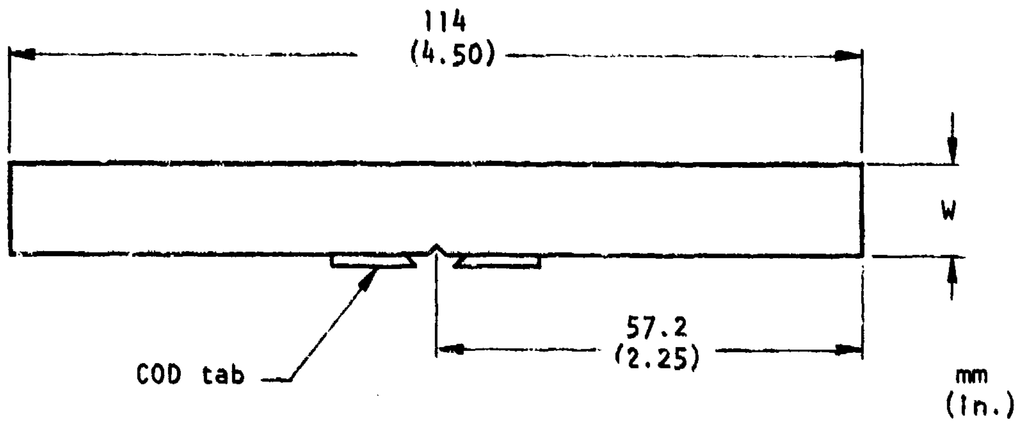
FIGURE 4. COMPACT TENSION FRACTURE SPECIMEN USED FOR FRACTURE TOUGHNESS AND FATIGUE CRACK PROPAGATION TESTING.



Notes: (1) Knife edges at notch opening are 5.1 mm (0.20 in.) apart.

(2) Notch is chevron shaped at tip and is 1.6 mm (0.063 in.) wide.

FIGURE 5. SINGLE-EDGE-NOTCHED FRACTURE SPECIMEN.

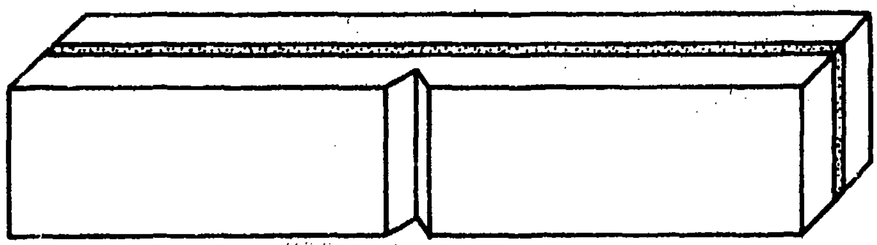


Notes: (1) W = 11.9 mm (0.47 in.), 12.7 mm (0.50 in.), 13.2 mm (0.52 in.) or 13.7 mm (0.54 in.), depending on plate thickness for each material tested.

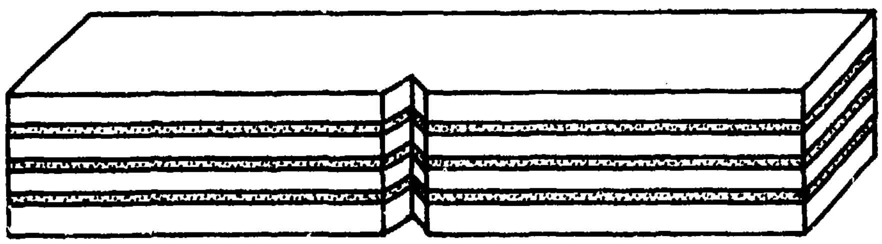
(2) Crack-opening-displacement aluminum tabs were adhesively bonded to fracture toughness specimens. Tabs were 1.6 mm (0.062 in.) thick and were 5.1 mm (0.20 in.) apart.

(3) Notch was 0.8 mm (0.032 in.) wide and 1.3 mm (0.050 in.) deep.

FIGURE 6. THREE POINT BEND FRACTURE SPECIMEN USED FOR FRACTURE TOUGHNESS AND FATIGUE CRACK PROPAGATION TESTING.



(a)



(b)

FIGURE 7. (a) CRACK ARREST AND
(b) CRACK DIVIDER LAMINATE ORIENTATIONS.

Compact Tension Fracture Specimen Stress-Intensity Determinations. Fracture toughness values determined from compact tension specimen tests were calculated using the following relation[22]:

$$K = \frac{P}{BW^{1/2}} \quad f(a/w) \tag{1}$$

where f(a/w) is given by:

$$f\left(\frac{a}{W}\right) = 29.6 \left(\frac{a}{W}\right)^{1/2} - 185.5\left(\frac{a}{W}\right)^{3/2} + 655.7\left(\frac{a}{W}\right)^{5/2} - 1017.0\left(\frac{a}{W}\right)^{7/2} + 638.9\left(\frac{a}{W}\right)^{9/2}$$

and

K - stress-intensity factor

P - load

B - specimen thickness

W - specimen width

a - specimen crack length

Single-Edge-Notched Fracture Specimen Stress-Intensity Determinations. Fracture toughness values determined from SEN specimen tests were evaluated using the following expression[25]:

$$K = \frac{Pa^{1/2}}{BW} \quad f(a/w) \tag{2}$$

where f(a/w) is given by:

$$f(a/W) = 1.99 - 0.41\left(\frac{a}{W}\right) + 18.70\left(\frac{a}{W}\right)^2 - 38.48\left(\frac{a}{W}\right)^3 + 53.85\left(\frac{a}{W}\right)^4$$

and

K - stress-intensity factor

P - load

a - specimen crack length

B - specimen thickness

W - specimen width

Three Point Bend Fracture Specimen Stress-Intensity Determinations. Three point bend specimens used in this investigation had span-to-width ratios, S/W, of approximately 8. Fracture toughness values determined using TPB specimens were evaluated from the following expression[25,26]:

$$K = \frac{6Ma^{1/2}}{BW^2} \quad f(a/W) \tag{3}$$

where f(a/W) is given by:

$$f(a/W) = 1.96 - 2.75\left(\frac{a}{W}\right) + 13.66\left(\frac{a}{W}\right)^2 - 23.98\left(\frac{a}{W}\right)^3 + 25.22\left(\frac{a}{W}\right)^4$$

and

K - stress-intensity factor

M - applied bending moment

a - specimen crack length

B - specimen thickness

W - specimen depth

2.4.3 Fatigue Tests

Fatigue crack propagation tests were performed using the L-T, crack divider orientation compact tension fracture specimen (Figure 4) and the L-S, crack arrest orientation three point bend fracture specimen (Figure 6). These tests were performed in a manner similar to the procedures recommended by the ASTM Task Group E24.04.01 on Fatigue Crack Growth Rate Testing.[27] Tests were conducted on either the CGS or MTS closed-loop testing systems described in Section 2.4.1. These tests were conducted at room temperature at 10 Hz under load control. All tests were run at R = 0.1. Crack lengths were measured using a 40X traveling microscope. A minimum of three specimens were tested for each material to arrive at a final crack growth rate (da/dN) vs. stress-intensity factor range (ΔK) curve. Crack propagation rates were determined using the secant method. Stress-intensity factor ranges for compact tension specimens were determined using the following expression[28,29]:

$$\Delta K = \frac{\Delta P}{BW^{1/2}} \quad f(\alpha) \tag{4}$$

where $f(\alpha)$ is given by:

$$f(\alpha) = \frac{(2 + \alpha)}{(1 - \alpha)^{3/2}} \left(0.866 + 4.64\,\alpha - 13.32\,\alpha^2 + 14.72\,\alpha^3 - 5.60\,\alpha^4 \right)$$

and:

ΔK - stress-intensity factor range

ΔP - $P_{max} - P_{min}$

P_{max} - maximum load

P_{min} - minimum load

α - a/W

a - specimen crack length

W - specimen width

B - specimen thickness

Stress-intensity factor ranges for three point bend specimens were determined using Equation 3, Section 2.4.2.

2.5 FRACTOGRAPHY

The fracture surfaces were examined using an optical metallograph and a Cambridge scanning electron microscope.

3.0 RESULTS AND DISCUSSION

3.1 CHARACTERIZATION OF BASELINE ALUMINUM AND TITANIUM ALLOYS

All primary sheet and monolithic plate alloys used in this investigation were characterized with respect to chemical composition, tensile properties, fracture properties and fatigue properties, so that direct comparisons could be made with properties of the laminated panels. For each of the seven laminates listed in Table 2, corresponding monolithic plate and single layer sheet alloys were tested. For example, diffusion bonded 7475 Al/1100 Al laminates DA1, DA2, and DA3, made from 2.3 mm (0.090 in.) 7475-T761 Al sheet (Lot 108 - 369, Table 2), were compared with the 2.3 mm (0.090 in.) sheet and with 11.9 mm (0.47 in.) 7475-T7651 Al monolithic plate [machined from the 13.2 mm (0.52 in.) thick baseline plate]. The chemical analyses of all the principal aluminum and titanium alloys used in this investigation are given in Tables 3 and 4, respectively.

Tensile Properties. The tensile properties of the baseline 2.3 mm (0.090 in.) 7475-T761 Al and 7075-T76 Al sheet, 12.7 mm (0.500 in.) 7075-T7651 Al plate, and 13.2 mm (0.520 in.) 7475-T7651 Al plate are given in Table 5. These properties were determined using the 50.8 mm (2.00 in.) gage length tensile specimen configuration illustrated in Figure 3.

The tensile properties of the baseline 3.2 mm (0.125 in.) Ti-6Al-4V alloy sheet and 13.7 mm (0.540 in.) Ti-6Al-4V alloy plate are given in Table 6. The tensile properties shown were determined using the 50.8 mm (2.00 in.) gage length tensile specimen illustrated in Figure 3. Two heat treatment conditions were documented for these baseline Ti-6Al-4V materials:

Condition A - mill annealed + 1 hr at 524°C (975°F)

Condition B - mill annealed + 1 hr at 524°C (975°F) + 1 hr at 527°C (980°F), water quench, 18 hr at 160°C (320°F)

These two heat treatment conditions are comparable to those heat treatments given the laminated Ti-6Al-4V/6061 Al DT1 panel. Condition A is the exact thermal treatment given to laminate DT1, since extra sheets of the 3.2 mm (0.125 in.) Ti-6Al-4V were included as baseline material in the diffusion bonding lay-up. Condition B includes a subsequent heat treatment given to some diffusion bonded laminate DT1 material in order to increase the interleaf

TABLE 3. CHEMICAL ANALYSES OF ALUMINUM ALLOYS

ALLOY	NOMINAL THICKNESS mm	(in.)	LOT NUMBER	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
7475 Sheet	2.3	(0.090)	108-369	0.04	0.08	1.37	0.00	2.33	0.22	5.64	0.03	Bal.
7475 Primary Roll Bonded Alloy	2.3	(0.090)	356891	0.05	0.06	1.41	0.00	2.57	0.20	5.63	0.03	Bal.
7475 Plate	13.2	(0.520)	---	0.04	0.06	1.42	0.00	2.34	0.20	5.65	0.03	Bal.
7075 Sheet	2.3	(0.090)	212251	0.09	0.24	1.43	0.05	2.74	0.20	5.71	0.02	Bal.
7075 Primary Roll Bonded Alloy	2.3	(0.090)	356917	0.11	0.24	1.38	0.05	2.47	0.21	5.43	0.05	Bal.
7075 Alclad Sheet (Primary Metal)	2.5	(0.099)	249231	0.09	0.21	1.29	0.03	2.62	0.20	5.64	0.02	Bal.
7075 Plate	12.7	(0.500)	---	0.07	0.24	1.42	0.03	2.44	0.20	5.56	0.04	Bal.

* Chemical analysis given in weight percent.

TABLE 4. CHEMICAL ANALYSES OF Ti-6Al-4V TITANIUM ALLOYS

ALLOY	NOMINAL THICKNESS mm (in.)	HEAT NUMBER	C	Fe	N	Al	V	H	O	Ti
Ti-6Al-4V Titanium Sheet	3.2 (0.125)	N6721	0.022	0.11	0.018	6.4	4.0	0.004	0.14	Bal.
Ti-6Al-4V Titanium Plate	13.7 (0.540)	N4555	0.022	0.16	0.010	6.2	4.2	0.009	0.19	Bal.

* Chemical analysis given in weight percent.

TABLE 5. TENSILE PROPERTIES OF 7475 AND 7075 ALUMINUM SHEET AND PLATE

ALLOY AND TEMPER	NOMINAL THICKNESS mm	(in.)	0.2% YIELD STRENGTH MPa	(ksi)	ULTIMATE STRENGTH MPa	(ksi)	% ELONGATION	% REDUCTION OF AREA
7475-T761	2.3	(0.090)	470	(68.2)	516	(74.9)	13.7	29.2
			467	(67.8)	512	(74.3)	12.9	36.6
			467	(67.8)	513	(74.4)	12.8	26.7
			avg. 468	(67.9)	avg. 514	(74.5)	avg. 13.1	avg. 30.8
7475-T7651	13.2	(0.520)	476	(69.1)	523	(75.8)	16.2	29.8
			471	(68.3)	519	(75.3)	16.4	42.1
			476	(69.1)	523	(75.9)	17.1	41.3
			avg. 474	(68.8)	avg. 522	(75.7)	avg. 16.6	avg. 37.7
7075-T76	2.3	(0.090)	476	(69.1)	536	(77.7)	11.7	20.9
			482	(69.9)	541	(78.4)	12.4	22.3
			478	(69.3)	536	(77.7)	11.9	20.7
			avg. 479	(69.4)	avg. 538	(77.9)	avg. 12.0	avg. 21.3
7075-T7651	12.7	(0.500)	480	(69.6)	531	(77.0)	15.6	35.8
			474	(68.7)	527	(76.4)	14.7	29.8
			479	(69.5)	531	(77.0)	15.0	29.0
			avg. 478	(69.3)	avg. 530	(76.8)	avg. 15.1	avg. 31.5

TABLE 6. TENSILE PROPERTIES OF Ti-6Al-4V TITANIUM ALLOY SHEET AND PLATE

ALLOY	HEAT TREATMENT	NOMINAL THICKNESS mm	(in.)	0.2% YIELD STRENGTH MPa	(ksi)	ULTIMATE STRENGTH MPa	(ksi)	% ELONGATION	% REDUCTION OF AREA
Ti-6Al-4V Sheet	CONDITION A	3.2	(0.125)	951	(138)	986	(143)	14.1	25.2
				938	(136)	979	(142)	14.6	27.3
				931	(135)	972	(141)	14.3	28.2
				avg. 940	(136)	avg. 979	(142)	avg. 14.3	avg. 26.9
Ti-6Al-4V Sheet	CONDITION B	3.2	(0.125)	938	(136)	972	(141)	14.8	24.2
				938	(136)	972	(141)	14.2	27.5
				938	(136)	972	(141)	14.6	26.3
				avg. 938	(136)	avg. 972	(141)	avg. 14.5	avg. 26.0
Ti-6Al-4V Plate	CONDITION A	13.7	(0.540)	945	(137)	965	(140)	21.0	41.3
				945	(137)	979	(142)	21.3	39.0
				958	(139)	986	(143)	20.5	38.2
				avg. 949	(138)	avg. 977	(142)	avg. 20.9	avg. 39.5

* Condition A: mill annealed + 1 hr @ 524°C (975°F).

** Condition B: mill annealed + 1 hr @ 524°C (975°F) + 1 hr @ 527°C (980°F), water quench, 18 hr @ 160°C (320°F).

(6061 Al) strength. Thus, Condition A baseline Ti-6Al-4V material was given the additional thermal processing for more direct comparability to the Condition B processed laminate DTI material. Table 6 gives the tensile properties of the 3.2 mm (0.125 in.) sheet for both Condition A and B. As is evident from these test results the additional thermal processing to the Condition B state had no effect on the tensile properties of the Ti-6Al-4V sheet.

Fracture Toughness Properties. The L-T orientation fracture toughness values of the baseline 2.3 mm (0.090 in.) 7475-T761 Al and 7075-T76 Al sheet, 12.7 mm (0.500 in.) 7075-T7651 Al plate, and 13.2 mm (0.520 in.) 7475-T7651 Al plate are given in Table 7. Fracture tests on the 13.2 mm (0.520 in.) 7475-T7651 Al plate were conducted on specimens with a thickness of 11.9 mm (0.470 in.), so that these specimens would be of the same dimensions as comparable 7475 Al/1100 Al laminate specimens. The 38.1 mm (1.50 in.) wide single-edge-notched specimen (Figure 5) was used for all fracture tests with the exception only of the 11.9 mm (0.470 in.) thick 7475-T7651 Al plate alloy, where additional compact tension (Figure 4) fracture tests were also conducted. Values of conditional fracture toughness (K_Q), apparent fracture toughness (K_{app}), and critical fracture toughness (K_c) have all been tabulated in Table 7.

The fracture values of the sheet alloys given in Table 7 are not directly comparable to most fracture values listed in such references as the Damage Tolerant Design Handbook[23] because of the small width of the specimens used for tests in this investigation. It was necessary to use small specimens in this program due to the limited quantities of laminate panel material available for testing. However, data for the 7475 Al and 7075 Al sheet does seem to compare well with data Wygonik[23] determined for 86.2 mm (3.0 in.) wide fracture specimens. Complete K_Q, K_{app}, and K_c data for the thick 7475 Al and 7075 Al plates were not available for comparison. The results of Table 7 show that 7475 Al possesses significantly higher fracture toughness than 7075 Al, as has been noted previously.[30-32]

Additional testing of the 7475 Al plate material was conducted using CT specimens, since these specimens were used for fatigue crack propagation tests, described in Section 3.4.1. As can be seen from Table 7 no significant differences were noted in the fracture toughness values for the SEN and CT specimen configurations.

TABLE 7. L-T ORIENTATION FRACTURE TOUGHNESS VALUES OF 7475 AND 7075 ALUMINUM SHEET AND PLATE

ALLOY AND TEMPER	NOMINAL THICKNESS		SPECIMEN TYPE	INITIAL CRACK LENGTH		CRITICAL CRACK LENGTH		5% OFFSET LOAD		MAXIMUM LOAD		CONDITIONAL FRACTURE TOUGHNESS, K_Q		APPARENT FRACTURE TOUGHNESS, K_{app}		CRITICAL FRACTURE TOUGHNESS, K_c	
	mm	(in.)		mm	(in.)	mm	(in.)	kN	(kips)	kN	(kips)	$MPa\sqrt{m}$	$(ksi\sqrt{in})$	$MPa\sqrt{m}$	$(ksi\sqrt{in})$	$MPa\sqrt{m}$	$(ksi\sqrt{in})$
7475-T761	2.3	(0.090)	SEN	17.3	(0.681)	19.8	(0.780)	5.87	(1.32)	9.88	(2.22)	38.6	(35.1)	64.8	(59.0)	85.5	(77.8)
				17.3	(0.681)	20.5	(0.806)	5.96	(1.34)	10.1	(2.28)	38.9	(35.4)	66.2	(60.2)	94.2	(85.7)
				16.8	(0.662)	20.0	(0.787)	5.78	(1.30)	10.3	(2.31)	35.9	(32.7)	64.0	(58.2)	90.6	(82.4)
												avg. 37.8	(34.4)	avg. 65.0	(53.1)	avg. 90.1	(82.0)
7475-T7651	11.9	(0.470)	SEN	17.9	(0.706)	18.8	(0.742)	38.3	(8.62)	44.3	(9.97)	52.0	(47.3)	60.1	(54.7)	66.5	(60.5)
				18.0	(0.707)	18.6	(0.732)	38.2	(8.58)	44.9	(10.1)	51.8	(47.1)	61.1	(55.6)	65.6	(59.7)
				18.2	(0.718)	19.3	(0.758)	38.0	(8.54)	42.7	(9.60)	53.3	(48.5)	59.9	(54.5)	66.8	(60.8)
												avg. 52.4	(47.6)	avg. 60.4	(54.3)	avg. 66.3	(60.3)
			CT	27.3	(1.074)	--	(--)	12.2	(2.75)	14.0	(3.15)	50.3	(45.8)	57.6	(52.4)	--	(--)
				26.9	(1.059)	28.2	(1.109)	12.1	(2.73)	14.4	(3.24)	48.5	(44.1)	57.6	(52.4)	62.6	(57.0)
				27.6	(1.087)	29.8	(1.172)	12.0	(2.70)	13.9	(3.13)	49.9	(45.4)	57.9	(52.7)	67.6	(61.5)
												avg. 49.6	(45.1)	avg. 57.7	(52.5)	avg. 65.2	(59.2)
7075-T76	2.3	(0.090)	SEN	17.6	(0.695)	19.5	(0.766)	4.89	(1.10)	7.83	(1.76)	33.3	(30.3)	53.3	(48.5)	65.0	(59.1)
				17.2	(0.677)	19.3	(0.760)	4.72	(1.06)	7.74	(1.74)	30.9	(28.1)	50.7	(46.1)	63.7	(58.0)
				17.0	(0.671)	19.3	(0.760)	4.89	(1.10)	7.47	(1.68)	31.9	(29.0)	48.7	(44.3)	62.3	(56.7)
												avg. 32.0	(29.1)	avg. 50.9	(46.3)	avg. 63.7	(57.9)
7075-T7651	12.7	(0.500)	SEN	18.8	(0.740)	20.9	(0.823)	23.4	(5.27)	24.2	(5.43)	34.2	(31.1)	35.2	(32.0)	44.9	(40.9)
				18.7	(0.738)	20.1	(0.792)	23.7	(5.32)	24.0	(5.39)	34.2	(31.1)	34.6	(31.5)	40.7	(37.0)
				18.4	(0.726)	20.8	(0.819)	24.4	(5.49)	25.3	(5.68)	34.1	(31.0)	35.3	(32.1)	46.4	(42.2)
												avg. 34.2	(31.1)	avg. 35.0	(31.9)	avg. 44.0	(40.0)

*7475-T7651 Al 11.9 mm (0.47 in.) thick specimens were machined from 13.2 mm (0.52 in.) plate.

**SEN - single-edge-notched fracture specimen; CT - compact tension fracture specimen.

The L-T orientation fracture properties of the baseline 3.2 mm (0.125 in.) Ti-6A-4V alloy sheet and 13.7 mm (0.540 in.) Ti-6Al-4V alloy plate are given in Table 8. K_Q, K_{app}, and K_c values were determined for the sheet material in both Condition A and Condition B heat treatments. As would be expected, the additional heat treatment involved in Condition B heat treating (a solution treatment, water quench, and age for the 6061 Al interleaf in the DT1 laminate) had no effect on the Ti-6Al-4V sheet fracture properties. Single-edge-notched fracture specimens were used for all tests except for additional compact tension tests included for the plate material. The CT tests were included because this specimen configuration was selected for fatigue crack propagation testing, described in Section 3.4.1. As was the case for the 7475 Al plate material, no differences in fracture toughness values were noted for tests conducted using either the SEN or CT specimen configurations.

Fatigue Crack Propagation Properties. Fatigue crack propagation tests of 2.3 mm (0.090 in.) 7475-T761 Al sheet, 11.9 mm (0.470 in.) 7475-T7651 Al plate, 3.2 mm (0.125 in.) Ti-6Al-4V alloy sheet, and 13.7 mm (0.540 in.) Ti-6Al-4V alloy plate were conducted using the compact tension specimen (Figure 4) and the three point bend specimen (Figure 6). The results of these tests are discussed in Section 3.4, where direct comparisons are made to similar tests on laminate panels.

3.2 TENSILE PROPERTIES AND MICROSTRUCTURES OF LAMINATE PANELS

3.2.1 Tensile Properties of Laminate Panels

Prior to sectioning and machining for tensile test specimens, each laminate panel was nondestructively inspected for unbonded areas using ultrasonic C-scan. The following observations were made relative to laminates fabricated by the three different lamination processes:

Diffusion Bonded Laminates - It was found that diffusion bonded 7475 Al/1100 Al laminates DA2 and DA3 showed several areas of poor bonding, as shown in Figure 8 for laminate DA2. The other diffusion bonded laminates (7475 Al/ 1100 Al laminate DA1 and Ti-6Al-4V/6061 Al laminate DT1) showed no unbonded areas by C-scan inspection.

Roll Bonded Laminates - These laminates were characterized by surface blisters which appeared after heat treatment. The

TABLE 8. L-T ORIENTATION FRACTURE TOUGHNESS VALUES OF Ti-6Al-4V TITANIUM ALLOY SHEET AND PLATE

ALLOY	NOMINAL THICKNESS mm (in.)	HEAT TREATMENT	SPECIMEN TYPE	INITIAL CRACK LENGTH mm (in.)	CRITICAL CRACK LENGTH mm (in.)	5% OFFSET LOAD kN (kips)	MAXIMUM LOAD kN (kips)	CONDITIONAL FRACTURE TOUGHNESS, K_Q MPa$\sqrt{m}$ (ksi$\sqrt{in}$)	APPARENT FRACTURE TOUGHNESS, K_{app} MPa$\sqrt{m}$ (ksi$\sqrt{in}$)	CRITICAL FRACTURE TOUGHNESS, K_c MPa$\sqrt{m}$ (ksi$\sqrt{in}$)
Ti-6Al-4V Titanium Sheet	3.2 (0.125)	CONDITION A	SEN	19.2 (0.754)	21.6 (0.849)	10.9 (2.45)	16.9 (3.81)	61.2 (55.7)	95.2 (86.6)	-- (--)
				18.0 (0.710)	22.0 (0.867)	12.0 (2.69)	20.3 (4.57)	58.8 (53.5)	99.9 (90.9)	158 (144)
				16.9 (0.664)	21.0 (0.826)	13.6 (3.06)	21.9 (4.92)	59.6 (54.2)	95.8 (87.2)	152 (138)
								avg. 59.9 (54.5)	avg. 97.0 (88.2)	avg. 155 (141)
		CONDITION B	SEN	16.5 (0.648)	20.5 (0.808)	12.8 (2.87)	22.6 (5.09)	53.8 (49.0)	95.6 (87.0)	149 (136)
				16.6 (0.652)	20.6 (0.812)	12.5 (2.82)	22.7 (5.10)	53.8 (49.0)	96.9 (88.2)	152 (138)
				16.7 (0.658)	20.7 (0.816)	12.2 (2.74)	22.2 (5.00)	52.1 (47.4)	95.1 (86.5)	148 (135)
								avg. 53.2 (48.5)	avg. 95.9 (87.2)	avg. 150 (136)
Ti-6Al-4V Titanium Plate	13.7 (0.540)	CONDITION A	SEN	19.8 (0.783)	22.9 (0.903)	29.9 (6.72)	30.8 (6.92)	44.6 (40.6)	45.9 (41.8)	65.7 (59.8)
				18.6 (0.734)	21.7 (0.856)	33.1 (7.43)	34.5 (7.76)	42.4 (38.6)	44.3 (40.3)	63.4 (57.7)
				18.7 (0.737)	21.6 (0.849)	32.2 (7.23)	33.0 (7.42)	41.5 (37.8)	42.6 (38.8)	59.2 (53.9)
								avg. 42.8 (39.0)	avg. 44.3 (40.3)	avg. 62.8 (57.1)
			CT	25.6 (1.008)	30.1 (1.186)	13.3 (3.00)	14.1 (3.17)	42.3 (38.5)	44.6 (40.6)	60.6 (55.1)
				25.5 (1.004)	30.6 (1.204)	13.9 (3.13)	14.8 (3.32)	44.3 (40.3)	46.9 (42.7)	66.4 (60.4)
				25.8 (1.014)	30.0 (1.182)	15.4 (3.46)	16.0 (3.60)	49.2 (44.8)	51.3 (46.7)	68.4 (62.2)
								avg. 45.3 (41.2)	avg. 47.6 (43.3)	avg. 65.1 (59.2)

* Condition A: Mill annealed + 1 hr @ 524°C (975°F).

** Condition B: Mill annealed + 1 hr @ 524°C (975°F) + 1 hr @ 527°C (980°F), water quench, 18 hr @ 160°C (320°F).

*** SEN - single-edge-notched fracture specimen; CT - compact tension fracture specimen.

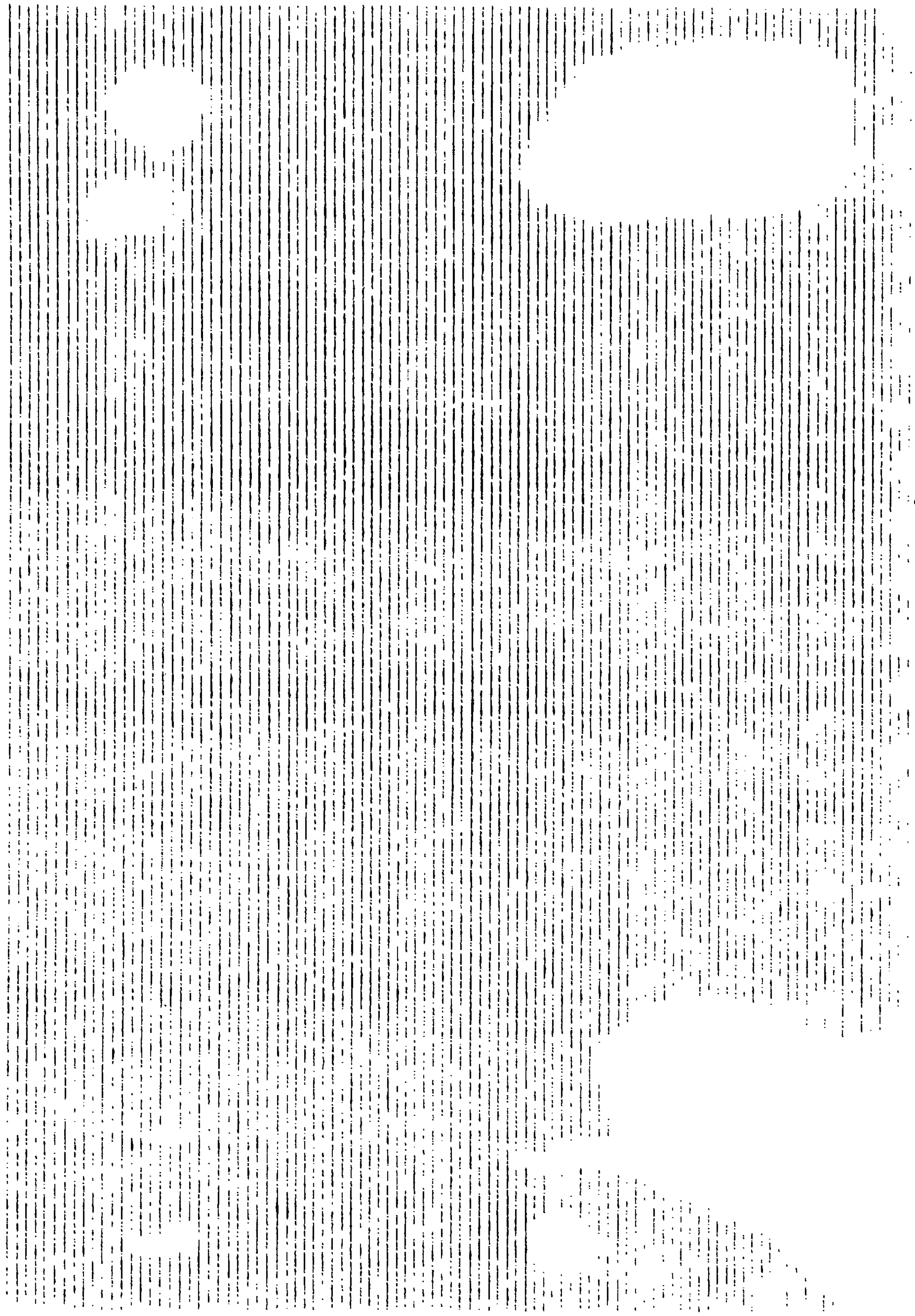


FIGURE 8. ULTRASONIC C-SCAN RECORD FOR A PORTION OF DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DA2 SHOWING UNBONDED AREAS.

blisters were quite numerous over the area of the panels and were easily identified visually. Ultrasonic C-scan (Figure 9) and subsequent metallographic analysis confirmed that the unbonded areas occurred at the outside primary/secondary bondlines.

Explosive Bonded Panel · Ultrasonic C-scan inspection of explosive bonded laminate 7075 Al/7072 Al revealed no unbonded areas.

Tensile Properties of Diffusion Bonded 7475 Al/1100 Al Laminates. The as-received diffusion bonded 7475 Al/1100 Al laminates DA1, DA2, and DA3 were heat treated at Vought Advanced Technology Center to achieve -T7651 tensile properties. These panels were heat treated according to the specifications of Alcoa 467 Process for 7475 Al sheet material. The primary 7475 Al layers comprising laminates DA1, DA2, and DA3 were cut from baseline sheet (Lot 108-369, Table 3) that had been processed to -T761 properties. Consequently, after the laminate bonding process, these primary layers were essentially given a resolution treatment, water quench, and age cycle similar to what they had been subjected to previously, except that the laminate panels were strained approximately 2% after the quench stage to relieve quenching stresses. It was found that approximately 20% of the heat treatment specimen blanks delaminated along 7475 Al/1100 Al interfaces due to the severity of the water quench. This delamination was more prevalent in the laminate blanks with the thinnest 1100 Al interleaf [laminate DA3 with the 0.05 mm (0.002 in.) thick 1100 Al interleaf]. Very few delaminations were noted for laminate DA2, which had the thickest 1100 Al interleaf [0.25 mm (0.010 in.)]. The tensile properties of laminate panels DA1, DA2, and DA3 heat treated in the manner described above are shown in Table 9. All properties shown are typical of 7475 Al processed to the -T7651 condition.

Tensile Properties of Roll Bonded 7475 Al/1100 Al and 7075 Al/7072 Al Laminates. The roll bonded laminates RA1 (7075 Al/7072 Al) and RA4 (7475 Al/1100 Al) were fabricated and heat treated to the -T7651 temper by Alcoa Technical Center. The tensile properties of these laminates are given in Table 10. All properties shown are representative of alloys 7075 and 7475 heat treated to the -T7651 temper.

Tensile Properties of Explosive Bonded 7075 Al/7072 Al Laminate EA1. This laminate was fabricated by Battelle Columbus Laboratories using five layers

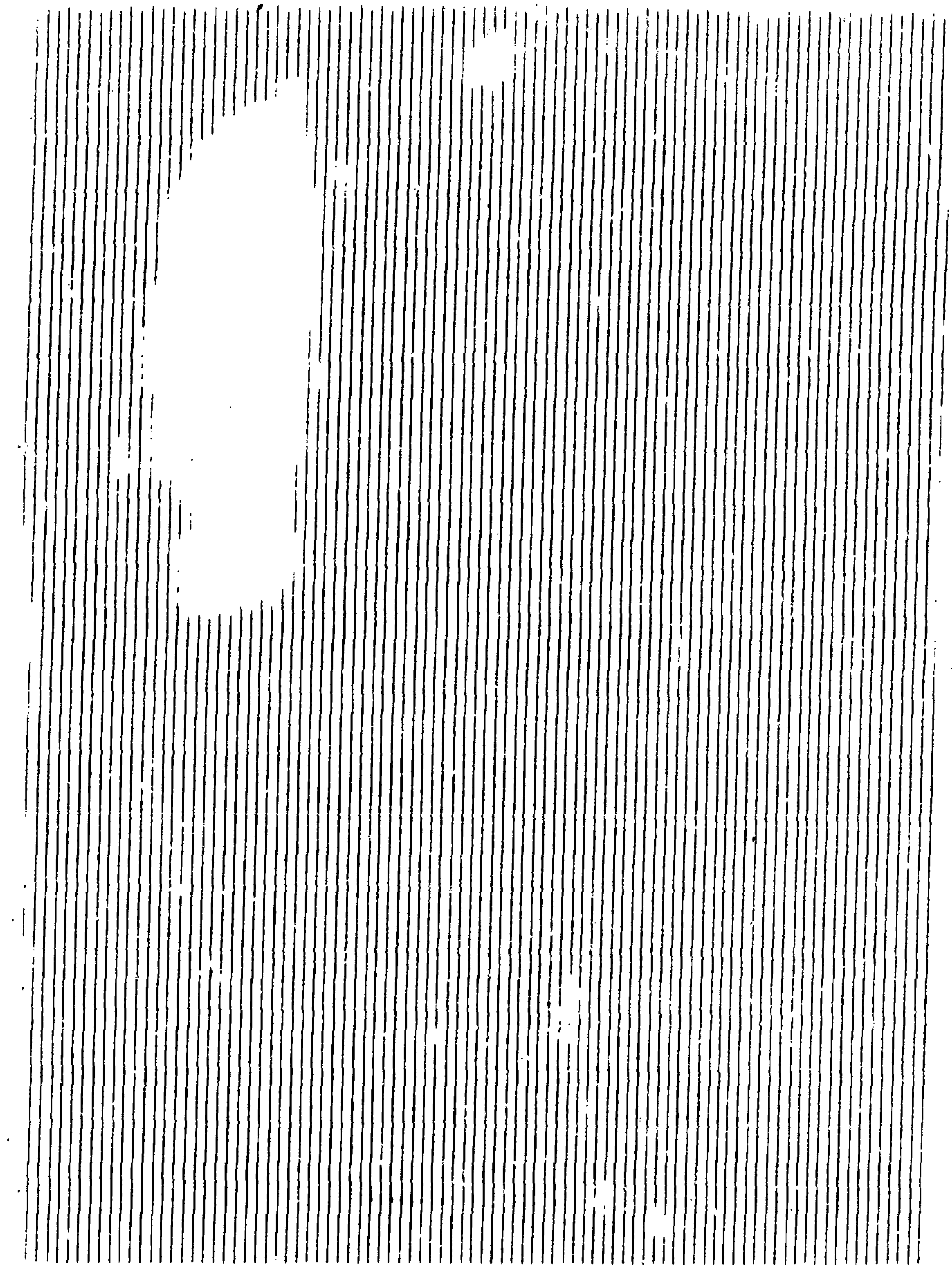


FIGURE 9. ULTRASONIC C-SCAN RECORD FOR A PORTION OF ROLL BONDED 7475 Al/1100 Al RA4. (NOTE THE PRESENCE OF BOTH LARGE AND SMALL SURFACE BLISTERS.)

TABLE 9. TENSILE PROPERTIES OF DIFFUSION BONDED 7475 Al/1100 Al LAMINATE PANELS

LAMINATE PANEL DESIGNATION	SECONDARY ALLOY (1100 Al) LAYER THICKNESS		0.2% YIELD STRENGTH		ULTIMATE STRENGTH		% ELONGATION
	mm	(in.)	MPa	(ksi)	MPa	(ksi)	
DA1	0.13	(0.005)	456	(66.2)	502	(77.8)	12.5
DA2	0.25	(0.010)	441	(64.0)	485	(70.3)	11.8
			444	(64.4)	489	(70.9)	12.0
			441	(64.0)	487	(70.6)	13.5
			avg. 442	(64.1)	avg. 487	(70.6)	avg. 12.4
DA3	0.05	(0.002)	470	(68.2)	518	(75.1)	11.8

*Laminates were heat treated to give -T7651 properties to the primary metal phase (7475 Al).

**Laminate panels were nominally 11.9 mm (0.47 in.) thick.

***Primary alloy (7475 Al) layers were nominally 2.3 mm (0.090 in.) thick.

TABLE 10. TENSILE PROPERTIES OF ROLL BONDED 7475 Al/1100 Al AND 7075 Al/7072 Al LAMINATE PANELS

LAMINATE PANEL DESIGNATION	PRIMARY/ SECONDARY ALLOYS	0.2% YIELD STRENGTH MPa	(ksi)	ULTIMATE STRENGTH MPa	(ksi)	% ELONGATION
RA4	7475 Al/ 1100 Al	454	(65.9)	512	(74.2)	16.0
		465	(67.4)	526	(76.3)	15.4
		462	(67.0)	524	(76.0)	14.9
		avg. 460	(66.8)	avg. 521	(75.5)	avg. 15.4
RA1	7075 Al/ 7072 Al	470	(68.1)	534	(77.4)	12.8
		4	(68.0)	537	(77.9)	13.5
		474	(68.7)	536	(77.8)	13.6
		avg. 471	(68.3)	avg. 536	(77.7)	avg. 13.3

* Laminates were heat treated to give -T7651 properties to the primary metal phase.

** Laminate panels were nominally 11.9 mm (0.47 in.) thick.

*** Primary alloy layers were nominally 2.3 mm (0.090 in.) thick, while secondary alloy layers were nominally 0.13 mm (0.005 in.) thick.

of 2.4 mm (0.099 in.) 7075-T6 Alclad Al sheet. Upon receipt of this material from Battelle samples were tempered according to normal heat treatment specifications for achieving -T76 tensile properties from previously heat treated -T6 sheet. [A recommended temper would be: 16.5 hr at 163°C (325°F)]. It was found that aging in this manner caused extensive overaging in the laminate, with corresponding low strength levels. For example, the yield strength was only 369 MPa (53.5 ksi) instead of the more typical value of 469 MPa (68.0 ksi) for 7075-T7651. Subsequent tempering, microhardness, and tensile evaluations were made on laminate EA1 to establish the appropriate aging time at 163°C (325°F) to achieve -T76 tensile properties. The tensile results of these evaluations are given in Table 11. It was found that an aging time of 2.8 hr was sufficient to obtain -T76 tensile properties in explosive bonded 7075 Al/7072 Al laminate EA1. The extreme amount of energy characteristic o the explosive bonding process sufficiently altered the aging kinetics of the primary 7075 Al alloy to cause the drastically reduced aging time noted in Table 11. All fracture specimens of laminate EA1, described in Section 3.3, were aged at 163°C (325°F) for 2.8 hr.

Tensile Properties of Diffusion Bonded Ti-6Al-4V/6061 Al Laminate DT1. The tensile properties of laminate DT1 were determined under two heat treatment conditions as noted previously in Section 3.1. These conditions were:

Condition A - the as-received laminate panel. This was considered equivalent to Ti-6Al-4V sheet in the mill annealed state given a 1 hr soak at 524°C (975°F).

Condition B - this treatment consisted of as-received laminate DT1 (Condition A) processed as follows: 1 hr at 527°C (980°F), water quenched, 18 hr at 160°C (320°F).

The Condition B treatment was used so that the 6061 Al interleaf strength could be increased to approach the -T6 temper for this alloy. Microhardness readings in the 6061 Al bondlines in laminate DT1 confirmed the Condition B interleaf had a higher strength level. (Condition A 6061 Al had a Knoop microhardness of 61, while Condition B 6061 Al had a Knoop microhardness of 94). The tensile properties of diffusion bonded Ti-6Al-4V/6061 laminate DT1 are given in Table 12. These values are slightly lower than the strength

TABLE 11. TENSILE PROPERTIES OF EXPLOSIVE BONDED 7075 Al/7072 Al LAMINATE EA1 AGED AT 163°C (325°F)

AGING TIME AT 163°C (325°F) hr	0.2% YIELD STRENGTH MPa	(ksi)	ULTIMATE STRENGTH MPa	(ksi)	% ELONGATION
0.0	591	(85.7)	612	(88.8)	11.5
1.0	514	(74.5)	547	(79.4)	14.0
2.0	496	(71.9)	536	(77.7)	14.0
2.8	476	(69.1)	524	(76.0)	13.5
	485	(70.3)	534	(77.4)	15.8
	456	(66.1)	516	(74.8)	15.4
	avg. 472	(68.5)	avg. 525	(76.1)	avg. 14.9
4.0	419	(60.8)	475	(68.9)	13.7
16.5	369	(53.5)	438	(63.5)	15.2

* 25.4 mm (1.0 in.) gage length tensile specimens were used for properties determinations.

** Laminate panel EA1 was nominally 12.4 mm (0.49 in.) thick.

*** Primary alloy (7075 Al) layers were nominally 2.4 mm (0.095 in.) thick, while secondary alloy (7072 Al) layers were nominally 0 13 mm (0.005 in.) thick.

TABLE 12. TENSILE PROPERTIES OF DIFFUSION BONDED Ti-6Al-4V/6061 Al LAMINATE DT1

HEAT TREATMENT	0.2% YIELD STRENGTH MPa	(ksi)	ULTIMATE STRENGTH MPa	(ksi)	% ELONGATION
Condition A	924	(134)	965	(140)	19.3
	924	(134)	965	(140)	18.2
	924	(134)	965	(140)	18.2
	avg. 924	(134)	avg. 965	(140)	avg. 18.6
Condition B	931	(135)	965	(140)	16.4
	924	(134)	965	(140)	16.4
	924	(134)	965	(140)	17.0
	avg. 926	(134)	avg. 965	(140)	avg. 16.6

* Laminate panel DT1 was nominally 13.2 mm (0.52 in.) thick.

** Primary alloy (Ti-6Al-4V) layers were nominally 3.2 mm (0.125 in.) thick, while secondary alloy (6061 Al) layers were nominally 0.10 mm (0.004 in.) thick.

*** Condition A: as received plate [mill annealed + 1 hr @ 524°C (975°F)].

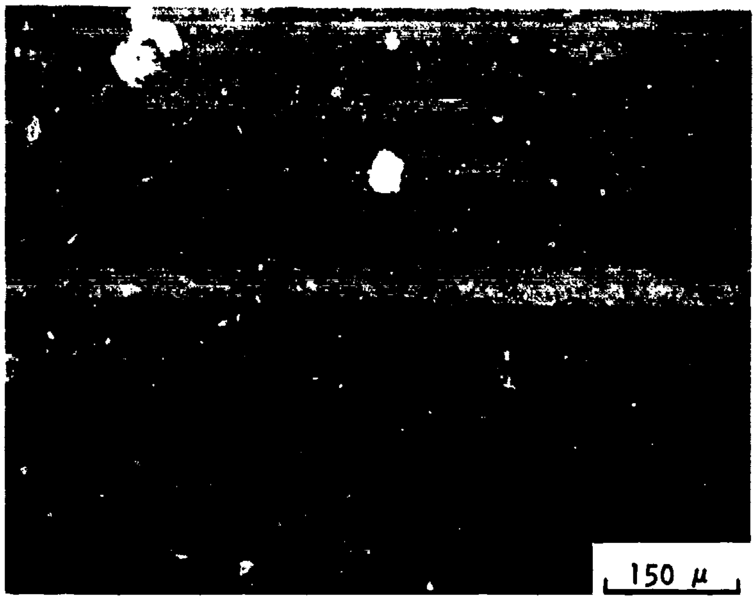
**** Condition B: as received plate [mill annealed + 1 hr @ 524°C (975°F)] + 1 hr @ 527°C (980°F), water quench, 18 hr @ 160°C (320°F).

values noted in Table 6 for the 3.2 mm (0.125 in.) Ti-6Al-4V baseline sheet from which laminate DT1 was made. The difference in values is attributed to the small volume fraction (approximately 2%) of lower strength 6061 Al in laminate DT1. There were no detectable differences in the tensile properties of laminate DT1 in the Condition A or B heat treat state.

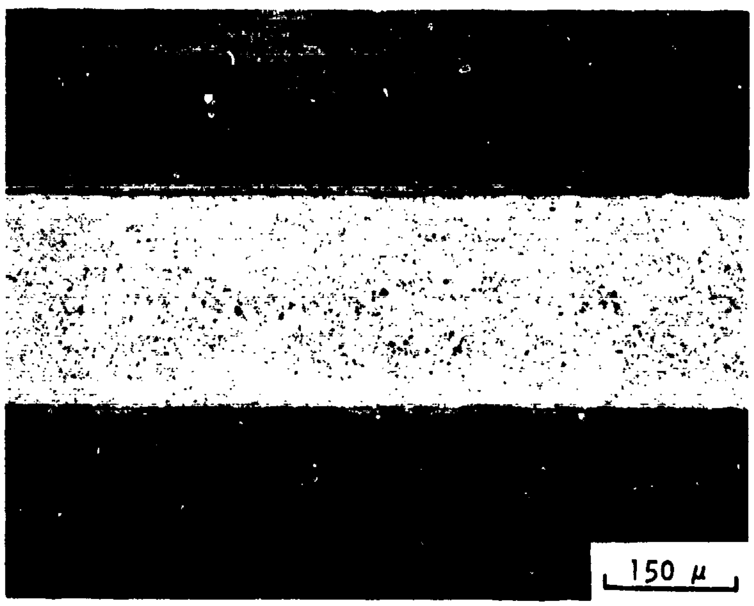
3.2.2 Microstructural Characterization of Laminate Panels

The microstructures of the diffusion bonded, roll bonded, and explosive bonded laminates were evaluated using optical metallography and electron probe microanalysis. Micrographs illustrating the microstructures of all seven laminates are given on the following pages in Figures 10 through 16. The significant features regarding the microstructures of these laminates are discussed in the following paragraphs.

Diffusion Bonded and Roll Bonded Al/Al Laminate Microstructures. In examining the micrographs of diffusion bonded 7475 Al/1100 Al laminates DA3, DA2, and DA1 in Figures 10 and 11, it can be seen that there exists a discontinuous third phase at the 7475 Al/1100 Al interface. Similar observations were found regarding roll bonded 7475 Al/1100 Al laminate RA4 and roll bonded 7075 Al/7072 Al laminate RA1 (Figures 12, 13, and 14). This phase was not definitely identified either by optical metallographic techniques or by electron probe microanalysis; however, it is likely that it is an oxide phase. As will be discussed at more length in Section 3.3, this phase had a direct effect on the failure mechanisms found in these laminates. It has already been noted in Section 3.2.1 that diffusion bonded laminates DA1, DA2, and DA3 all were subject to delamination along the 7475 Al/1100 Al bondlines during water quenching from the solution temperature during heat treatment. These delaminations were observed always to be "adhesive" in nature (i.e., separation always occurred at the original interface between the 7475 Al and the 1100 Al and not within the soft 1100 Al phase). Similar "adhesive" delamination was also noted for the roll bonded laminates RA1 and RA4, which developed surface blisters during heat treatment. Figure 13 shows an example of such "adhesive" delamination at a surface blister in roll bonded 7475 Al/1100 Al laminate RA4. Although the "adhesive" bondline failures noted above have been attributed to the presence of a third phase at the Al/Al interface in these laminates, "adhesive" failure was not the only mode of failure noted for these materials. In fact roll bonded laminates RA1 and RA4 exhibited a

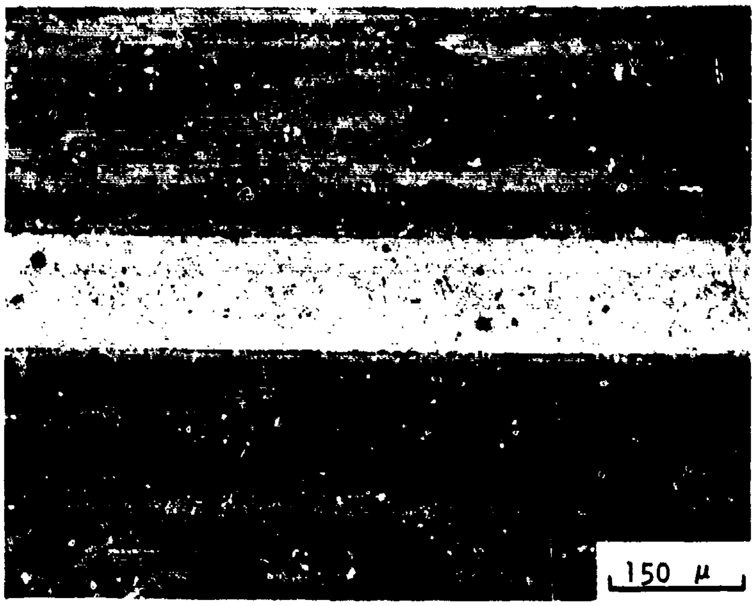


(a)

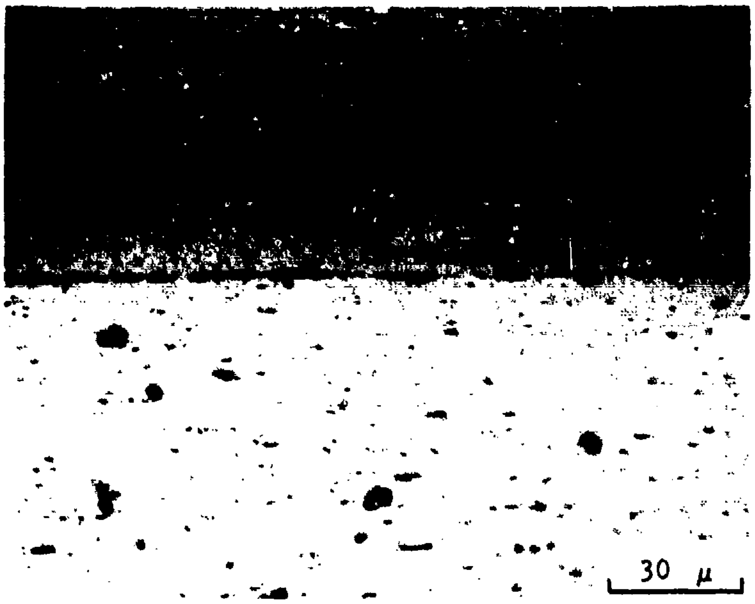


(b)

FIGURE 10. MICROGRAPHS OF DIFFUSION BONDED 7475 Al/1100 Al LAMINATES DA3 AND DA2 SHOWING: (a) 1100 Al INTERLEAF IN LAMINATE DA3; (b) 1100 Al INTERLEAF IN LAMINATE DA2.

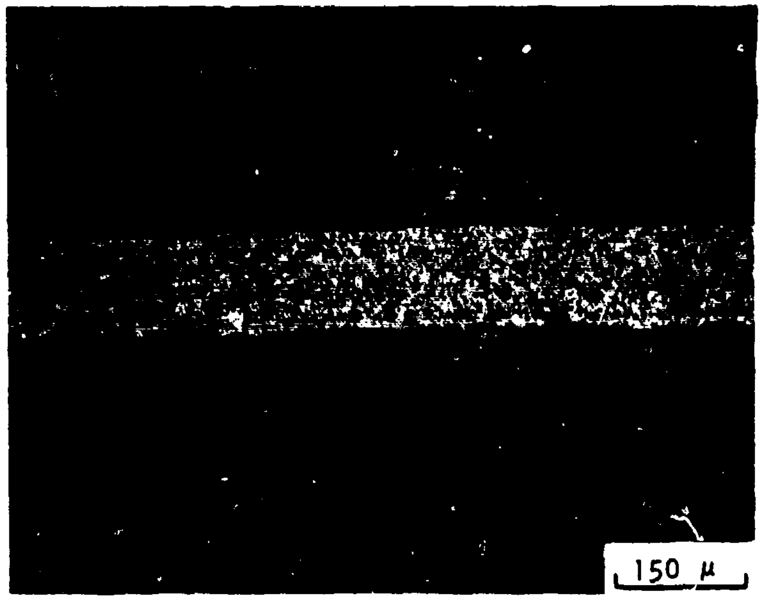


(a)

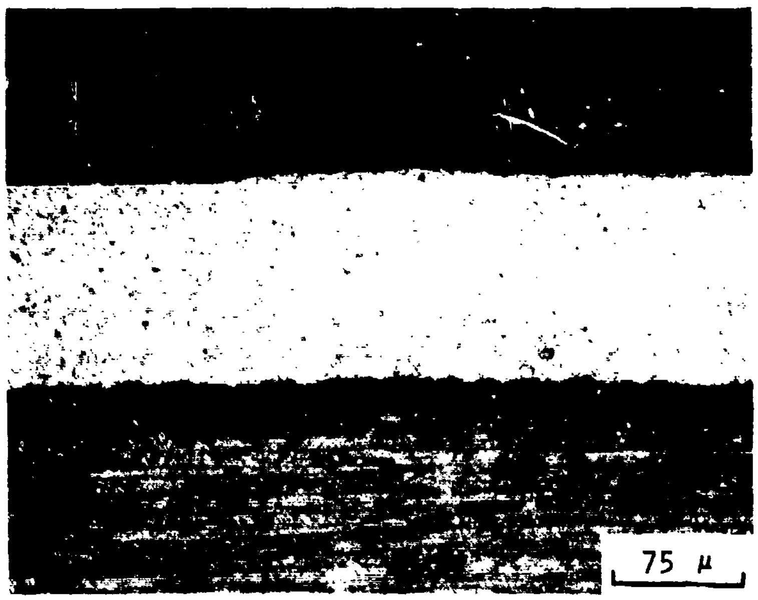


(b)

FIGURE 11. MICROGRAPHS OF DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DA1 SHOWING: (a) 1100 Al INTERLEAF; (b) 7475 Al/1100 Al INTERFACE.

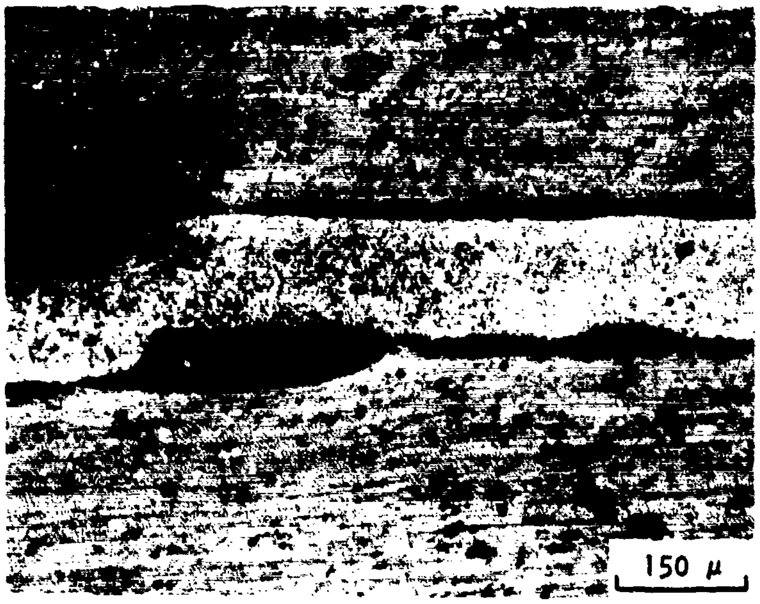


(a)



(b)

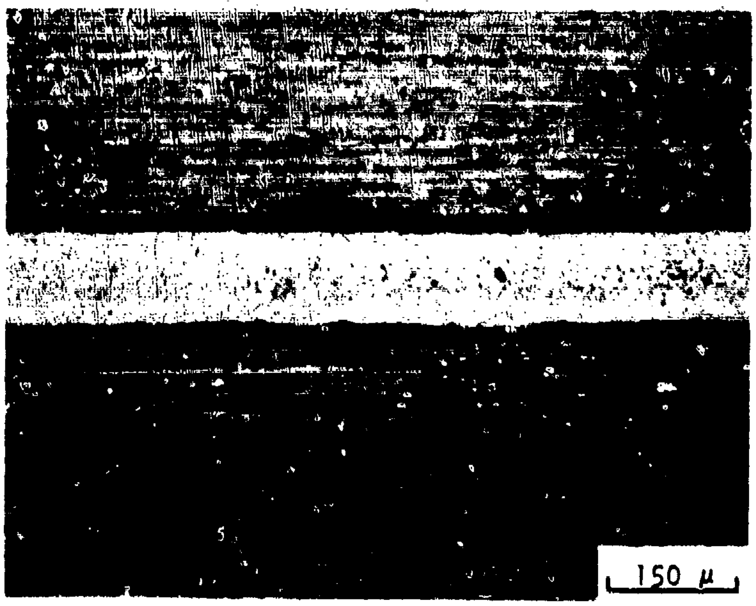
FIGURE 12. MICROGRAPHS OF ROLL BONDED 7475 Al/1100 Al LAMINATE RA4 SHOWING: (a) 1100 Al INTERLEAF; (b) 1100 Al INTERLEAF.



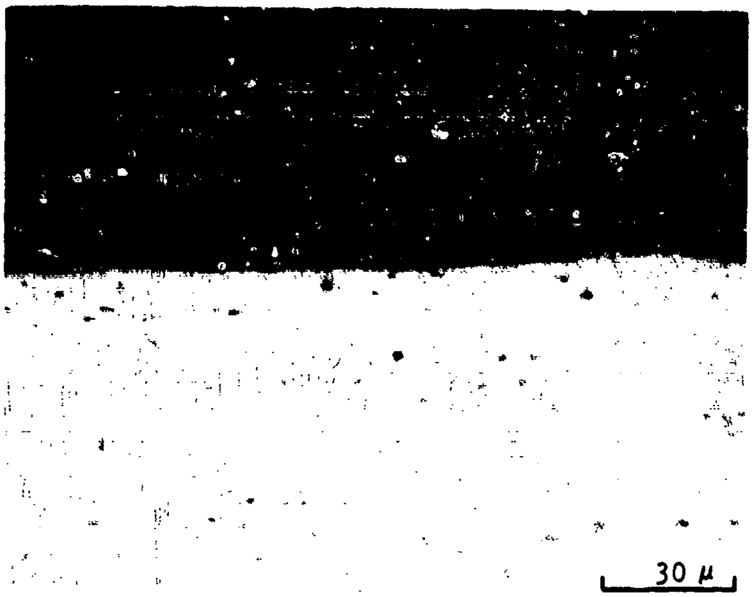
(a)

(b)

FIGURE 13. MICROGRAPHS OF ROLL BONDED 7475 Al/1100 Al LAMINATE RA4 SHOWING: (a) DEBONDED AREAS AT 7475 Al/1100 Al INTERFACES CAUSED DURING HEAT TREATMENT (TOP 7475 Al LAYER IS AN OUTSIDE PANEL LAYER); (b) 7475 Al/1100 Al INTERFACE.

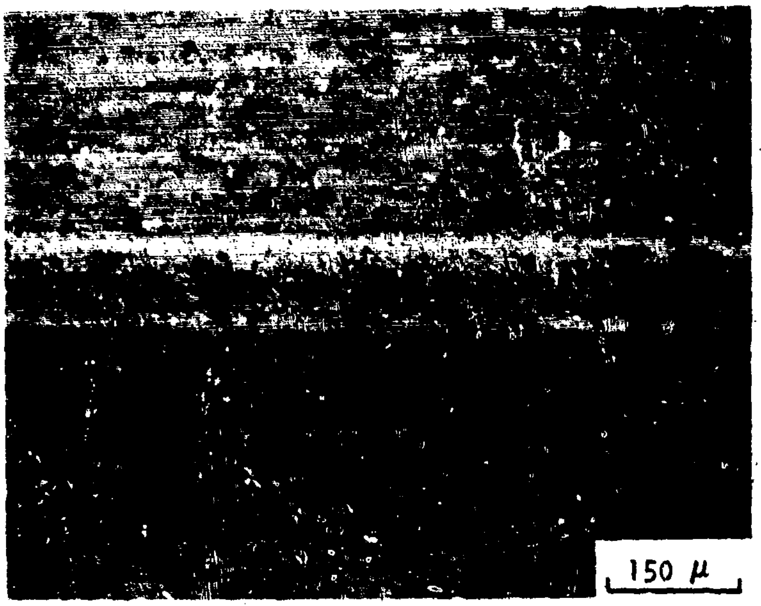


(a)

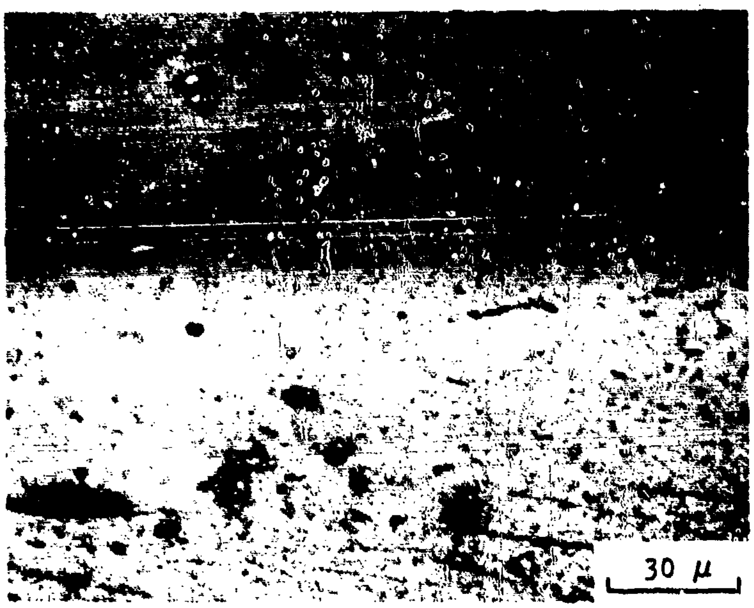


(b)

FIGURE 14. MICROGRAPHS OF ROLL BONDED 7075 Al/7072 Al LAMINATE RA1 SHOWING: (a) 7072 Al INTERLEAF; (b) 7075 Al/7072 Al INTERFACE.



(a)



(b)

FIGURE 15. MICROGRAPHS OF EXPLOSIVE BONDED 7075 Al/7072 Al LAMINATE EA1 SHOWING: (a) 7072 Al INTERLEAF; (b) 7075 Al/7072 Al INTERFACE.

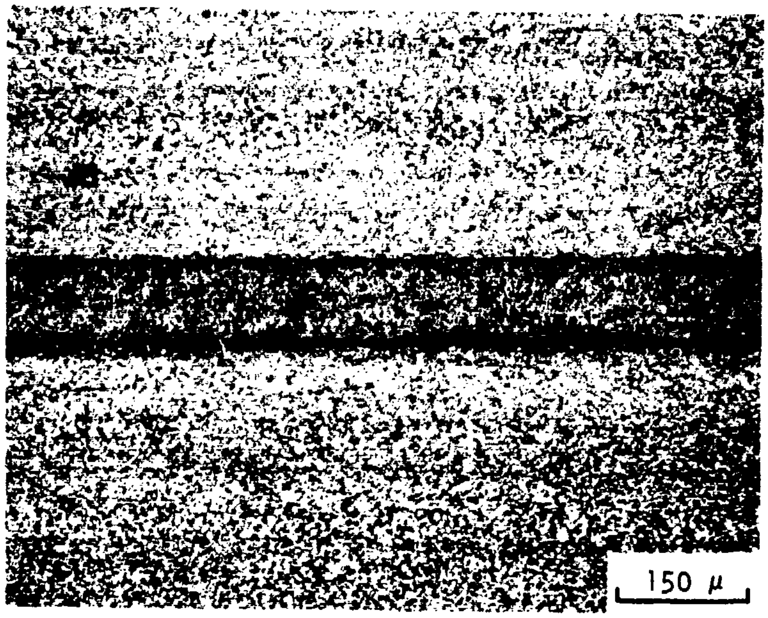


FIGURE 16. MICROGRAPH OF DIFFUSION BONDED Ti-6Al-4V/6061 Al LAMINATE DTi SHOWING 6061 Al INTERLEAF.

significant tendency for "cohesive" failure within the soft 1100 Al or 7072 Al interleaf, as will be discussed at more length in Section 3.3.

Explosive Bonded 7075 Al/7072 Al Laminate EA1 Microstructure. The microstructure of the explosive bonded laminate EA1 was characterized by a remarkably smooth, well bonded interface between the 7075 Al primary alloy and the 7072 Al interleaf alloy, shown in Figure 15. The 7075 Al/7072 interface showed no evidence of waviness that would be characteristic of an over-welded explosively bonded system.

Diffusion Bonded Ti-6Al-4V/6061 Al Laminate DT1 Microstructure. Laminate DT1's microstructure is shown in Figure 16. Close examination of the Ti-6Al-4V/6061 Al interface using optical metallography and electron probe microanalysis revealed no evidence of chemical reaction at the interface.

Electron Probe Microanalysis of Laminate Panels. Electron probe microanalysis was used to evaluate the amount of chemical diffusion across the secondary metal interleaf alloys for all seven laminate configurations studied in this program. Diffusion profiles for the major alloying elements in the primary alloy across the secondary alloy interleafs are shown in Figures 17 through 21 for laminates DA1, RA4, RA1, EA1, and DT1. The diffusion gradients of Zn, Mg, and Cu were determined for the diffusion bonded, roll bonded, and explosive bonded Al/Al laminates, since these are the three principal alloying elements in both 7475 Al and 7072 Al. Figures 17 (DA1), 18 (RA4), 19 (RA1), and 20 (EA1) all illustrate diffusion gradients that show substantial diffusion of Zn, Mg and Cu from the primary alloy (7475 Al or 7075 Al) into the interleaf alloy (1100 Al or 7072 Al). This observation was noted for all the Al/Al laminates, regardless of whether the fabrication process was diffusion bonding, roll bonding, or explosive bonding. It was found, however, that the interleaf thickness significantly affected the diffusion profiles. This is shown in Figure 22 for the diffusion of Zn from the primary 7475 Al into 1100 Al in diffusion bonded laminates DA3, DA1, and DA2. These laminates had 1100 Al interleaf thicknesses of 0.05 mm (0.002 in.), 0.13 mm (0.005 in.), and 0.25 mm (0.010 in.), respectively. As is evident from Figure 22 it is possible that sufficient diffusion had occurred in laminate DA3 (0.05 mm interleaf thickness) to make the interleaf hardenable by precipitation hardening thermal treatments. An increase in strength in the interleaf alloy could cause the laminate to fail

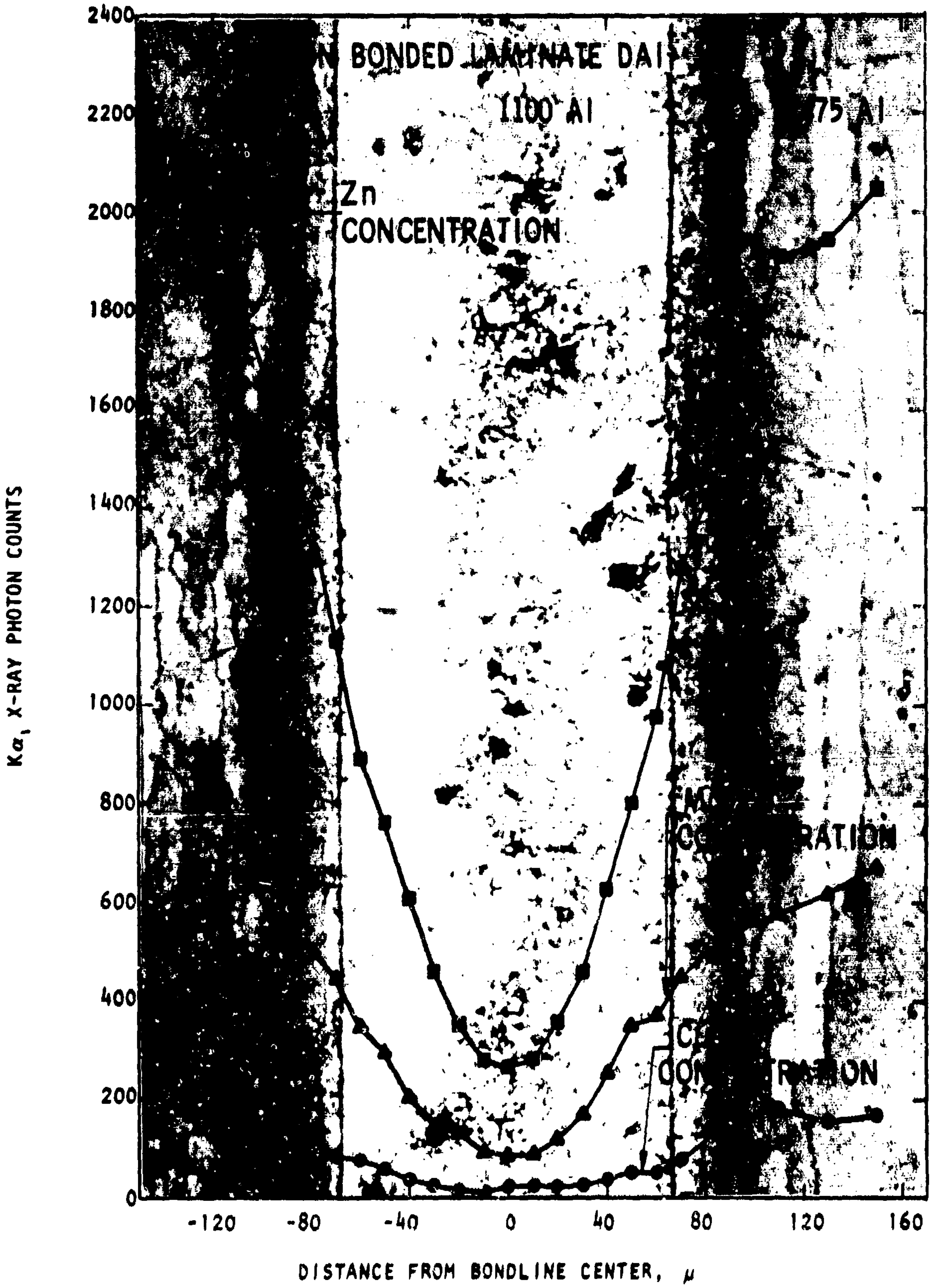


FIGURE 17. Zn, Mg, AND Cu DIFFUSION PROFILES ACROSS 0.13 mm (0.005 in.) 1100 Al INTERLEAF IN DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DA1 (HEAT TREATED TO -T7651 TEMPER).

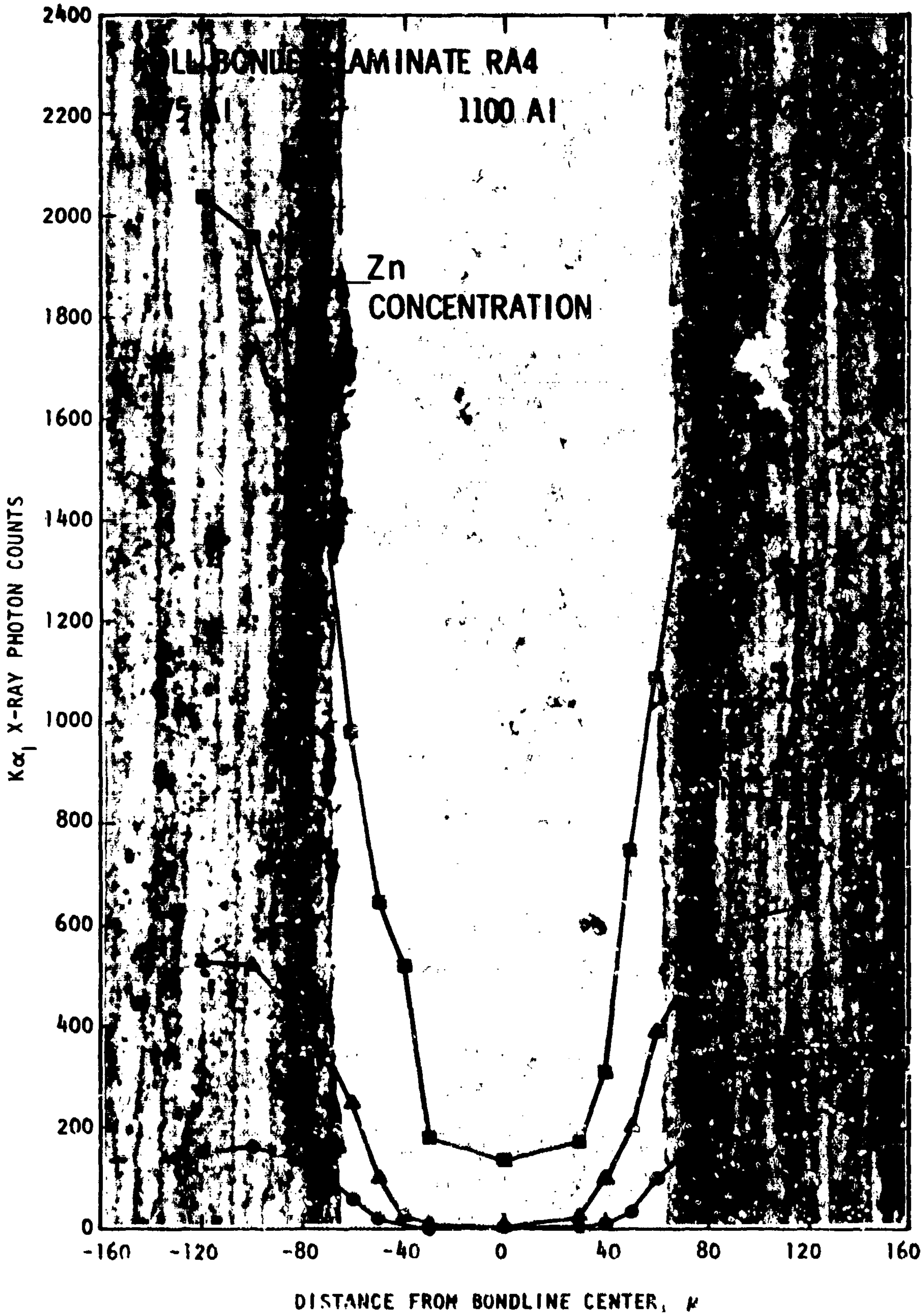


FIGURE 18. Zn, Mg, AND Cu DIFFUSION PROFILES ACROSS 0.13 mm (0.005 IN.) 1100 Al INTERLEAF IN ROLL BONDED 7475 Al/1100 Al LAMINATE RA4 (HEAT TREATED TO -T7651 TEMPER).

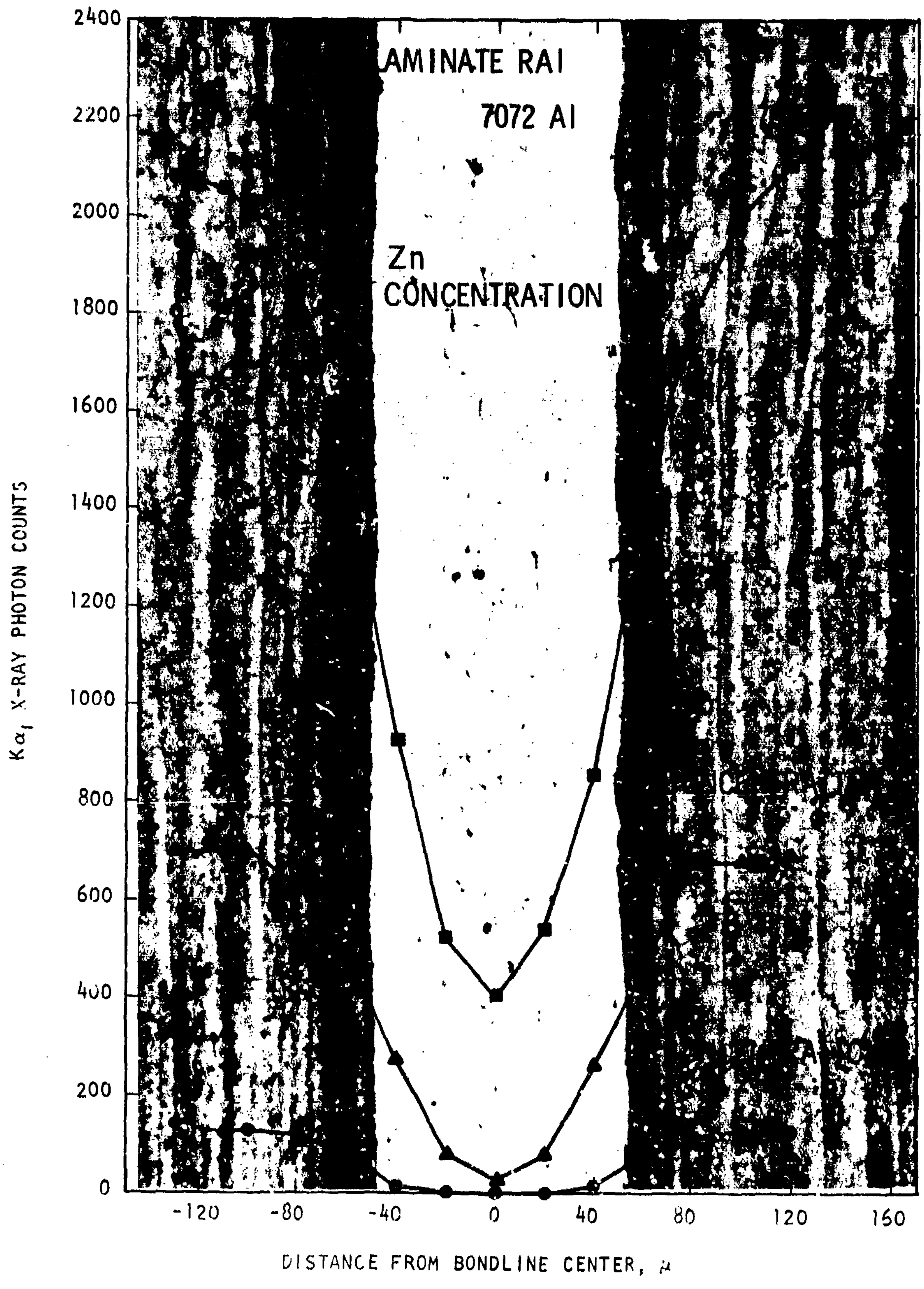


FIGURE 19. Zn, Mg, AND Cu DIFFUSION PROFILES ACROSS 0.13 mm (0.005 in.) 7072 Al INTERLEAF IN ROLL BONDED 7075 Al/7072 Al LAMINATE RA1 (HEAT TREATED TO -T7651 TEMPER).

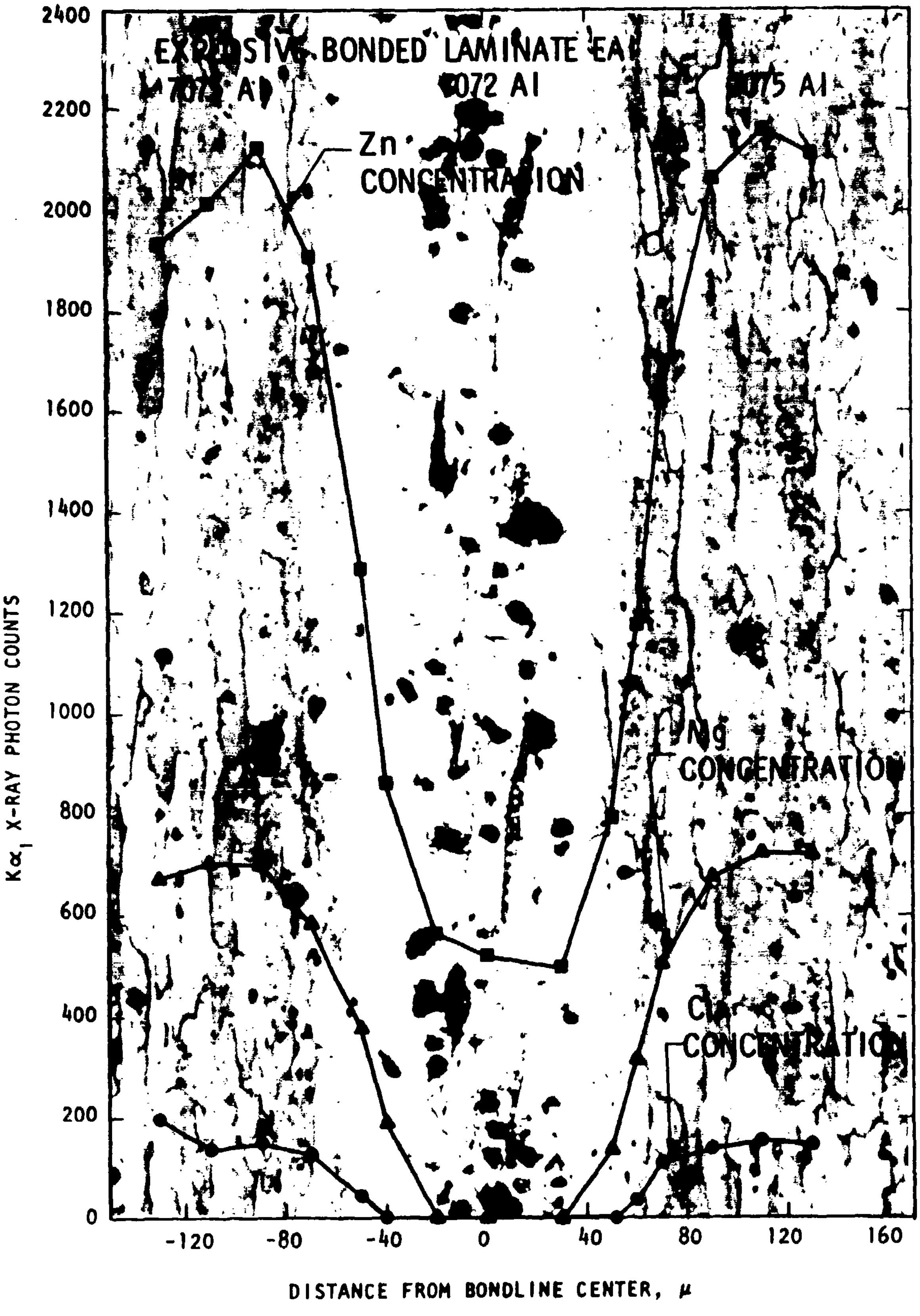


FIGURE 20. Zn, Mg, AND Cu DIFFUSION PROFILES ACROSS 0.13 mm (0.005 in.) 7072 Al INTERLEAF IN EXPLOSIVE BONDED 7075 Al/7072 Al LAMINATE EA1 (HEAT TREATED TO HAVE -T7651 TENSILE PROPERTIES).

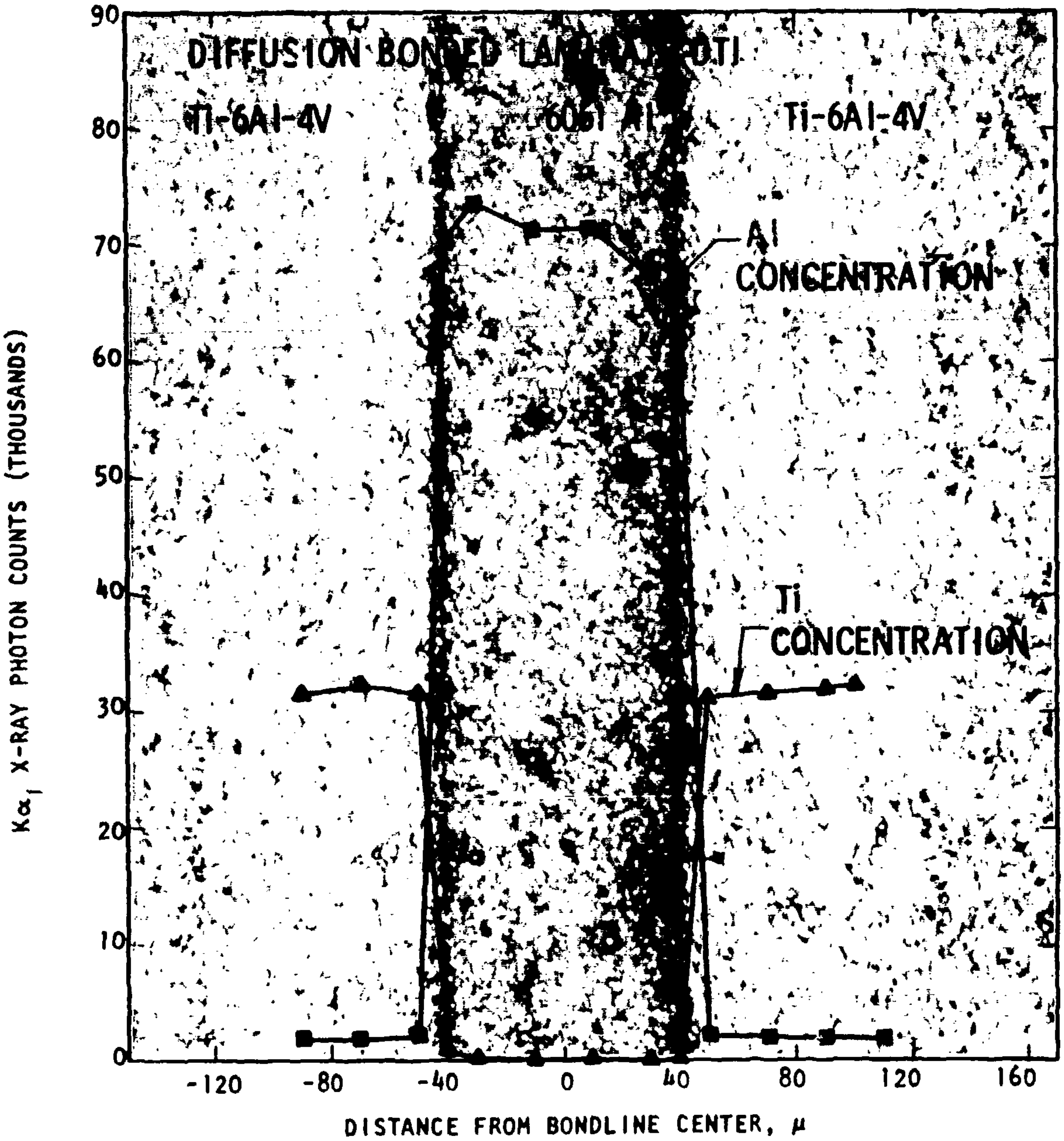


FIGURE 21. Al AND Ti DIFFUSION PROFILES ACROSS 0.10 mm (0.004 in.) 6061 Al INTERLEAF IN DIFFUSION BONDED Ti-6Al-4V/6061 Al LAMINATE DT1, HEAT TREATMENT (CONDITION A): AS RECEIVED [MILL ANNEALED + 1 HR AT 524°C (975°F)].

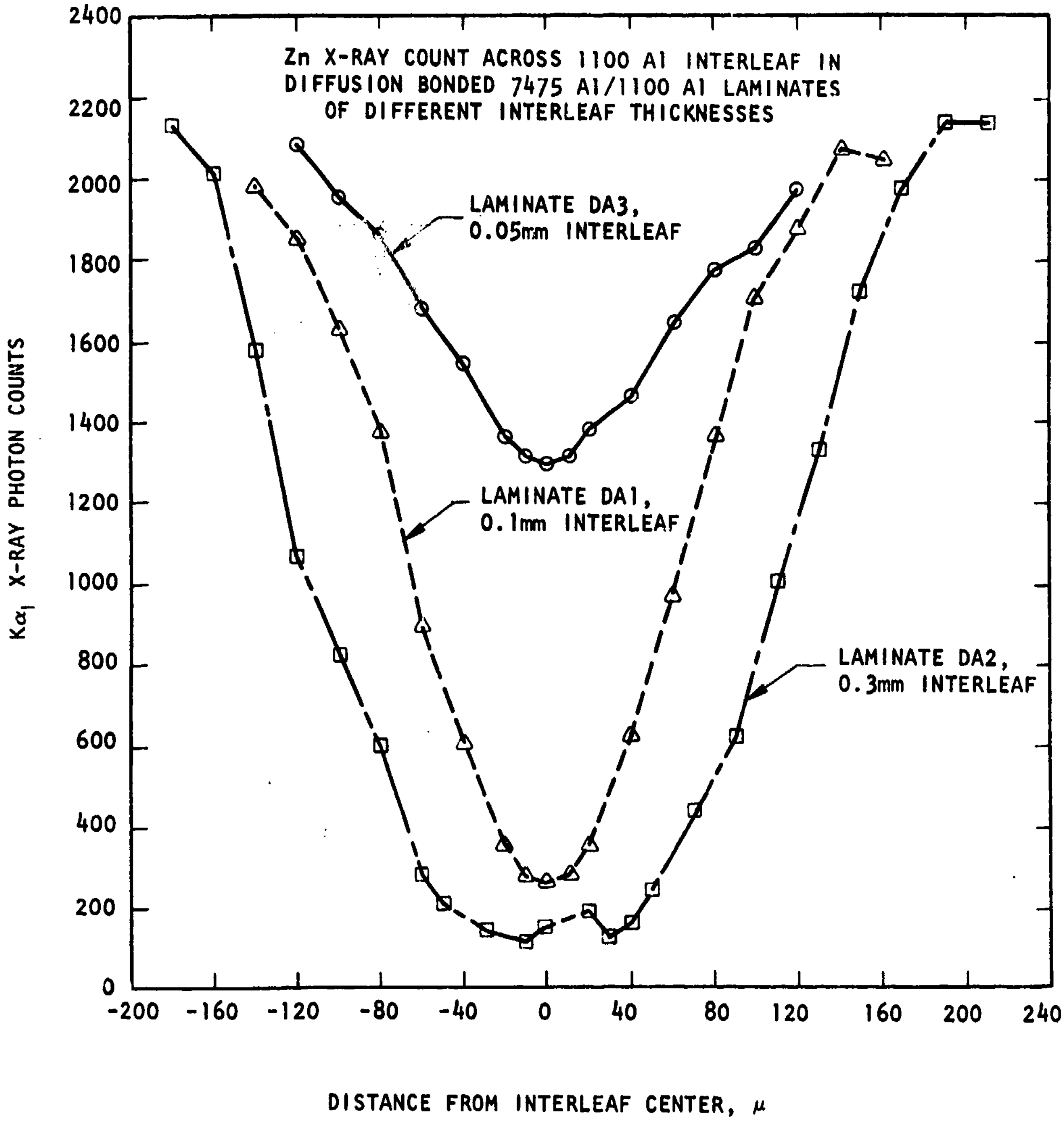


FIGURE 22. COMPARISON OF Zn DIFFUSION PROFILES ACROSS 1100 Al INTERLEAVES OF DIFFERENT THICKNESSES IN 7475 Al/1100 Al DIFFUSION BONDED LAMINATES DA1, DA2, AND DA3 (HEAT TREATED TO -T7651 TEMPER).

as a monolithic material rather than as separate layers as is required to achieve higher crack divider fracture toughness. Thus, the 0.05 mm interleaf was deemed too thin for use in diffusion bonded Al/Al laminates that must be subjected to precipitation hardening.

In comparing the diffusion gradients of laminates processed by the three different techniques, it was found that the diffusion profiles across the secondary alloy interleaves were very similar. Direct comparisons alloy-to-alloy for a given interleaf thickness (0.13 mm) for diffusion bonding vs. roll bonding and roll bonding vs. explosive bonding are shown in Figures 23 and 24. It was anticipated that the diffusion bonding and roll bonding fabrication techniques would yield microstructures having similar diffusion gradients; however, the similar behavior of explosive bonded laminate EA1 is somewhat unexpected, since this laminate was heated to only 160°C (320°F) during aging to achieve -T76 tensile properties. The microanalysis results shown in Figures 20 and 24 clearly show that extensive diffusion of Zn, Mg, and Cu occurred in laminate EA1 due to the 160°C (320°F) aging treatment.

3.3 FRACTURE PROPERTIES OF LAMINATE PANELS

3.3.1 Fracture of Crack Divider Metal/Metal Laminates

Diffusion Bonded and Roll Bonded 7475 Al/1100 Al Laminate Fracture Results. The fracture toughness values of diffusion bonded 7475 Al/1100 Al laminates DA1, DA2, and DA3 are given in Table 13. Fracture results on roll bonded 7475 Al/1100 Al laminate RA4 are given in Table 14. These fracture results were all determined on laminate material heat treated to the -T7651 primary alloy temper. All tests were conducted with the single-edge-notched specimen configuration (Figure 5), with the exception only of additional compact tension tests for laminates DA1 and RA4. These tests were included to evaluate specimen geometry effects, since the compact tension specimen was selected for use in fatigue crack propagation testing described in Section 3.4.1. It is evident from comparing SEN and CT fracture results for DA1 and RA4, no significant differences in fracture properties were noted for tests completed with these two specimen types.

The results illustrated in Tables 13 and 14 show that all laminate panels had remarkably improved critical fracture toughness (K_c)

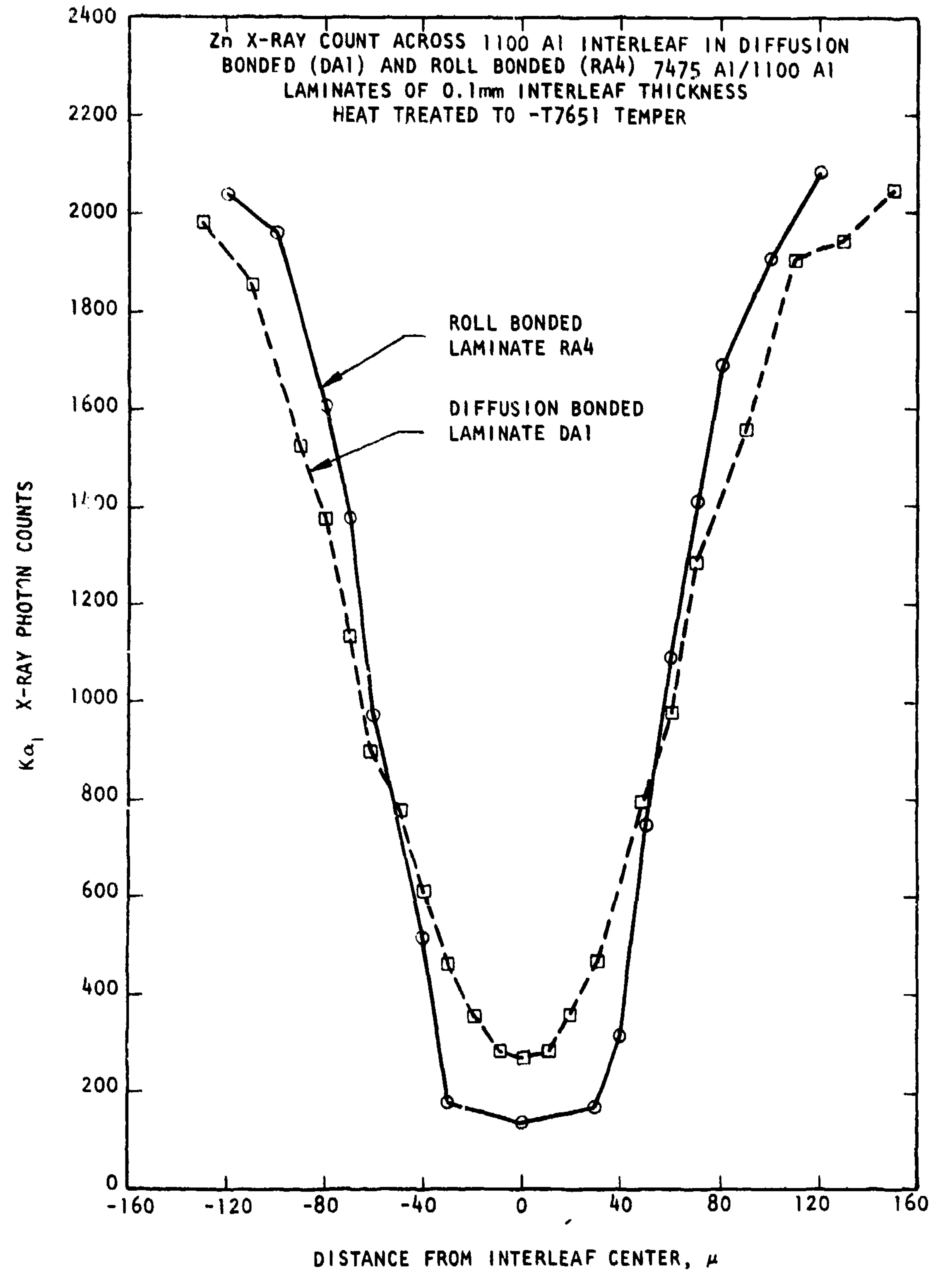


FIGURE 23. COMPARISON OF Zn DIFFUSION PROFILES ACROSS 1100 Al INTERLEAVES FOR 7475 Al/1100 Al ROLL BONDED AND DIFFUSION BONDED LAMINATES RA4 AND DA1.

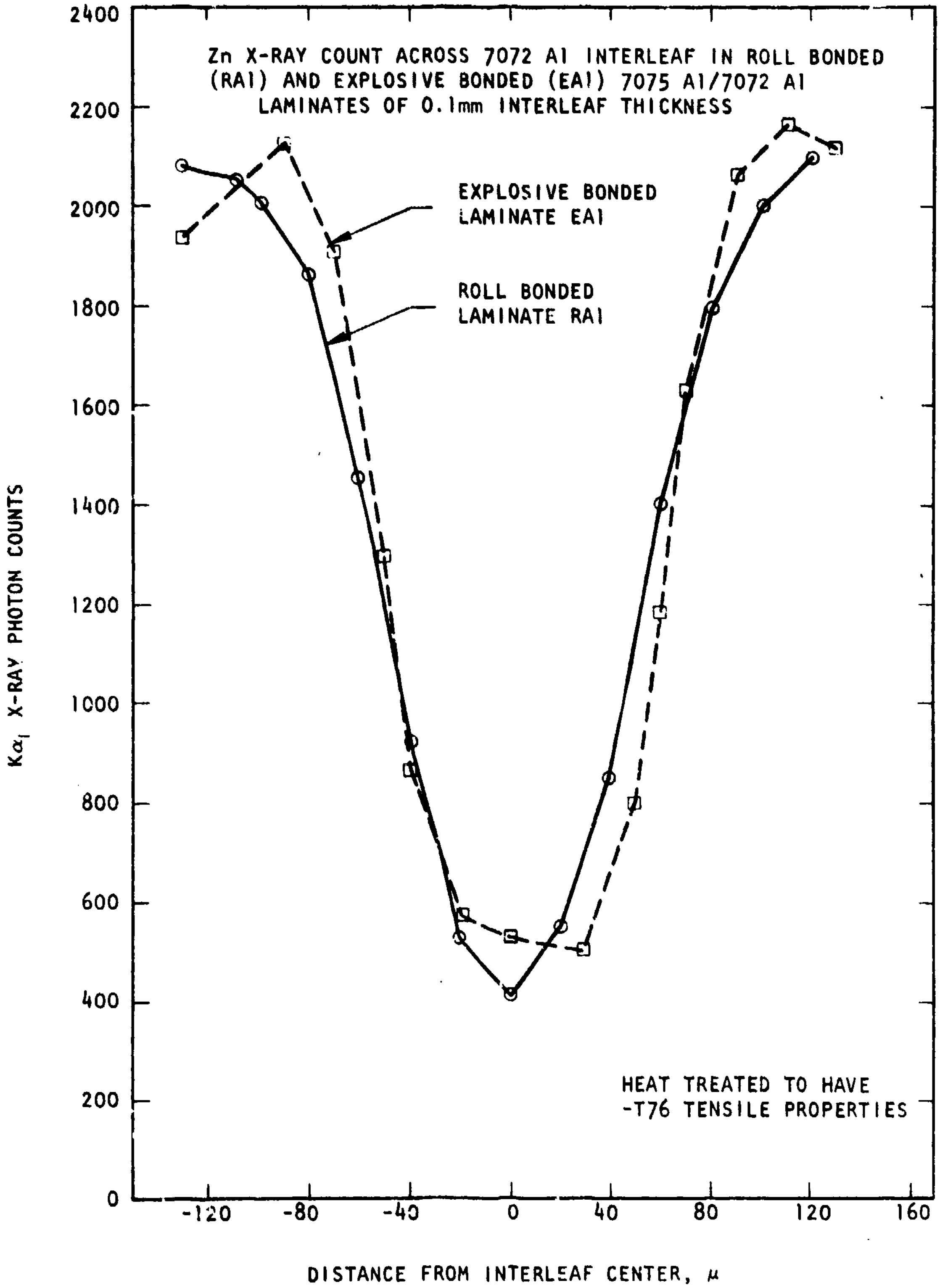


FIGURE 24. COMPARISON OF Zn DIFFUSION PROFILES ACROSS 7072 Al INTERLEAVES FOR 7075 Al/7072 Al ROLL BONDED AND EXPLOSIVE BONDED LAMINATES RAl and EAl.

TABLE 13. CRACK DIVIDER, L-T ORIENTATION FRACTURE TOUGHNESS VALUES OF DIFFUSION BONDED 7475 Al/1100 Al LAMINATE PANELS

LAMINATE PANEL DESIGNATION	SECONDARY ALLOY (1100 Al) THICKNESS		SPECIMEN TYPE	INITIAL CRACK LENGTH		CRITICAL CRACK LENGTH		5% OFFSET LOAD		MAXIMUM LOAD		CONDITIONAL FRACTURE TOUGHNESS, K_Q		APPARENT FRACTURE TOUGHNESS, K_{app}		CRITICAL FRACTURE TOUGHNESS, K_c	
	mm	(in.)		mm	(in.)	mm	(in.)	kN	(kips)	kN	(kips)	$MPa\sqrt{m}$	$(ksi\sqrt{in})$	$MPa\sqrt{m}$	$(ksi\sqrt{in})$	$MPa\sqrt{m}$	$(ksi\sqrt{in})$
DA1	0.13	(0.005)	SEN	11.8	(0.466)	15.4	(0.608)	45.8	(10.3)	71.2	(16.0)	41.3	(37.6)	64.4	(58.6)	97.8	(89.0)
				16.8	(0.662)	20.9	(0.823)	30.8	(6.93)	55.2	(12.4)	37.5	(34.1)	67.1	(61.1)	105.7	(96.2)
				16.8	(0.661)	20.7	(0.814)	32.3	(7.27)	56.9	(12.8)	39.2	(35.7)	69.2	(63.0)	106.4	(96.9)
												avg. 39.3	(35.8)	avg. 66.9	(60.9)	avg. 103.3	(94.0)
			CT	25.9	(1.020)	30.6	(1.204)	10.8	(2.42)	18.7	(4.20)	41.3	(37.6)	71.7	(65.2)	98.8	(89.9)
				25.9	(1.018)	30.3	(1.194)	10.9	(2.46)	19.3	(4.35)	41.8	(38.0)	73.9	(67.2)	100.1	(91.1)
				26.3	(1.034)	30.8	(1.214)	11.2	(2.52)	18.7	(4.20)	44.0	(40.0)	73.2	(66.6)	100.8	(91.7)
				25.9	(1.018)	30.7	(1.208)	10.4	(2.33)	18.6	(4.18)	39.6	(36.0)	71.1	(64.7)	99.1	(90.2)
												avg. 41.7	(37.9)	avg. 72.5	(65.9)	avg. 99.7	(90.7)
DA2	0.25	(0.010)	SEN	17.4	(0.686)	20.9	(0.822)	30.6	(6.89)	46.7	(10.5)	41.5	(37.8)	63.3	(57.6)	92.9	(84.5)
				17.2	(0.679)	21.1	(0.832)	29.0	(6.52)	48.9	(11.0)	38.8	(35.3)	65.6	(59.7)	101.4	(92.3)
				18.0	(0.707)	21.9	(0.862)	27.7	(6.23)	48.5	(10.9)	38.0	(34.6)	66.4	(60.4)	103.7	(94.4)
												avg. 39.4	(35.9)	avg. 65.1	(59.2)	avg. 99.3	(90.4)
DA3	0.05	(0.002)	SEN	16.9	(0.666)	20.5	(0.808)	31.1	(7.00)	53.8	(12.1)	40.1	(36.5)	69.6	(63.3)	103.5	(94.2)

* Laminates were heat treated to give -T7651 properties to the primary metal phase (7475 Al).

** Laminate panels were nominally 11.9 mm (0.47 in.) thick.

*** Primary alloy (7475 Al) layers were nominally 2.3 mm (0.090 in.) thick.

**** SEN - single-edge-notched fracture specimen, CT - compact tension fracture specimen.

TABLE 14. CRACK DIVIDER, L-T ORIENTATION FRACTURE TOUGHNESS VALUES OF ROLL BONDED 7475 Al/1100 Al AND 7075 Al/7072 Al LAMINATE PANELS

LAMINATE PANEL DESIGNATION	PRIMARY/ SECONDARY ALLOYS	SPECIMEN TYPE	INITIAL CRACK LENGTH mm	(in.)	CRITICAL CRACK LENGTH mm	(in.)	5% OFFSET LOAD kN	(kips)	MAXIMUM LOAD kN	(kips)	CONDITIONAL FRACTURE TOUGHNESS $MPa\sqrt{m}$	$(ksi\sqrt{in.})$	APPARENT FRACTURE TOUGHNESS $MPa\sqrt{m}$	$(ksi\sqrt{in.})$	CRITICAL FRACTURE TOUGHNESS $MPa\sqrt{m}$	$(ksi\sqrt{in.})$
RA4	7475 Al/ 1100 Al	SEN	17.9	(0.706)	20.9	(0.822)	31.6	(7.10)	46.7	(10.5)	43.0	(39.1)	63.5	(57.8)	88.4	(80.4)
			18.7	(0.735)	21.3	(0.840)	30.2	(6.78)	44.2	(9.94)	44.3	(40.3)	65.0	(59.1)	88.1	(80.2)
			18.6	(0.732)	21.3	(0.837)	30.7	(6.90)	44.5	(10.0)	44.8	(40.8)	65.0	(59.1)	88.0	(80.1)
											avg. 44.0	(40.1)	avg. 64.5	(58.7)	avg. 88.2	(80.2)
		CT	27.1	(1.065)	30.2	(1.189)	12.0	(2.69)	18.1	(4.06)	47.9	(43.6)	72.3	(65.8)	89.9	(81.8)
			27.1	(1.065)	29.9	(1.178)	12.2	(2.74)	18.2	(4.10)	47.9	(43.6)	71.5	(65.1)	88.7	(80.7)
			26.9	(1.061)	30.3	(1.194)	11.7	(2.62)	17.3	(3.90)	51.3	(46.7)	76.4	(69.5)	100.1	(91.1)
											avg. 49.0	(44.6)	avg. 73.4	(66.8)	avg. 92.9	(84.5)
RA1	7075 Al/ 7072 Al	SEN	18.2	(0.718)	20.2	(0.796)	24.2	(5.44)	32.4	(7.28)	33.7	(30.7)	45.2	(41.1)	56.5	(51.4)
			18.1	(0.712)	20.0	(0.788)	24.6	(5.54)	33.9	(7.61)	33.8	(30.8)	46.5	(42.3)	57.5	(52.3)
			18.1	(0.712)	20.6	(0.810)	24.2	(5.44)	35.3	(7.94)	33.2	(30.2)	48.5	(44.1)	64.1	(58.3)
											avg. 33.6	(30.6)	avg. 46.7	(42.5)	avg. 59.4	(54.0)

* Laminates were heat treated to give -T7651 properties to the primary metal phase.

** Laminate panels were nominally 11.9 mm (0.47 in.) thick.

*** Primary alloy layers were nominally 2.3 mm (0.090 in.) thick, while secondary alloy layers were nominally 0.13 mm (0.005 in.) thick.

**** SEN - single-edge-notched fracture specimen; CT - compact tension fracture specimen.

values above the corresponding monolithic 7475-T7651 values listed earlier in Table 7 of Section 3.1. (Critical fracture toughness is considered the most representative measure of toughness improvement in these laminate materials, since they do not approach plane strain fracture behavior. This same conclusion has been reached by previous investigators[3,7], who used K_c as the most representative measure of toughness in crack divider laminates). Table 15 shows comparative average K_c values for single layer 7475-T761 Al, monolithic 7475-T7651 Al plate, and diffusion bonded and roll bonded 7475 Al/1100 Al laminates. Several observations can be made from the comparisons given in Table 15:

(1) The diffusion bonded 7475 Al/1100 Al laminates DA1, DA2 and DA3 had essentially the same fracture toughness, regardless of the secondary alloy interleaf thickness.

(2) The diffusion bonded laminates possessed significantly higher K_c values than monolithic 7475 Al of the same thickness. This improvement in K_c ranged from 50% to 56%.

(3) The single layer 7475 Al sheet toughness was retained in all diffusion bonded laminates. The K_c values of these laminates were even slightly higher than the average K_c value for the single layer sheet from which these laminates were composed.

(4) The roll bonded 7475 Al/1100 Al laminate RA4 showed a significantly higher (33%) average K_c value over monolithic 7475 Al of the same thickness.

(5) The single layer 7475 Al sheet toughness was retained in roll bonded laminate RA4. The average K_c value of the laminate was essentially the same as the average K_c value for 7475 Al single layer sheet of the same thickness as the primary 7475 layers in the laminate.

<u>Roll Bonded and Explosive 7075 Al/7072 Al Laminate Fracture Results.</u> The fracture toughness values for roll bonded and diffusion bonded 7075 Al/7072 Al laminates RA1 and EA1 are given in Table 14 and 16. These fracture results were determined on laminate material heat treated to have -T76 tensile properties. All tests were conducted using the SEN specimen. As was

TABLE 15. COMPARISON OF AVERAGE CRITICAL FRACTURE TOUGHNESS VALUES (CRACK DIVIDER, L-T ORIENTATION) FOR 7475-T761 Al SHEET, MONOLITHIC 7475-T7651 Al PLATE, AND DIFFUSION BONDED AND ROLL BONDED 7475 Al/1100 Al LAMINATE PANELS

MATERIAL	NOMINAL THICKNESS mm	(in.)	1100 Al INTERLEAF THICKNESS mm	(in.)	CRITICAL FRACTURE TOUGHNESS, K_c MPa$\sqrt{m}$	(ksi$\sqrt{in}$)	% RETENTION OF SINGLE LAYER SHEET TOUGHNESS	% INCREASE ABOVE MONOLITHIC PLATE TOUGHNESS
Single Layer 7475-T761 Al Sheet	2.3	(0.090)	---		90.1	(82.0)	---	---
Monolithic 7475-T7651 Al Plate	11.9	(0.47)	---		66.3	(60.3)	---	---
Diffusion Bonded 7475 Al/1100 Al Laminates	11.9	(0.47)	0.05	(0.002)	103.5	(94.2)	115%	56%
			0.13	(0.005)	103.3	(94.0)	115%	56%
			0.25	(0.010)	99.3	(90.4)	110%	50%
Roll Bonded 7475 Al/1100 Al Laminate	11.9	(0.47)	0.13	(0.005)	88.2	(80.2)	98%	33%

*K_c values determined using single-edge-notched fracture specimens.

**Laminate panels heat treated to -T7651 temper.

TABLE 16. CRACK DIVIDER, L-T ORIENTATION FRACTURE TOUGHNESS VALUES OF EXPLOSIVE BONDED 7075 Al/7072 Al LAMINATE EA1 AGED AT 163°F (325°F) FOR 2.8 HOURS

LAMINATE PANEL DESIGNATION	PRIMARY/ SECONDARY ALLOYS	SPECIMEN TYPE	INITIAL CRACK LENGTH mm (in.)	CRITICAL CRACK LENGTH mm (in.)	5% OFFSET LOAD kN (kips)	MAXIMUM LOAD kN (kips)	CONDITIONAL FRACTURE TOUGHNESS MPa$\sqrt{m}$ (ksi$\sqrt{in}$)	APPARENT FRACTURE TOUGHNESS MPa$\sqrt{m}$ (ksi$\sqrt{in}$)	CRITICAL FRACTURE TOUGHNESS MPa$\sqrt{m}$ (ksi$\sqrt{in}$)
EA1	7075 Al/ 7072 Al	SEN	17.9 (0.705) 17.9 (0.704) 18.1 (0.712)	20.5 (0.807) 20.9 (0.821) 20.8 (0.820)	27.7 (6.22) 27.2 (6.12) 26.8 (6.03)	37.1 (8.34) 38.8 (8.72) 35.5 (7.98)	35.9 (32.7) 35.1 (31.3) 35.1 (31.9)	48.0 (43.7) 50.0 (45.5) 46.4 (42.2)	64.3 (58.5) 69.9 (63.6) 63.3 (57.6)
							avg. 35.4 (32.2)	avg. 48.1 (43.8)	avg. 65.8 (59.9)

* Laminate panel EA1 was nominally 12.4 mm (0.49 in.) thick.

** Primary alloy (7075 Al) layers were nominally 2.4 mm (0.095 in.) thick, while secondary alloy (7072 Al) layers were nominally 0.13 mm (0.005 in.) thick.

*** SEN - single-edge-notched fracture specimen.

the case for the diffusion bonded and roll bonded 7475 Al/1100 Al laminates, the roll bonded and explosive bonded 7075 Al/7072 Al laminates possessed significantly higher K_c values than corresponding monolithic 7075-T7651 Al of the same thickness. Also, the single layer 7075 Al sheet toughness was completely retained in the 7075 Al/7072 Al laminates. Comparative K_c values for single layer 7075-T76 Al sheet, monolithic 7075-T7651 Al plate, and roll bonded and explosive bonded 7075 Al/7072 Al laminates RA1 and EA1 are given in Table 17. Observations similar to those made earlier for the 7475 Al/1100 Al laminates can be made for the 7075 Al/7072 Al laminates based on Table 17:

(1) The roll bonded 7075 Al/7072 Al laminate RA1 showed a significant improvement in K_c over monolithic 7075 Al of the same thickness.

(2) The single layer 7075 Al sheet toughness was retained in the roll bonded laminate. The average K_c value of the laminate was only 7% lower than the average K_c value for 7075 Al single layer sheet of approximately the same thickness as the primary 7075 layers in the laminate.

(3) The explosive bonded laminate EA1 possessed a K_c value that was 50% higher than monolithic 7075 Al of the same thickness.

(4) The single layer 7075 Al sheet toughness was retained in the explosive bonded laminate. The laminate had an average K_c value that was 3% higher than that for single layer 7075 Al sheet of approximately the same thickness as the primary 7075 Al layers in the laminate.

Diffusion Bonded Ti-6Al-4V/6061 Al Laminate DT1 Fracture Results. The fracture toughness values of diffusion bonded Ti-6Al-4V/6061 Al laminate DT1 are given in Table 18. The fracture results were determined on laminate specimens heat treated to the two states discussed in Section 3.1 and 3.2: Condition A (as-received) and Condition B (to give higher strength to the 6061 Al interleaf). All tests were conducted using the single-edge-notched fracture specimen. Although there was a slight difference in fracture values between Condition A and Condition B heat treat states, this difference did not seem to be of significance, especially when compared to the Condition A

TABLE 17. COMPARISON OF AVERAGE CRITICAL FRACTURE TOUGHNESS VALUES (CRACK DIVIDER, L-T ORIENTATION) FOR 7075-T76 Al SHEET, MONOLITHIC 7075-T7651 Al PLATE, AND ROLL BONDED AND EXPLOSIVE BONDED 7075 Al/7072 Al LAMINATE PANELS

MATERIAL	NOMINAL THICKNESS		7072 Al INTERLEAF THICKNESS		CRITICAL FRACTURE TOUGHNESS, K_c		% RETENTION OF SINGLE LAYER SHEET TOUGHNESS	% INCREASE ABOVE MONOLITHIC PLATE TOUGHNESS
	mm	(in.)	mm	(in.)	$MPa\sqrt{m}$	$(ksi\sqrt{in})$		
Single Layer 7075-T76 Al Sheet	2.3	(0.090)	---		63.7	(57.9)	---	---
Monolithic 7075-T7651 Al Plate	12.7	(0.50)	---		44.0	(40.0)	---	---
Rolled Bonded 7075 Al/7072 Al Laminate	11.9	(0.47)	0.13	(0.005)	59.4	(54.0)	93%	35%
Explosive Bonded 7075 Al/7072 Al Laminate	12.4	(0.49)	0.13	(0.005)	65.8	(59.9)	103%	50%

* K_c values determined using single-edge-notched fracture specimens.

** Laminate panels heat treated to -T7651 and -T76 tempers for roll bonded and explosive bonded panels, respectively.

TABLE 18. CRACK DIVIDER, L-T ORIENTATION FRACTURE TOUGHNESS VALUES OF DIFFUSION BONDED Ti-6Al-4V/6061 Al LAMINATE DT1

HEAT TREATMENT	INITIAL CRACK LENGTH		CRITICAL CRACK LENGTH		5% OFFSET LOAD		MAXIMUM LOAD		CONDITIONAL FRACTURE TOUGHNESS, K_Q		APPARENT FRACTURE TOUGHNESS, K_{app}		CRITICAL FRACTURE TOUGHNESS, K_c	
	mm	(in.)	mm	(in.)	kN	(kips)	kN	(kips)	MPa$\sqrt{m}$	(ksi$\sqrt{in.}$)	MPa$\sqrt{m}$	(ksi$\sqrt{in.}$)	MPa$\sqrt{m}$	(ksi$\sqrt{in.}$)
Condition A	21.9	(0.864)	24.5	(0.965)	38.9	(8.74)	47.6	(10.7)	74.5	(67.8)	90.9	(82.7)	124	(113)
	19.2	(0.754)	22.7	(0.895)	45.4	(10.2)	69.4	(15.6)	62.9	(57.2)	95.4	(87.7)	146	(133)
	18.7	(0.735)	22.8	(0.897)	42.9	(9.64)	65.8	(14.8)	56.5	(51.4)	86.4	(78.6)	140	(127)
									avg. 64.6	(58.8)	avg. 91.2	(83.0)	avg. 137	(124)
Condition B	17.1	(0.674)	21.4	(0.841)	49.4	(11.1)	84.1	(18.9)	54.1	(49.2)	92.1	(83.8)	148	(135)
	20.2	(0.797)	22.7	(0.893)	40.4	(9.08)	72.5	(16.3)	62.5	(56.9)	112	(102)	149	(136)
	20.2	(0.795)	23.7	(0.934)	35.8	(8.04)	59.2	(13.3)	55.7	(50.7)	92.2	(83.9)	141	(128)
									avg. 57.4	(52.3)	avg. 98.2	(89.9)	avg. 146	(133)

* Laminate panel DT1 was nominally 13.2 mm (0.52 in.) thick.

** Fracture values determined using single-edge-notched specimens.

*** Primary alloy (Ti-6Al-4V) layers were nominally 3.2 mm (0.125 in.) thick, while secondary alloy (6061 Al) layers were nominally 0.10 mm (0.004 in.) thick.

**** Condition A: as received plate [mill annealed + 1 hr @ 524°C (975°F)].

***** Condition B: as received plate [mill annealed + 1 hr @ 524°C (975°F)] + 1 hr @ 527°C (980°F), water quench, 18 hr @ 160°C (320°F).

and B tensile and fracture values of single layer 3.2 mm (0.125 in.) Ti-6Al-4V sheet in Tables 6 and 8. Both Condition A and B heat treat states showed much higher critical fracture toughness compared to monolithic Ti-6Al-4V plate of the same thickness. Table 19 summarizes the comparative critical fracture toughness values for single layer Ti-6Al-4V sheet, monolithic Ti-6Al-4V plate, and diffusion bonded Ti-6Al-4V/6061 Al laminate DTI (all in the Condition A state). The following observations can be made from these results:

(1) The diffusion bonded Ti-6Al-4V/6061 Al laminate possessed an average critical fracture toughness that was 117% higher than corresponding monolithic Ti-6Al-4V plate of the same thickness.

(2) The single layer Ti-6Al-4V sheet toughness was essentially retained in the Ti-6Al-4V/6061 Al laminate. The average K_c value for the laminate was 12% less than that for single layer Ti-6Al-4V sheet of the same thickness as the primary titanium layers in the laminate.

Failure in Laminate Panels. It was found that all laminate fracture specimens tested under this program exhibited plane stress (or slant) failure surfaces of the individual primary layers. Failure surfaces of several SEN fracture specimens are shown in Figures 25 and 26. The plane stress failure behavior of the individual layers contrasted sharply with the predominantly plane strain (or flat) failure surfaces exhibited by the monolithic baseline 7475 Al, 7075 Al, and Ti-6Al-4V plate specimens (two of which are shown in Figure 26). The plane stress failure of the individual primary layers is indicative of the much higher toughness values noted for these laminates. Similar failure surfaces in laminated panels have been noted in previous evaluations of laminate failures by other workers and this type of failure mechanism is considered essential for obtaining high toughness in laminate materials.

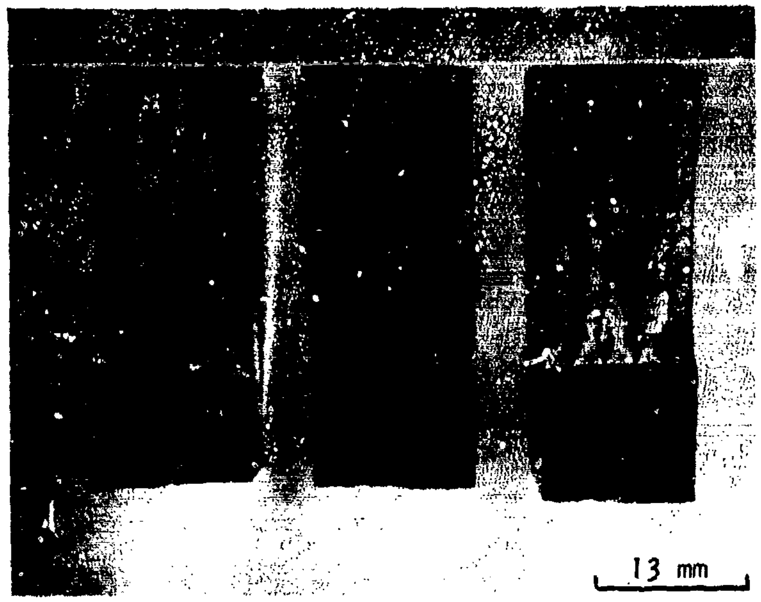
Fractography of fracture specimens from each of the seven laminate systems was conducted using scanning electron fractography. Fractographs illustrating the various modes of failure in these laminates are given in Figures 27 through 32. It was found that all diffusion bonded laminates (both 7475 Al/1100 Al and Ti-6Al-4V/6061 Al) exhibited "adhesive" delamination at the primary/secondary alloy interface. Fractographs illustrating this type of failure in these laminates are shown in Figures 27 and 28. It was noted

TABLE 19. COMPARISON OF AVERAGE CRITICAL FRACTURE TOUGHNESS VALUES (CRACK DIVIDER, L-T ORIENTATION) FOR Ti-6Al-4V SHEET AND MONOLITHIC PLATE AND DIFFUSION BONDED Ti-6Al-4V/6061 Al LAMINATE PANEL DT1.

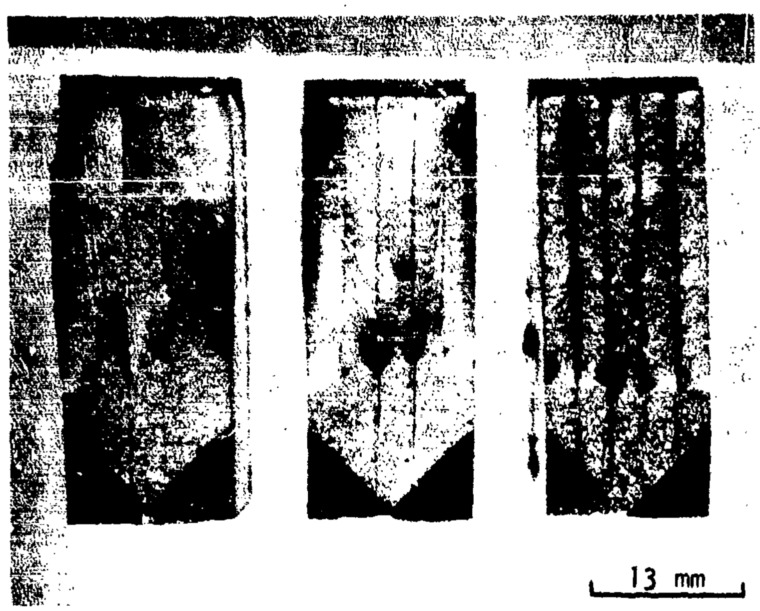
MATERIAL	NOMINAL THICKNESS mm	(in.)	6061 Al INTERLEAF THICKNESS mm	(in.)	CRITICAL FRACTURE TOUGHNESS, K_c $MPa\sqrt{m}$	$(ksi\sqrt{in})$	% RETENTION OF SINGLE LAYER SHEET TOUGHNESS	% INCREASE ABOVE MONOLITHIC PLATE TOUGHNESS
Single Layer Ti-6Al-4V Sheet	3.2	(0.125)	---		155	(141)	---	---
Monolithic Ti-6Al-4V Plate	13.7	(0.54)	---		62.8	(57.1)	---	---
Diffusion Bonded Ti-6Al-4V/6061 Al Laminate	13.2	(0.52)	0.10	(0.004)	137	(124)	88%	117%

*All materials in Condition A heat treat condition: mill annealed + 1 hr @ 524°C (975°F).

**K_c values determined using single-edge-notched fracture specimens.

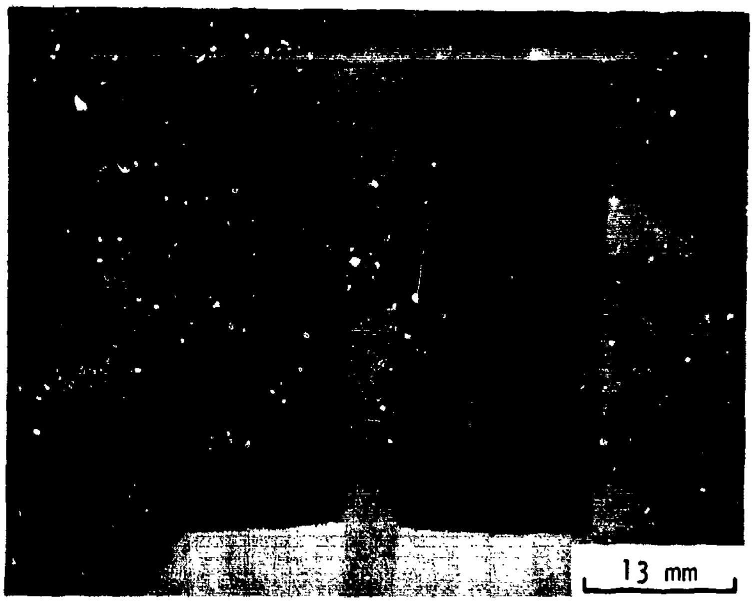


(a)

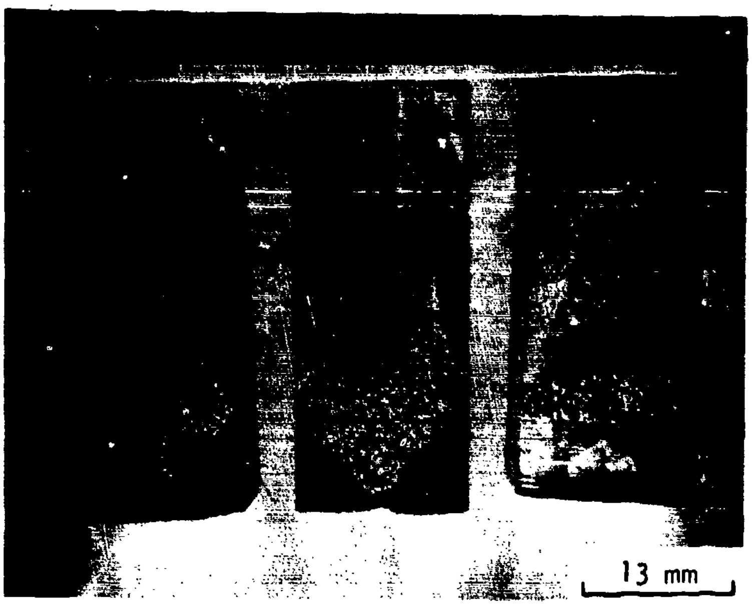


(b)

FIGURE 25. FAILURE SURFACES OF CRACK DIVIDER SEN SPECIMENS, IDENTIFIED LEFT TO RIGHT: (a) DIFFUSION BONDED 7475 Al/1100 Al LAMINATES DA3, DA1, DA2; (b) ROLL BONDED 7075 Al/7072 Al LAMINATE RA1, ROLL BONDED AND DIFFUSION BONDED 7475 Al/1100 Al LAMINATES RA4 AND DA1.



(a)



(b)

FIGURE 26. FAILURE SURFACES OF CRACK DIVIDER SEN FRACTURE SPECIMENS, IDENTIFIED LEFT TO RIGHT: (a) DIFFUSION BONDED Ti-6Al-4V/6061 LAMINATE DT1, MONOLITHIC Ti-6Al-4V; (b) ROLL BONDED AND EXPLOSIVE BONDED 7075 Al/7072 Al LAMINATES RA1 AND EA1, MONOLITHIC 7075 Al.

(a)

(b)

FIGURE 27. FRACTOGRAPHS OF DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DAl SEN FAILURE SURFACE: (a) "ADHESIVE" DELAMINATION AT 1100 Al INTERLEAF; (b) 1100 Al "ADHESIVELY-FAILED SURFACE".

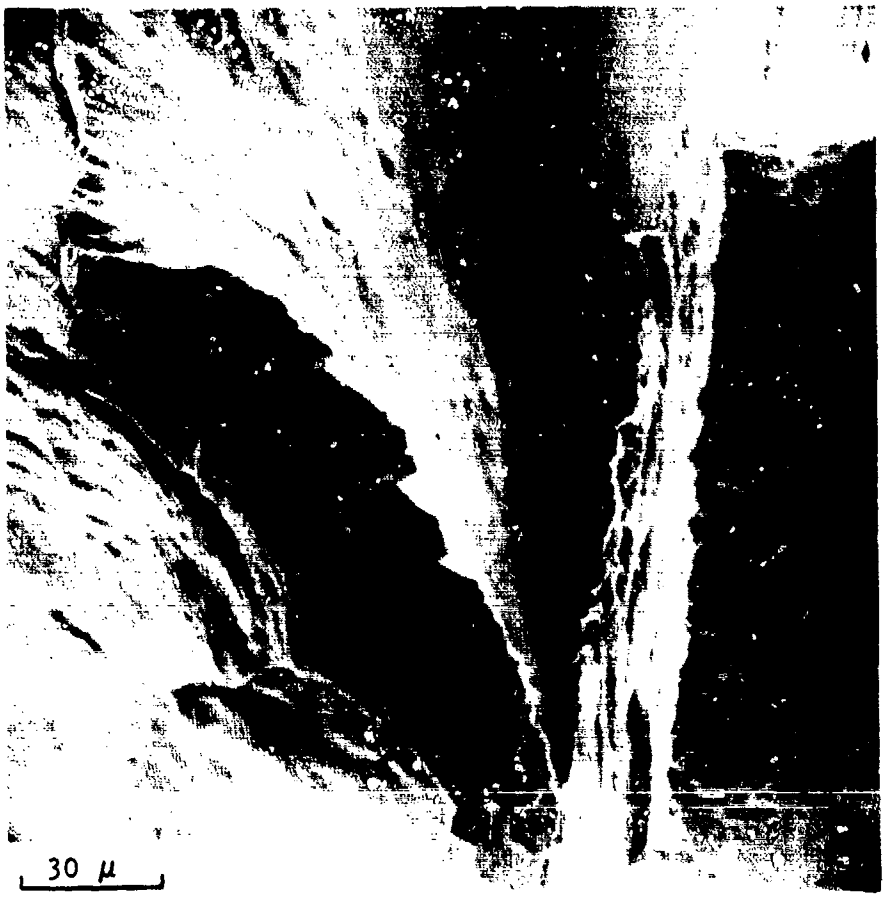


FIGURE 28. FRACTOGRAPH OF DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DA3 SEN FAILURE SURFACE SHOWING "ADHESIVE" DELAMINATION OF 1100 Al INTERLEAF FROM ADJACENT 7475 Al PRIMARY LAYERS.

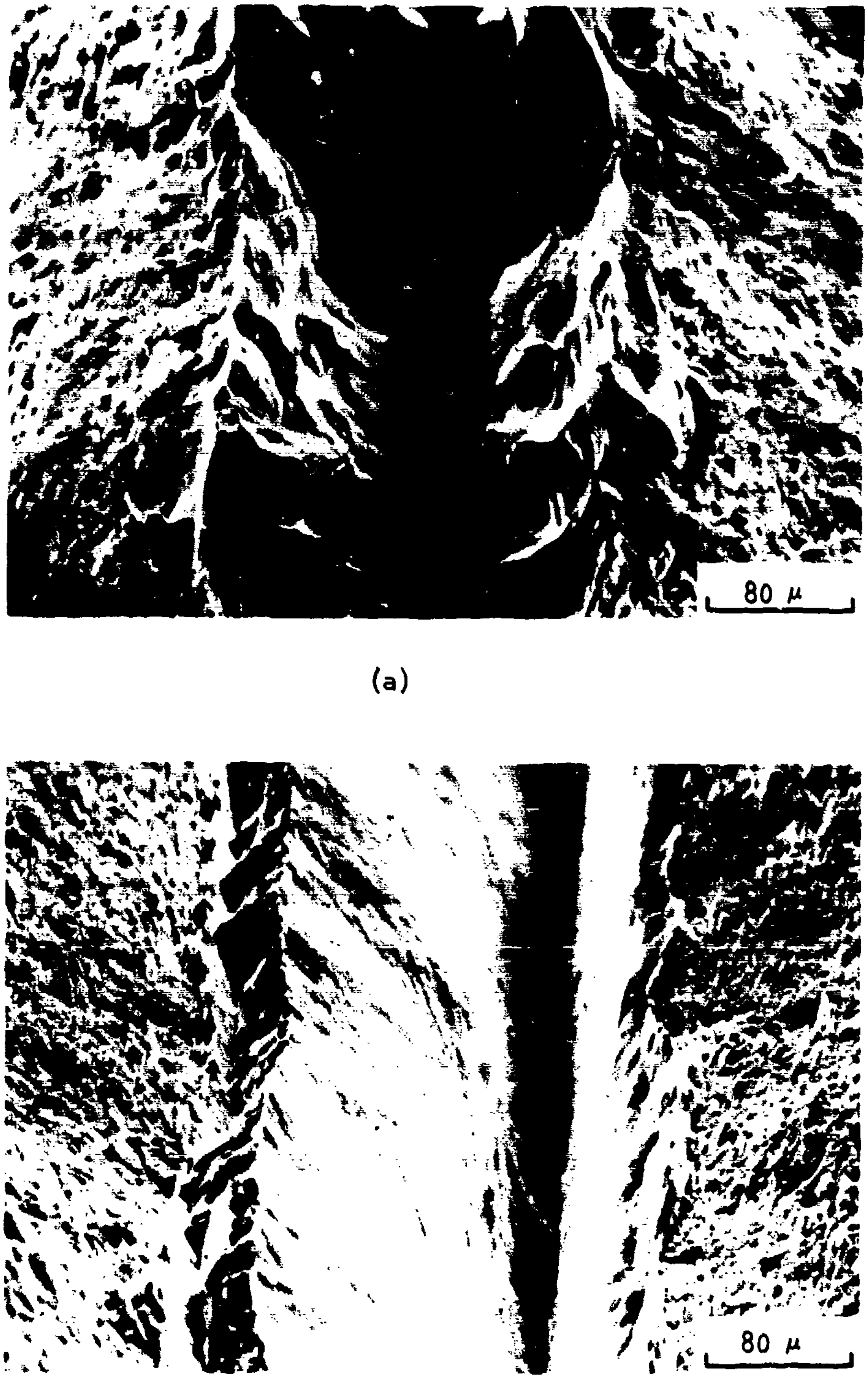
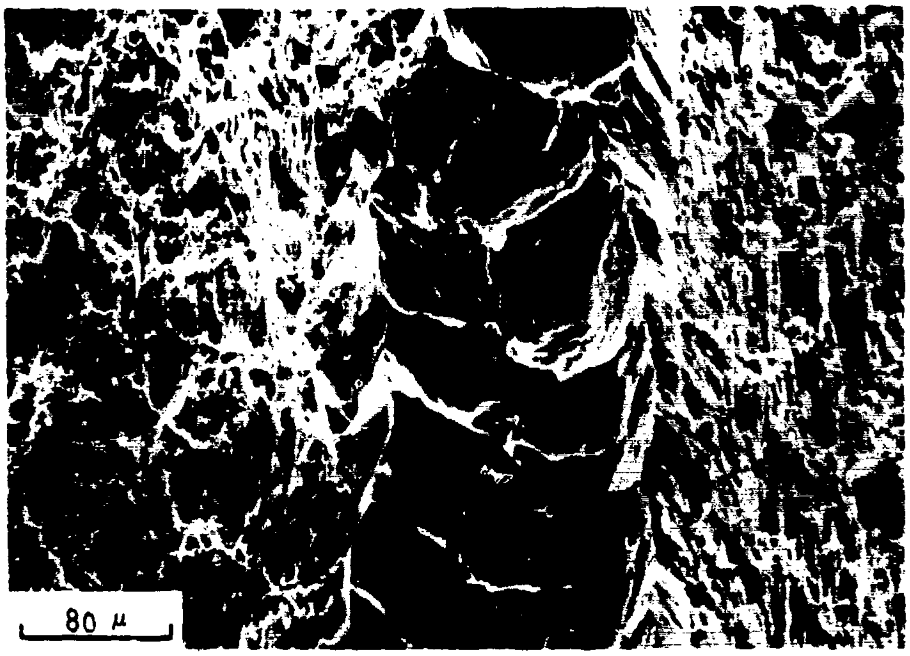
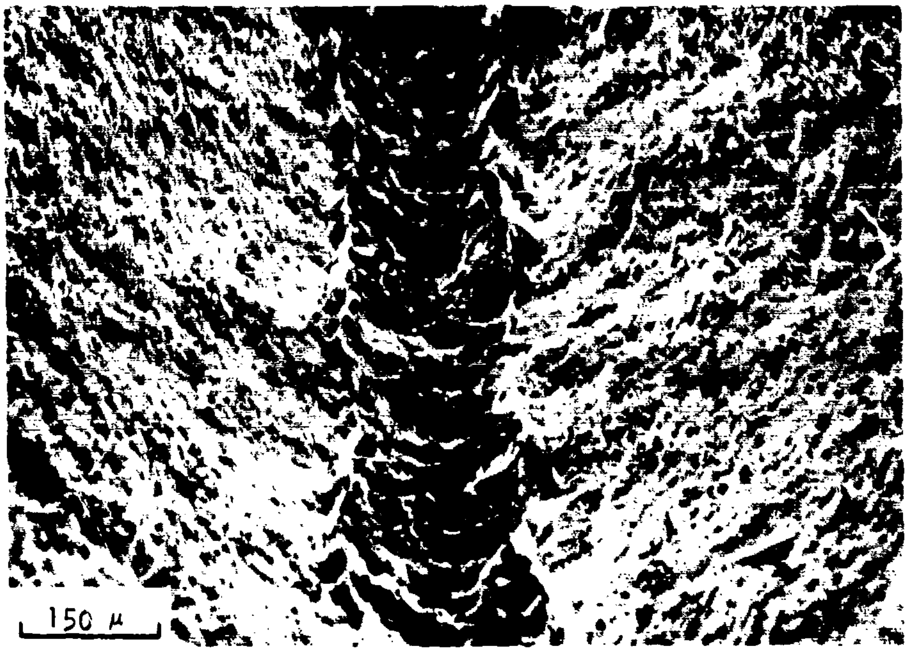


FIGURE 29. FRACTOGRAPHS OF ROLL BONDED LAMINATES RA1 AND RA4 SEN FAILURE SURFACES: (a) "COHESIVE" FAILURE IN 7072 Al INTERLEAF IN RA1; (b) "ADHESIVE" DELAMINATION AT 7475 Al/1100 Al INTERFACE IN RA4.

FIGURE 30. FRACTOGRAPH OF ROLL BONDED 7075 Al/7072 Al LAMINATE RAl SEN FAILURE SURFACE SHOWING SHEAR LIP SURFACES OF 7075 Al PRIMARY LAYERS AND DIMPLED RUPTURE FAILURE IN 7072 Al INTERLEAVES(A) AND (B) AND "ADHESIVE" DELAMINATION AT (C).



(a)



(b)

FIGURE 31. FRACTOGRAPHS OF 7075 Al/7072 Al ROLL BONDED (RAl) AND EXPLOSIVE BONDED (EAl) LAMINATES SEN FAILURE SURFACES SHOWING DIMPLED RUPTURE ACROSS 7072 Al INTERLEAVES: (a) RAl; (b) EAl.

FIGURE 32. FRACTOGRAPH OF DIFFUSION BONDED Ti-6Al-4V/6061 Al LAMINATE DTI SEN FAILURE SURFACE SHOWING DEVELOPMENT OF SHEAR LIPS IN ADJACENT Ti-6Al-4V LAYERS.

previously that all diffusion bonded 7475 Al/1100 Al failed at essentially the same toughness level, regardless of interleaf thickness. The "adhesive" nature of bondline failure in these laminates precluded any evaluation of interleaf thickness effects on the fracture toughness, since the interleaf strength level had no effect on the bondline separation (delamination) strength.

In the roll bonded 7475 Al/1100 Al and 7075 Al/7072 Al laminates it was found that both "adhesive" delamination and "cohesive" interleaf failure occurred, as illustrated in Figures 29, 30 and 31. The mixed "adhesive", "cohesive" failure modes in the roll bonded laminates had no effect on development of plane stress failure shear lips in the primary layers in these laminates. The "cohesive" failure mode in the interleaf is preferable to "adhesive" failure, since the failure strength of the bondline can be easily controlled and predicted. If the failure is "adhesive" in nature, little control can be exercised over what strength the bondline will fail, and premature or excessive delamination could result. The explosive bonded 7075 Al/7072 Al laminate exhibited 100% dimpled rupture across the 7072 Al interleaf and had very little tendency to separate completely in the bondline, as shown in Figure 31. The low strength and high ductility of the 7072 Al interleaf material in this laminate allowed full development of plane stress shear lips in all primary 7075 Al layers. It was considered that this laminate failed in an "ideal" manner.

A schematic illustration of the failure modes discussed in the previous paragraphs is shown in Figure 33. This figure shows the well known transition from flat fracture (plane strain) for thick sections to slant fracture (plane stress) for thin sections. The beneficial effect for obtaining plane stress failure in thick laminated panels was documented in Tables 15, 17 and 19 earlier. Figures 34 and 35 show experimental load/crack-opening displacement record comparisons for laminated and monolithic 7475 Al (Figure 34) and laminated and monolithic Ti-6Al-4V (Figure 35). These show dramatically the effect that plane stress failure in laminated panels has on the ultimate load carrying capacity of a thick section. The improvement in fracture toughness that can be achieved through lamination is summarized schematically in Figure 36. Here it is shown that:

(1) The toughness of a laminate depends ultimately on the plane stress toughness of the individual layers comprising the laminate.

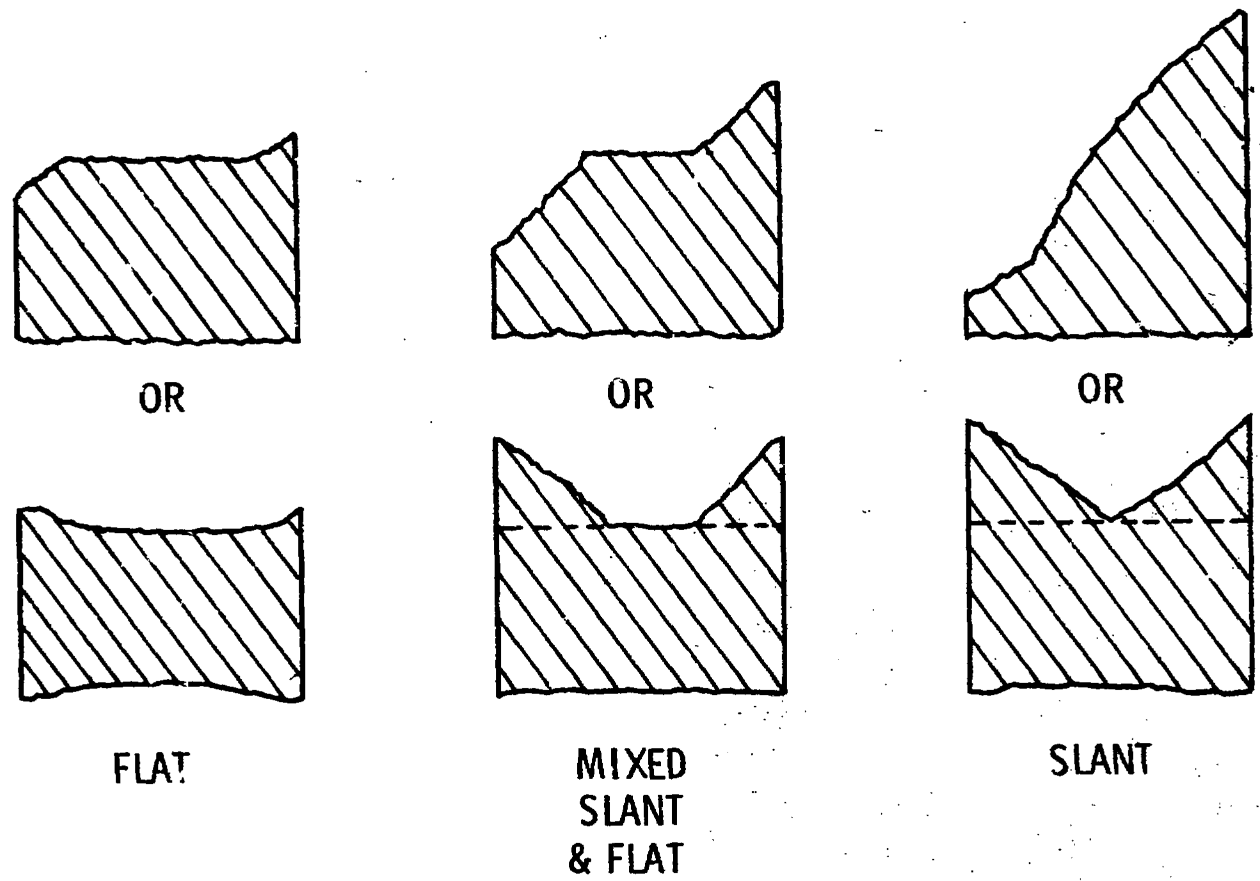


FIGURE 33. TRANSITION IN FAILURE APPEARANCE FROM FLAT FRACTURE FOR THICK SECTIONS UNDER PLANE STRAIN TO SLANT FRACTURE FOR THIN SECTIONS UNDER PLANE STRESS.

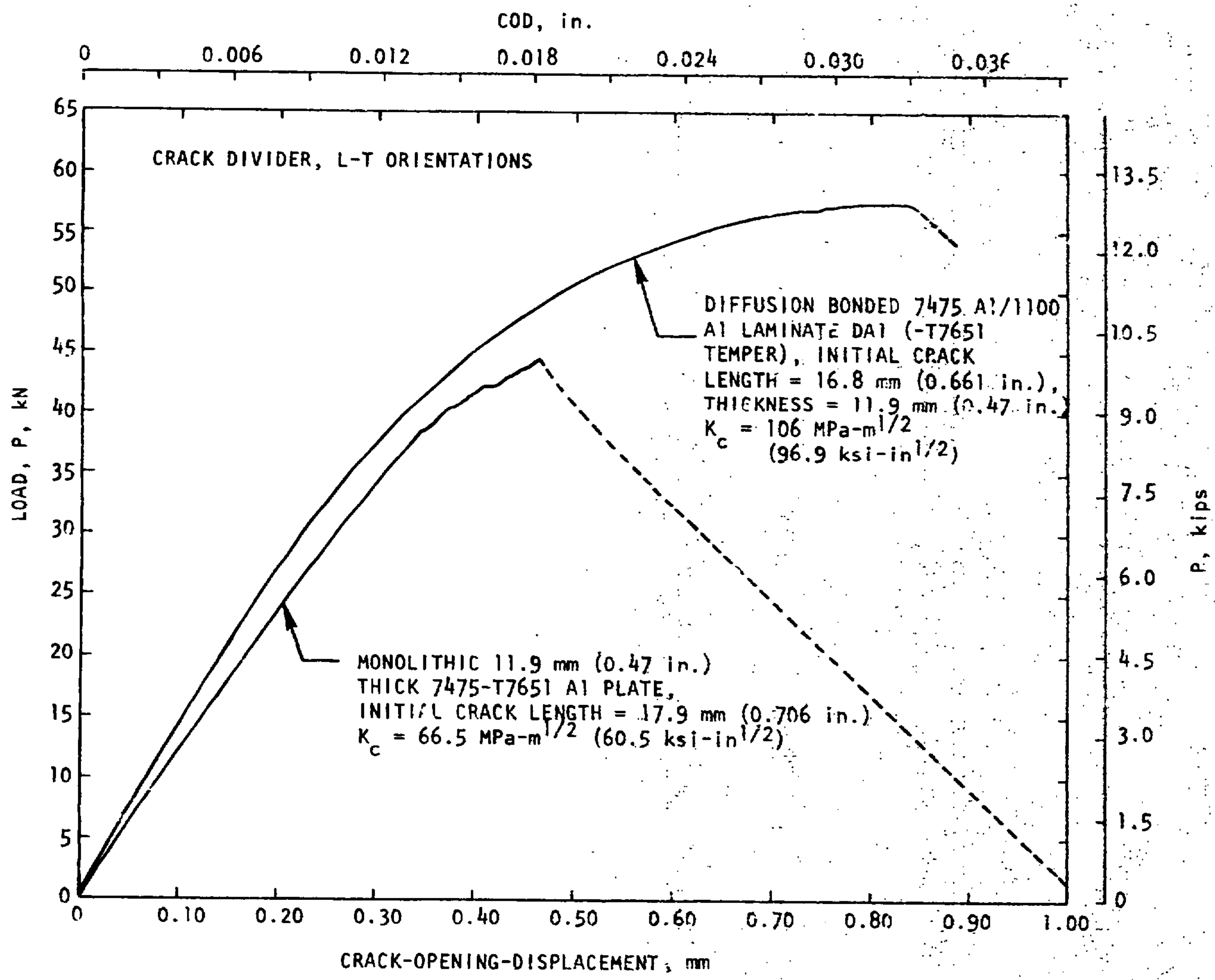


FIGURE 34. COMPARISON OF LOAD/CRACK-OPENING-DISPLACEMENT FRACTURE TOUGHNESS TEST RESULTS FOR DIFFUSION BONDED 7475 Al/1100 Al LAMINATE DAI AND MONOLITHIC 7475-T7651 Al PLATE, CRACK DIVIDER, L-T ORIENTATIONS.

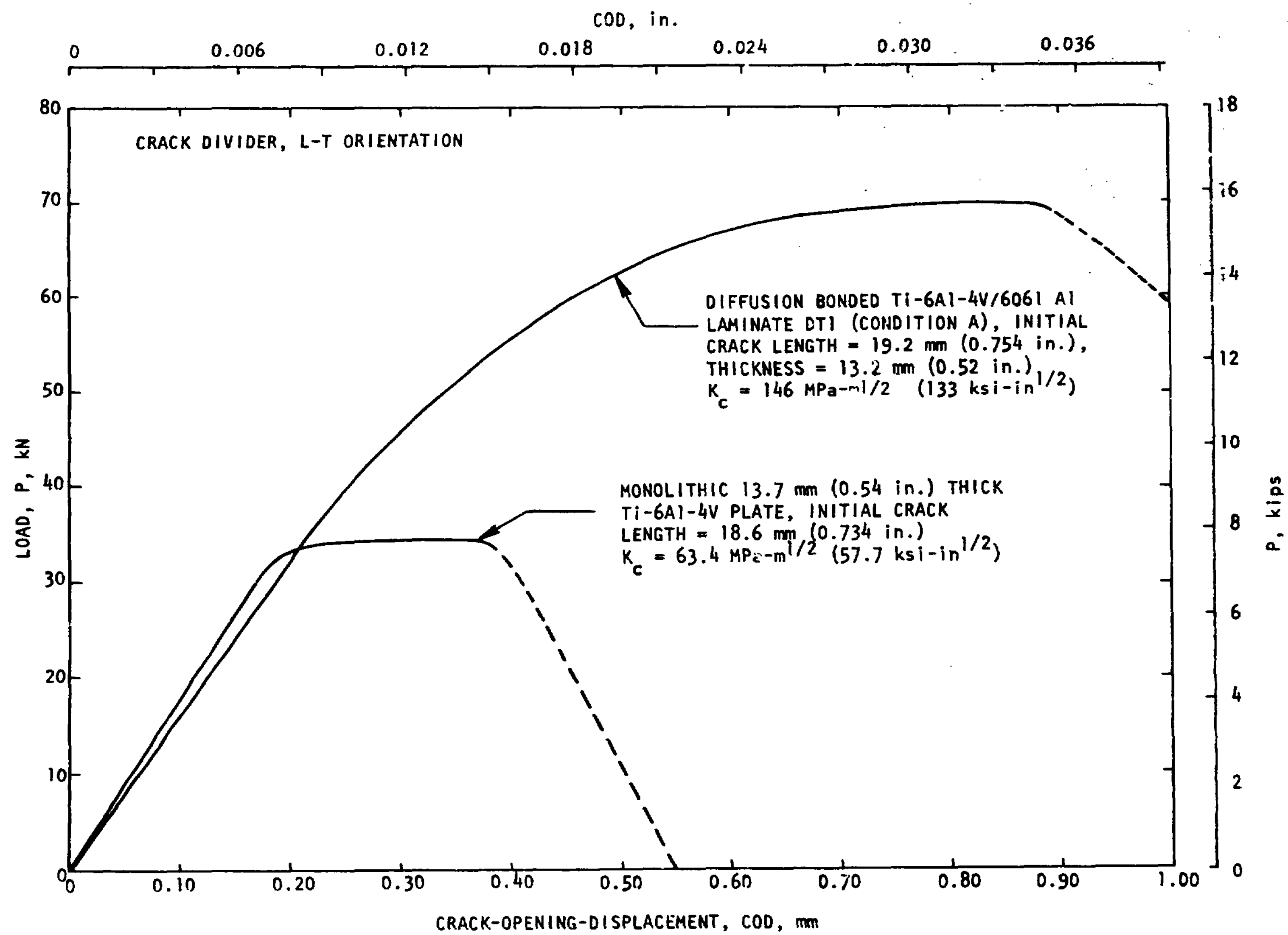


FIGURE 35. COMPARISON OF LOAD/CRACK-OPENING-DISPLACEMENT FRACTURE TOUGHNESS TEST RESULTS FOR DIFFUSION BONDED Ti-6Al-4V/6061 Al LAMINATE DTI AND MONOLITHIC Ti-6Al-4V PLATE, CRACK DIVIDER, L-T ORIENTATIONS.

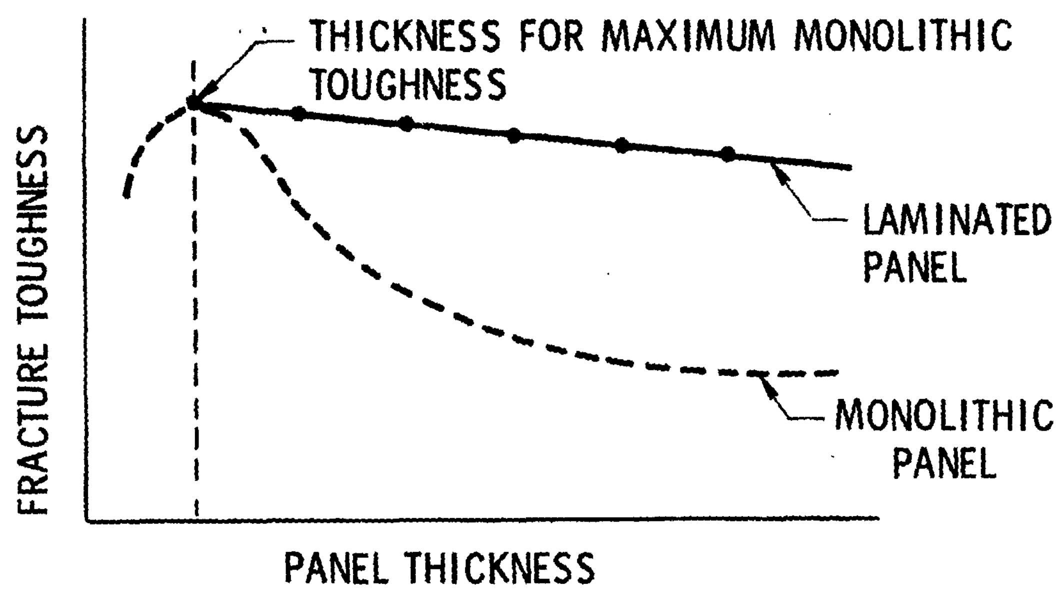


FIGURE 36. EFFECT OF LAMINATION ON CRACK DIVIDER FRACTURE TOUGHNESS

(2) Maximum toughness is achieved by selecting the primary layer thickness to correspond to that thickness at which the K_c vs. thickness curve for single layer metal reaches a peak.

These conclusions are based on the important requirement that the primary layers in a laminate be bonded together in such a way that they fail individually under plane stress conditions. This fact has been recognized by numerous investigators of laminate fracture properties. The key factor controlling plane stress failure of the primary layers is that failure occur in the interleaf bondline prior to development of a plane strain condition through the thickness of the laminate. This means that the interleaf bondline strength must be somewhat lower than the primary metal strength. A higher ductility in the interleaf metal insures that excessive delamination does not occur.

3.3.2 Fracture of Crack Arrest Metal/Metal Laminates

The crack arresting properties of metal/metal laminates are as attractive as the fracture toughness properties of crack divider laminates, if not more so. Three point bend fracture specimens of L-S, crack arrest orientation (Figure 6) were used to document the crack arrest properties of the seven laminate configurations evaluated in this investigation. Corresponding tests were also conducted on monolithic 7475 Al, 7075 Al, and Ti-6Al-4V plate. The crack arrest properties for all laminate materials tested under rising load are given in Table 20. As noted in Table 20, with only one exception, every laminate specimen tested under rising load fracture conditions arrested the propagating crack at the first interleaf the crack encountered. Typically these three point bend specimens had notches of 1.3 mm (0.050 in.) depth with fatigue precracks of 0.25 mm (0.010 in.) length. The specimens were tested under rising load and the following sequence was noted for each specimen:

(1) The load increased until the primary layer containing the crack suffered catastrophic failure.

(2) The crack did not propagate beyond the first secondary alloy interleaf that it encountered.

(3) Loading was continued until the specimen was subjected to a total mid-span stroke displacement of 10.2 mm (0.4 in.).

TABLE 20. CRACK ARREST, L-S ORIENTATION THREE POINT BEND FRACTURE TEST RESULTS FOR ALL LAMINATED PANELS

LAMINATE PANEL DESIGNATION	PRIMARY/ SECONDARY ALLOYS	BONDING PROCESS	TEST NO.	CRACK ARREST @ 1st INTERLEAF	REMARKS
DA1	7475 Al/ 1100 Al	Diffusion	1 2 3	Yes Yes Yes	Also, delamination @ 3rd interleaf
DA2	7475 Al/ 1100 Al	Diffusion	1 2 3	Yes No Yes	Crack arrested @ 2nd interleaf
DA3	7475 Al/ 1100 Al	Diffusion	1	Yes	
RA1	7075 Al/ 7072 Al	Roll	1 2 3	Yes Yes Yes	
RA4	7475 Al/ 1100 Al	Roll	1 2 3	Yes Yes Yes	
EA1	7075 Al/ 7072 Al	Explosive	1 2 3	Yes Yes Yes	
DT1 (Condition A)	Ti-6Al-4V/ 6061 Al	Diffusion	1 2 3	Yes Yes Yes	Also, delamination @ 2nd interleaf

In two of the specimens tested in this manner, secondary delamination occurred at high loads in interleaf bondlines other than the one which arrested the crack. In all other tests loading after crack arrest caused general yielding of the specimen, but no crack extension was noted.

This behavior contrasted sharply with the three point bend behavior of similarly fatigue precracked L-S orientation TPB specimens of monolithic plate metal. As would be expected, all monolithic plate alloys (7475 Al, 7075 Al, and Ti-6Al-4V) suffered catastrophic failure once the critical crack extension load had been attained. Figure 37 shows load/crack-opening-displacement failure records that demonstrate the sharp difference in behavior observed for diffusion bonded Ti-6Al-4V/6061 Al laminate DTI and monolithic Ti-6Al-4V plate specimens. Typical TPB failure specimens tested in the manner described are shown in Figures 38 and 39. The results discussed here show that these metal/metal laminate systems all possessed a substantial capacity for arresting cracks that had become catastrophic in nature under rising load condition. This same crack arrest potential documented for cracks propagating under rising loads was also established for cracks propagating under fatigue loads, as described later in Section 3.4.2.

3.4 FATIGUE CRACK PROPAGATION IN LAMINATE PANELS

3.4.1 Fatigue Crack Propagation in Crack Divider Metal/Metal Laminates

Compact tension specimens (Figure 4) were used to document the crack divider, fatigue crack propagation rates in 7475-T761 Al sheet, Ti-6Al-4V sheet, monolithic 7475-T7651 Al plate, monolithic Ti-6Al-4V plate, roll bonded 7475 Al/1100 Al laminate RA4, and diffusion bonded Ti-6Al-4V/6061 Al laminate DTI. These tests were conducted at room temperature at 10 Hz and an R ratio (ratio of minimum to maximum load) of 0.1. The results for 11.9 mm (0.47 in.) roll bonded laminate RA4 are shown in Figure 40, while the results for 2.3 mm (0.090 in.) 7475 Al sheet and 11.9 mm (0.47 in.) monolithic 7475 Al are given in Figures 41 and 42. Figure 43 gives the relative comparisons between these three materials. Although there are some differences in the propagations rates at given stress intensity range values for these three material types, these differences are not large and are not attributable to any effects from lamination. These results are not unexpected since the

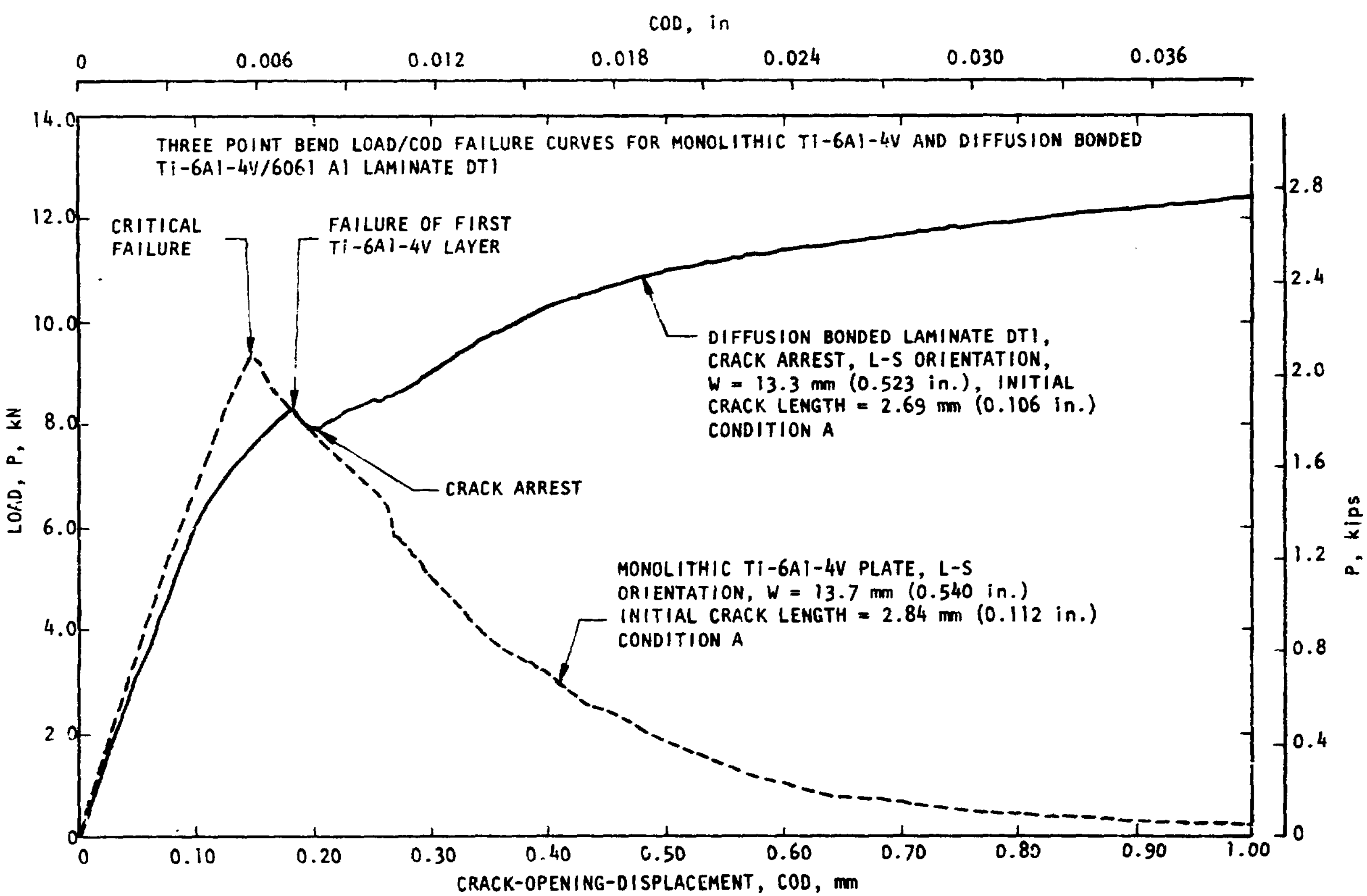
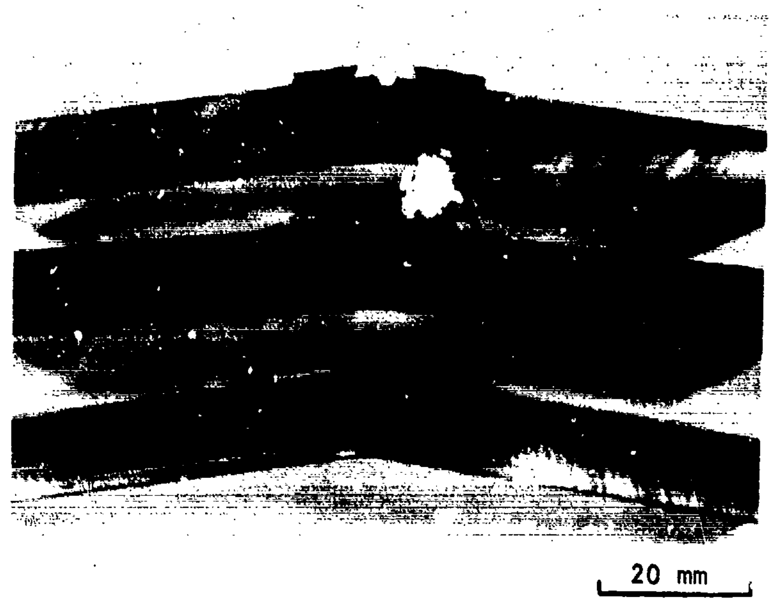
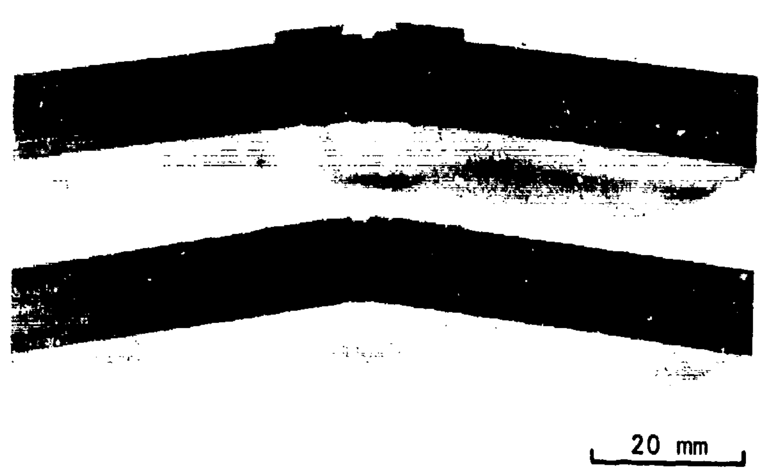


FIGURE 37. COMPARISON OF LOAD/CRACK-OPENING-DISPLACEMENT THREE POINT BEND FRACTURE TEST RESULTS FOR DIFFUSION BONDED Ti-6Al-4V/6061 Al LAMINATE DT1 AND MONOLITHIC Ti-6Al-4V PLATE, CRACK ARREST, L-S ORIENTATIONS.

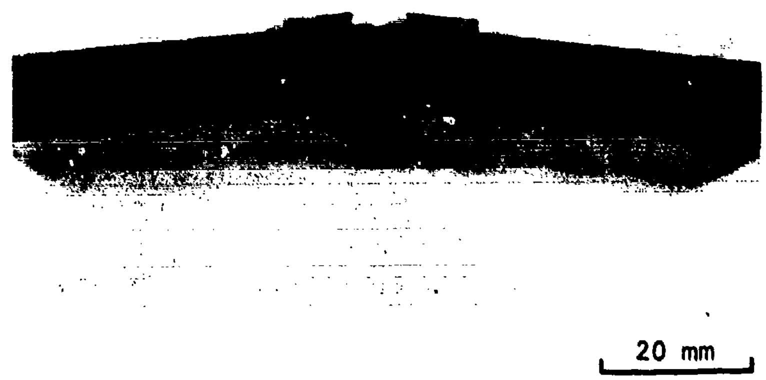


(a)

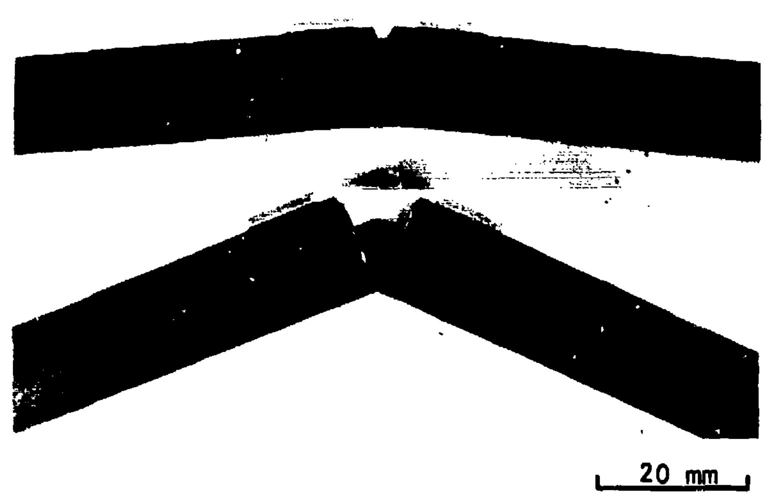


(b)

FIGURE 38. THREE POINT BEND FRACTURE SPECIMENS FOR DIFFUSION BONDED 7475 Al/1100 Al LAMINATES DA1, DA2, DA3: (a) CRACK ARREST AT FIRST 1100 Al INTERLEAF (DA3, DA1, DA2 TOP TO BOTTOM); (b) CRACK ARREST IN DA1 (TOP) AND DA2, BUT DELAMINATION IN THIRD 1100 Al INTERLEAF IN DA1.



(a)



(b)

FIGURE 39. THREE POINT BEND FRACTURE SPECIMENS: (a) EXPLOSIVE BONDED 7075 Al/7072 Al LAMINATE EA1 SHOWING CRACK ARREST AT FIRST 7072 Al INTERLEAF; (b) DIFFUSION BONDED Ti-6Al-4V/6061 Al LAMINATE DT1 (TOP) SHOWING CRACK ARREST AT FIRST 6061 Al INTERLEAF; MONOLITHIC Ti-6Al-4V PLATE SHOWING TOTAL FAILURE.

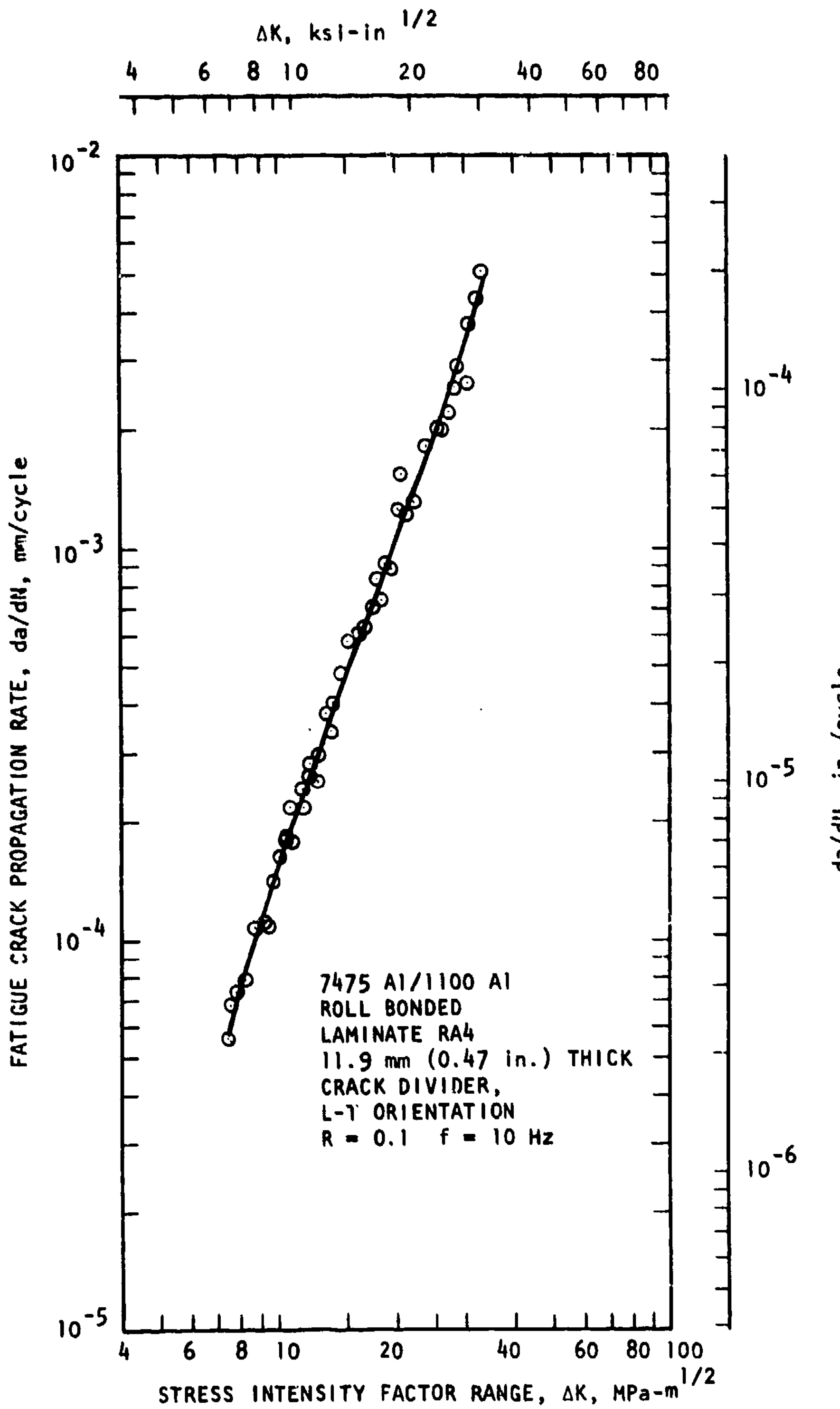


FIGURE 40. FATIGUE CRACK PROPAGATION RATES FOR 11.9 mm (0.47 in.) THICK ROLL BONDED LAMINATE RA4, CRACK DIVIDER, L-T ORIENTATION.

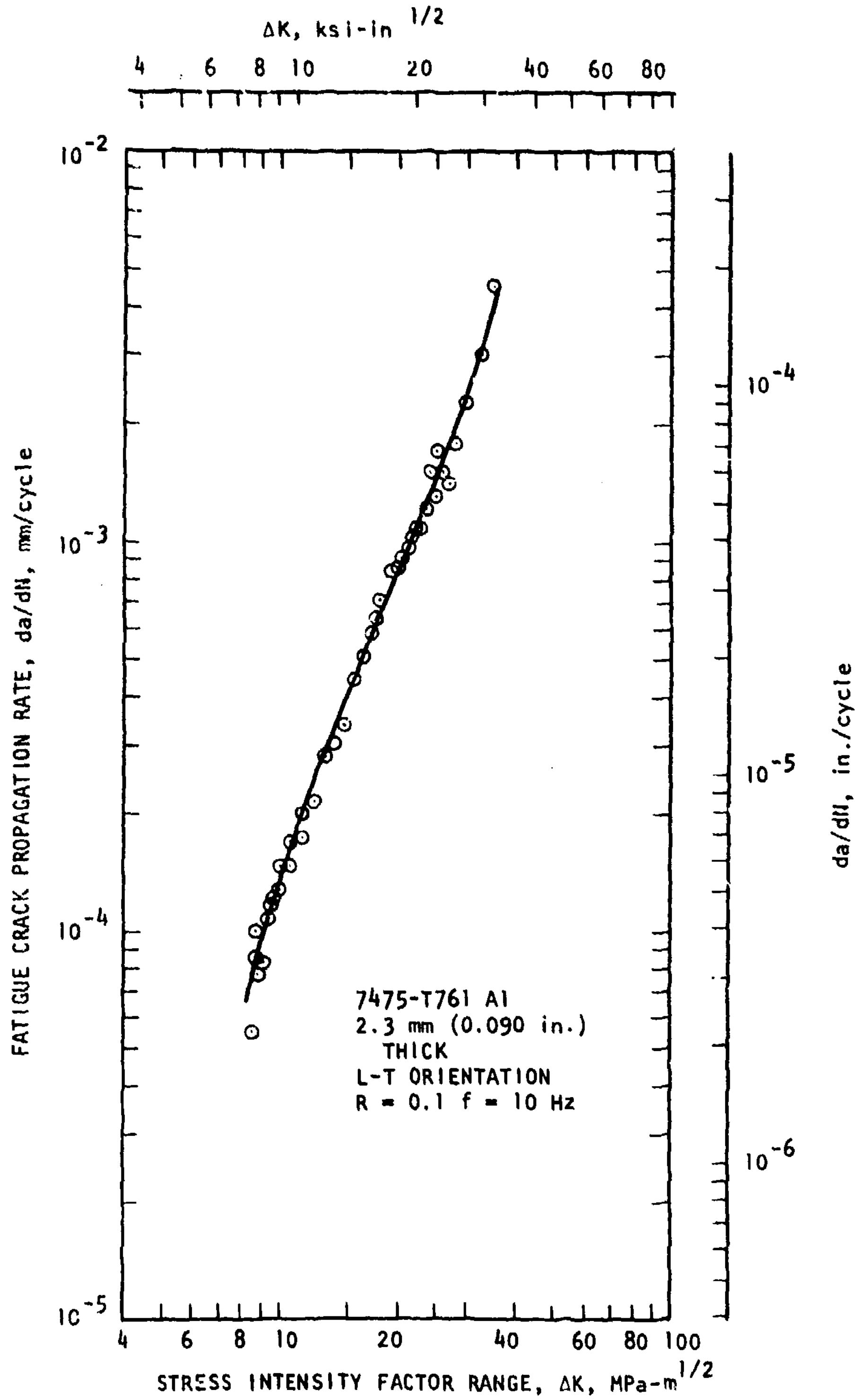


FIGURE 41. FATIGUE CRACK PROPAGATION RATES FOR 2.3 mm (0.090 in.) THICK 7475-T761 Al, L-T ORIENTATION.

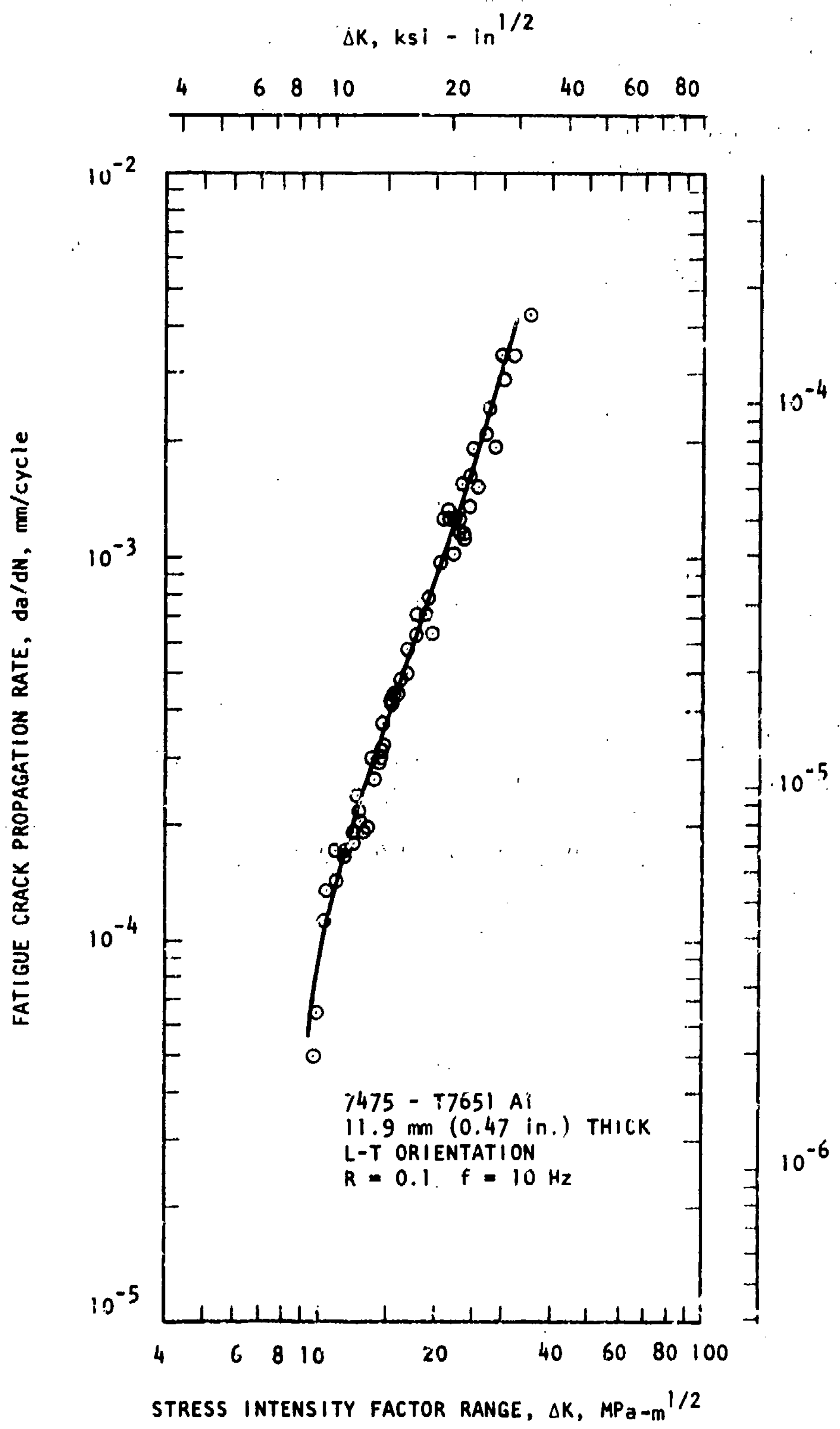


FIGURE 42. FATIGUE CRACK PROPAGATION RATES FOR 11.9 mm (0.47 in.) THICK 7475-T7651 Al, L-T ORIENTATION.

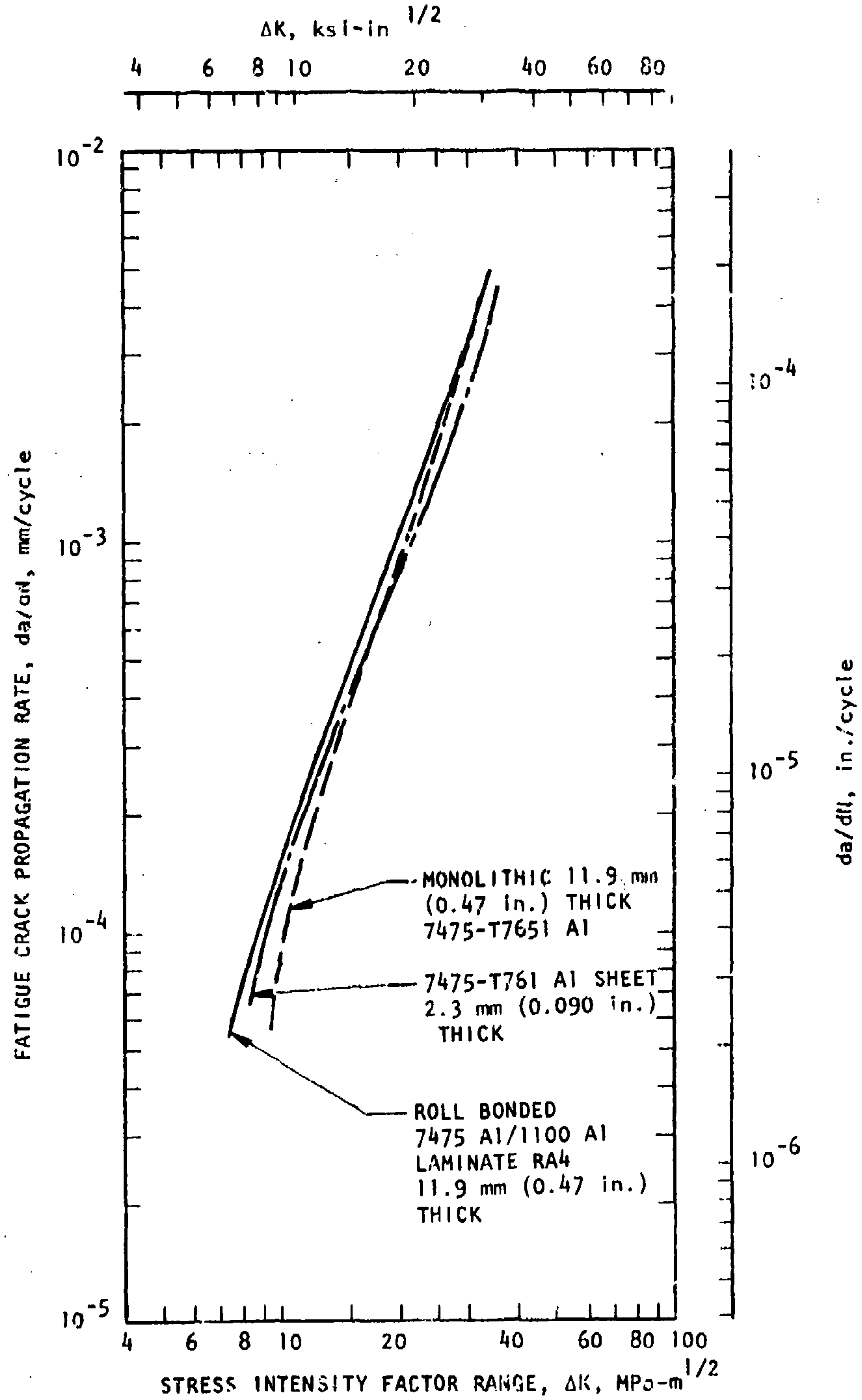


FIGURE 43. COMPARISON OF FATIGUE CRACK PROPAGATION RATES FOR MONOLITHIC 7475-T761, -T7651 Al SHEET AND PLATE AND ROLL BONDED LAMINATE RA4, CRACK DIVIDER, L-T ORIENTATION.

basic size of the plastic zone at the crack tip is significantly smaller under fatigue loading than under rising loading. The development of large plastic zones under plane stress conditions is the key factor which allows crack divider laminates to possess significantly higher fracture toughness than corresponding monolithic metal. Except at high stress intensity factor ranges, the plastic zone size in fatigue is small regardless of specimens thickness; thus, there is relatively little section thickness effect on fatigue crack propagation rates.

The crack divider fatigue crack propagation test results for 3.2 mm (0.12 in.) Ti-6Al-4V sheet, 13.2 mm (0.52 in.) diffusion bonded Ti-6Al-4V/6061 Al laminate DT1, and 13.7 mm (0.54 in.) Ti-6Al-4V monolithic plate are given in Figures 44 through 47. Except at high stress intensity factor ranges (where the plastic zone size may be affected by the specimen thickness), essentially the same conclusion can be made regarding the Ti-6Al-4V materials as was noted above for the 7475 Al materials. At the high stress intensity factor ranges (ΔK) for the Ti-6Al-4V materials, the curves in Figure 47 separate farther with the thinnest material (3.2 mm thick sheet) having the lowest fatigue crack growth rate and the 13.7 mm monolithic plate material having the highest growth rate. The differences in growth rates at the high ΔK ranges could be attributable to decrease in the plastic zone size from thin section to thick section.

3.4.2 Fatigue Crack Propagation in Crack Arrest Metal/Metal Laminates

Three point bend, L-S crack arrest orientation fracture tests were conducted on 11.9 mm (0.47 in.) roll bonded 7475 Al/1100 Al laminate RA4, 11.9 mm (0.47 in.) monolithic 7475-T7651 Al plate, 13.2 mm (0.52 in.) diffusion bonded Ti-6Al-4V/6061 Al laminate DT1, and 13.7 mm (0.54 in.) monolithic Ti-6Al-4V plate. Four TPB specimens were run for each material, with the width dimension of each specimen being equal to the material thickness. The specimens had machined notches 1.3 mm (0.050 in.) deep. Fatigue precracks were grown approximately 0.25 mm (0.010 in.) in length prior to measurement of crack growth. The fatigue crack propagation tests were conducted at room temperature at 10 Hz and a R ratio of 0.1. In all laminate TPB fatigue crack propagation tests the fatigue crack was arrested at the first secondary metal interleaf that the crack encountered. Further cycling only led to delamination at the interleaf at which the crack was arrested. The laminate tests

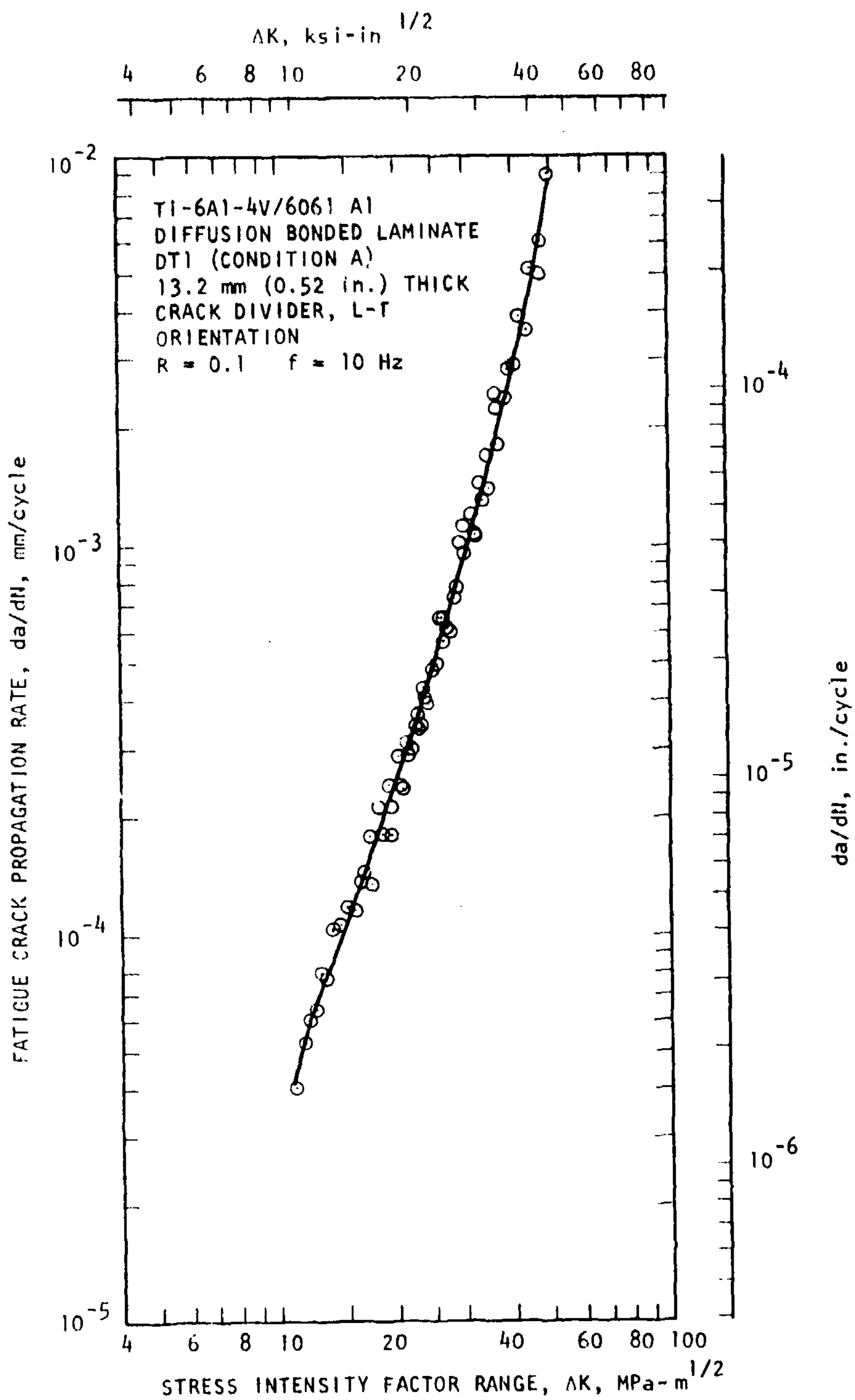


FIGURE 44. FATIGUE CRACK PROPAGATION RATES FOR 13.2 mm (0.52 in.) THICK DIFFUSION BONDED LAMINATE DT1, CRACK DIVIDER, L-T ORIENTATION.

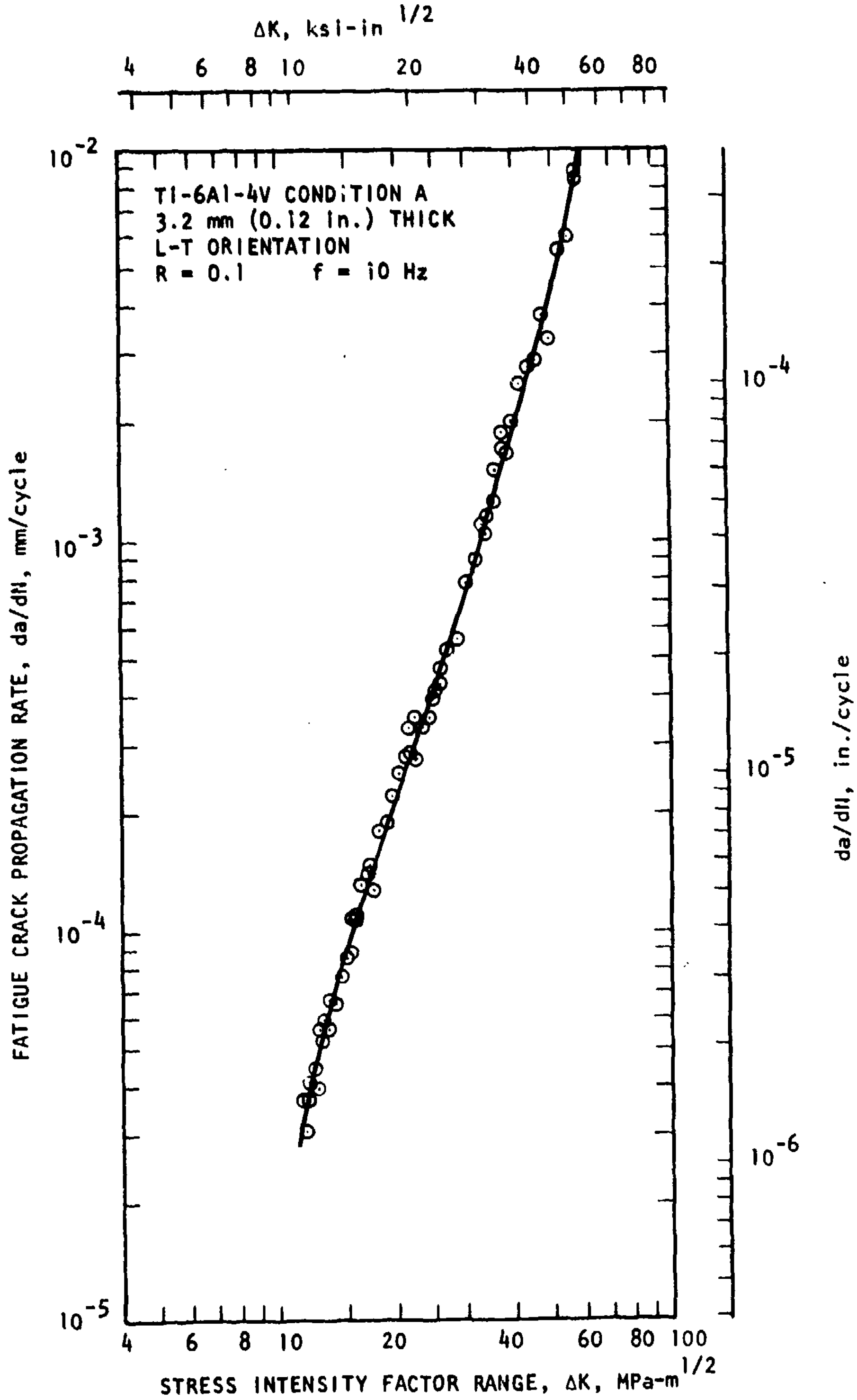


FIGURE 45. FATIGUE CRACK PROPAGATION RATES FOR 3.2 mm (0.12 in.) THICK Ti-6Al-4V, L-T ORIENTATION.

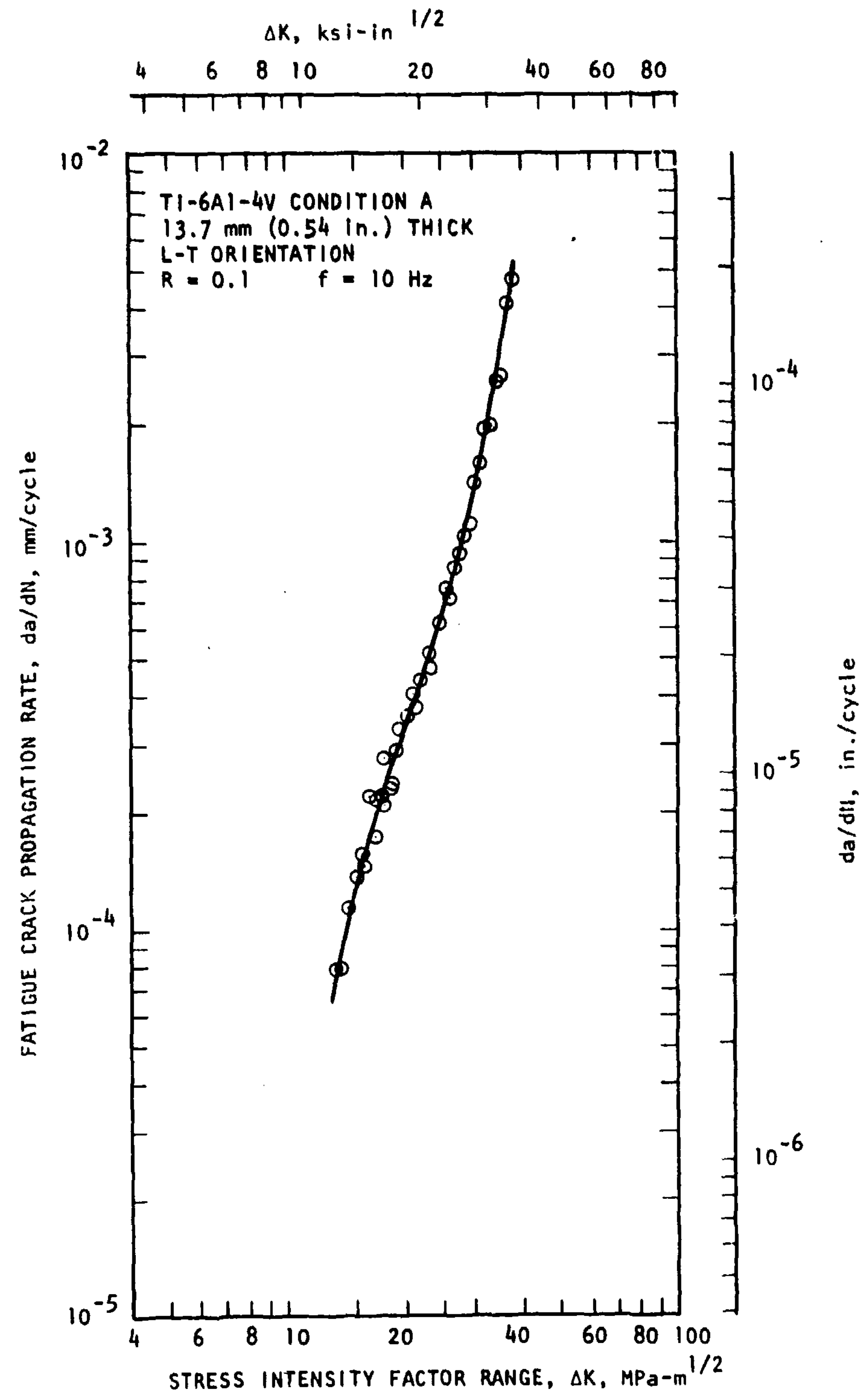


FIGURE 46. FATIGUE CRACK PROPAGATION RATES FOR 13.7 mm (0.54 in.) THICK Ti-6Al-4V, L-T ORIENTATION.

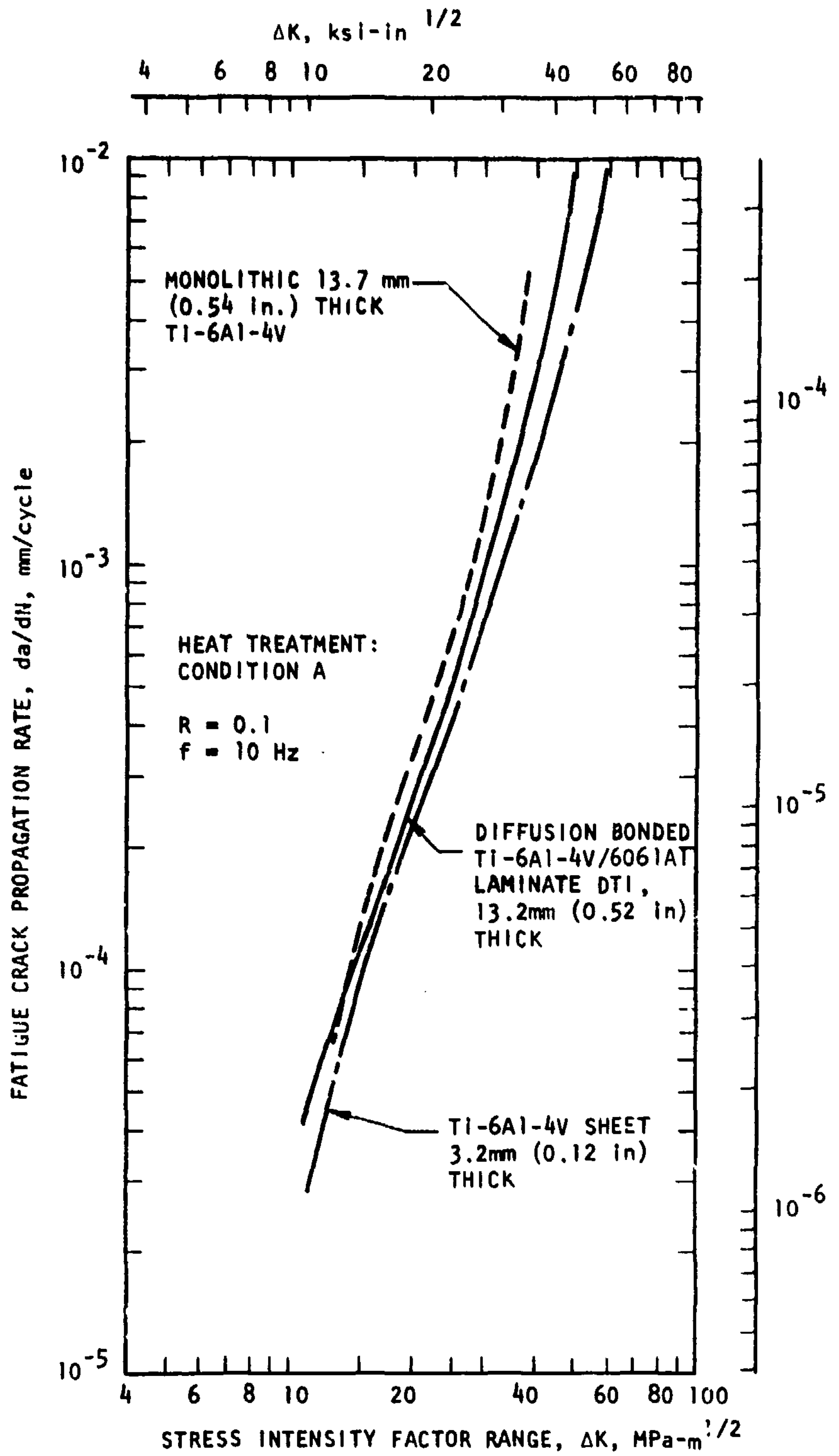


FIGURE 47. COMPARISON OF FATIGUE CRACK PROPAGATION RATES FOR MONOLITHIC TI-6Al-4V SHEET AND PLATE AND DIFFUSION BONDED LAMINATE DTI, CRACK DIVIDER, L-T ORIENTATIONS.

were continued until 100,000 cycles had been applied, and then the tests were arbitrarily stopped. Test results for these laminate specimens are given in Table 21. Typical crack growth curves for roll bonded 7475 Al/1100 Al laminate RA4 and diffusion bonded Ti-6Al-4V/6061 Al laminate DT1 are given in Figures 48 and 49. Comparative tests were conducted on monolithic 7475 Al and Ti-6Al-4V. In all cases the specimens failed catastrophically within 20,000 cycles for the monolithic 7475 Al for the same applied stress intensity range [approximately 10 $MPa\text{-}m^{1/2}$ (9 $ksi\text{-}in^{1/2}$)]. Likewise the monolithic Ti-6Al-4V specimens failed within 30,000 cycles at the same applied stress intensity range given DT1 specimens [approximately 20 $MPa\text{-}m^{1/2}$ (18 $ksi\text{-}in^{1/2}$)]. Photographs of comparative three point bend fatigue specimens are shown in Figure 50. These tests (combined with the results of rising load crack arrest discussed in Section 3.3.2) show that metal/metal laminates of this type possess unique crack arrest properties than can be used to great advantage in structural design for improved damage tolerance.

TABLE 2[illegible]. CRACK ARREST, L-S ORIENTATION THREE POINT BEND FATIGUE CRACK PROPAGATION TEST RESULTS FOR ROLL BONDED 7475 Al/1100 Al LAMINATE RA4 AND DIFFUSION BONDED Ti-6Al-4V/6061 Al LAMINATE DT1.

LAMINATE PANEL DESIGNATION	PRIMARY/ SECONDARY ALLOYS	TEST NO.	LOAD RANGE ΔP		INITIAL CRACK LENGTH		CRACK LENGTH AT ARREST		# CYCLES TO ARREST
			kN	(kips)	mm	(in.)	mm	(in.)	
RA4	7475 Al/ 1100 Al	1	1.42	(0.320)	1.70	(0.067)	2.44	(0.096)	2500
		2	1.60	(0.360)	1.96	(0.077)	2.44	(0.096)	750
		3	1.42	(0.320)	1.63	(0.064)	2.41	(0.095)	2600
		4	1.42	(0.320)	1.70	(0.067)	2.36	(0.093)	1250
DT1 (Condition A)	Ti-6Al-4V/ 6061 Al	1	2.76	(0.620)	1.45	(0.057)	3.30	(0.130)	7800
		2	2.76	(0.620)	1.52	(0.060)	3.28	(0.129)	7300
		3	2.76	(0.620)	1.50	(0.059)	3.25	(0.128)	9900
		4	2.76	(0.620)	1.50	(0.059)	3.28	(0.129)	8600

* R = 0.1, f = 10 Hz for all tests.

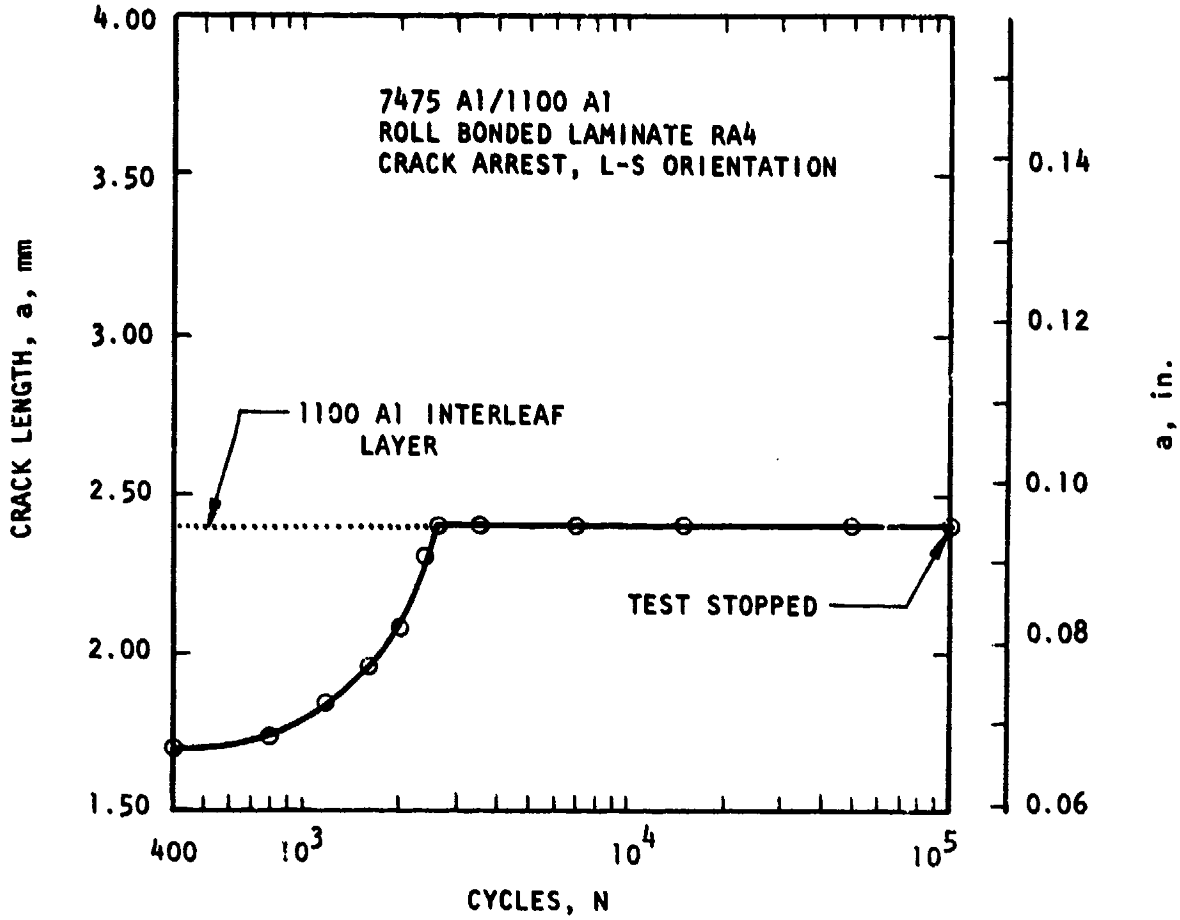


FIGURE 48. FATIGUE CRACK PROPAGATION IN 7475 Al/1100 Al ROLL BONDED LAMINATE RA4, CRACK ARREST, L-S ORIENTATION, THREE POINT BEND SPECIMEN, - T7651 TEMPER.

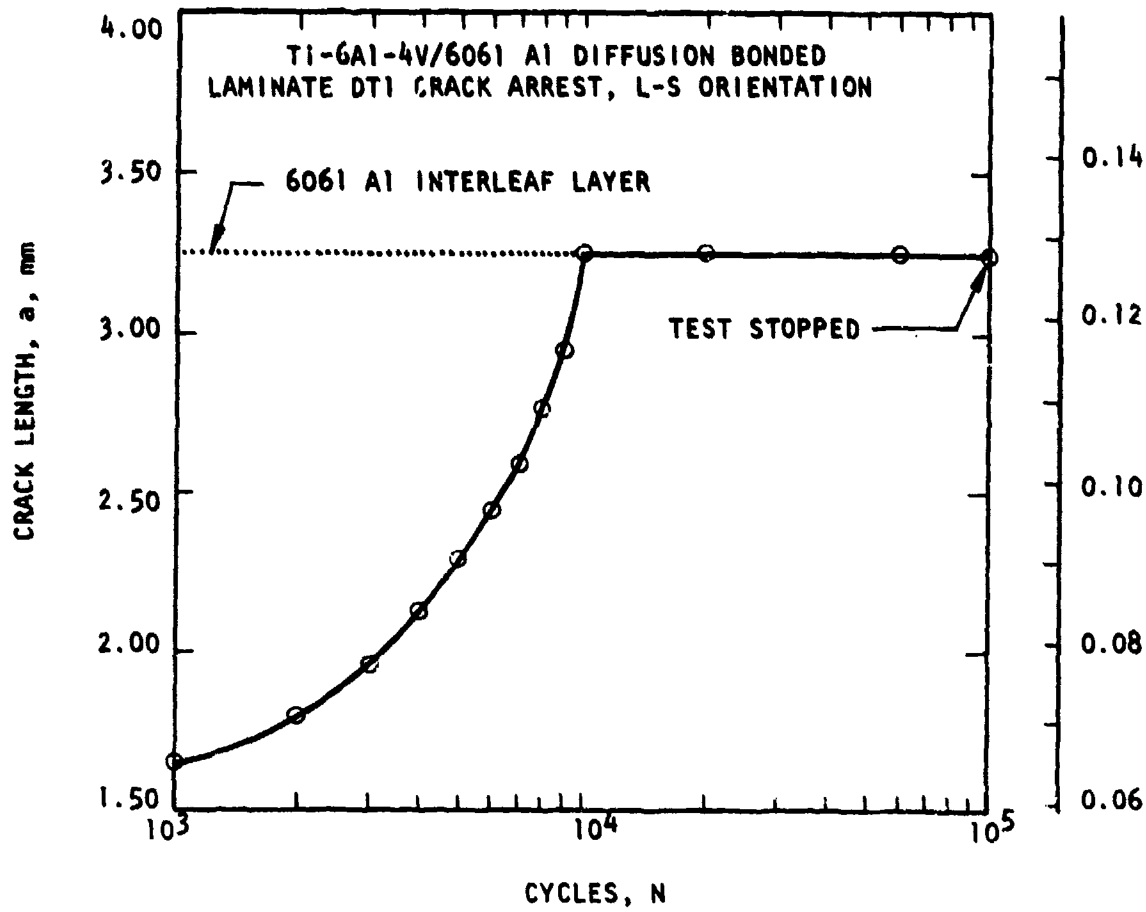
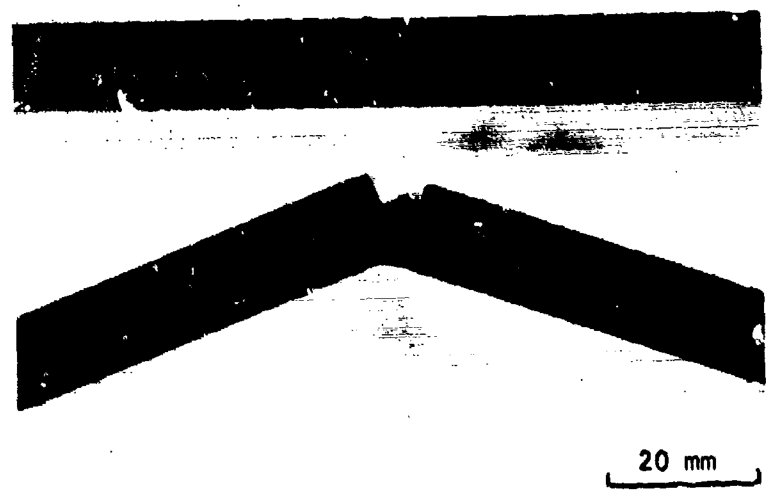


FIGURE 49. FATIGUE CRACK PROPAGATION IN TI-6Al-4V/6061 Al DIFFUSION BONDED LAMINATE DT1, CRACK ARREST, L-S ORIENTATION, THREE POINT BEND SPECIMEN; HEAT TREATMENT: CONDITION A.



(a)

(b)

FIGURE 50. THREE POINT BEND FATIGUE CRACK PROPAGATION TEST SPECIMENS: (a) CRACK ARREST AT FIRST 1100 Al INTERLEAF IN ROLL BONDED 7475 Al/1100 Al LAMINATE RA4 (TOP) AND COMPLETE FAILURE UNDER FATIGUE FOR MONOLITHIC 7475 Al (BOTTOM); (b) SAME OBSERVATIONS NOTED FOR (a) FOR DIFFUSION BONDED Ti-6Al-4V/6061 Al LAMINATE DT1 (TOP) AND MONOLITHIC Ti-6Al/4V (BOTTOM).

4.0 SUMMARY AND CONCLUSIONS

An experimental investigation of the fracture and fatigue crack propagation behavior of Al/Al and Ti/Al laminates was conducted. Seven laminate panels were fabricated using three processing methods: diffusion bonding, roll bonding, and explosive bonding. The specific laminate configurations that were fabricated and evaluated included the following alloy systems:

Diffusion bonded laminates	7475 Al/1100 Al alloys Ti-6Al-4V/6061 Al alloys
Roll bonded laminates	7475 Al/1100 Al Alloys 7075 Al/7072 Al alloys
Explosive bonded laminate	7075 Al/7072 Al alloys

These laminates typically consisted of five layers of primary metal [e.g., 2.3 mm (0.090 in.) 7475 Al] interleaved with four layers of thin secondary metal [e.g., 0.13 mm (0.005 in.) 1100 Al], so that overall laminate thicknesses were approximately 11.9 mm (0.47 in.). Crack divider and crack arrest fracture toughness and fatigue crack propagation tests were conducted on these laminate panels, and the test results were compared to similar tests on sheet and monolithic plate alloys of the same strengths and chemical compositions as the primary layer alloys. The following conclusions were made from this program:

General Metal/Metal Laminate Properties

1. All metal/metal laminate systems investigated showed substantially higher fracture toughness in the crack divider orientation than corresponding monolithic plate alloys.

2. The primary alloy single layer sheet toughness was retained in all metal/metal laminate systems evaluated. Thus, the average K_c values of the laminates were measured to be 88% to 115% of the K_c values for the single layer primary alloy sheets of approximately the same thickness as the primary layers in the laminates.

3. All metal/metal laminate systems tested exhibited significant capacity for crack arrest under both rising load and fatigue load conditions.

4. The crack divider fracture toughness of a laminate depends ultimately on the plane stress toughness of the individual primary metal layers comprising the laminates. Therefore, maximum toughness is achieved through lamination by selecting the primary metal layer thickness to correspond to that thickness at which the K_c vs. thickness relation for that single layer metal is at a maximum.

5. The principle requirement for attaining high fracture toughness in laminates is that the primary metal layers in a laminate be bonded together in such a way that they fail individually under plane stress conditions. The key factor controlling plane stress failure of the primary layers is is that failure occur at the primary/secondary bond prior to development of a plane strain condition through the thickness of the laminate. In metal/metal laminates, this means that the interleaf metal strength must be less than the primary metal strength. A high ductility in the interleaf metal insures that excessive delamination does not occur.

6. There were no significant differences in the fatigue crack propagation rates of crack divider laminates and corresponding monolithic plate alloys.

7. All three fabrication processes employed (diffusion bonding, roll bonding, and explosive bonding) were used to successfully produce highly damage tolerant laminate panels.

Al/Al Laminate Properties

1. Three diffusion bonded 7475 Al/1100 Al laminates (having three different 1100 Al interleaf thicknesses) had 50% to 56% higher critical fracture toughness values than monolithic 7475 Al plate of the same thickness.

2. Measurements of diffusion profiles across 1100 Al interleaves of three different thicknesses indicated that interleaves of 0.13 mm (0.005 in.) and 0.25 mm (0.010 in.) had chemical compositions that would insure soft ductile interleaf properties. These interleaves would fail prior to development of a plane strain stress state through the thickness of the laminate. Measurements on the 0.05 mm (0.002 in.) 1100 Al interleaf

indicated excessive diffusion had occurred of principal alloying elements from the primary alloy through the 1100 Al interleaf. This interleaf thickness was concluded to be unsuitable for use in Al/Al laminate design.

3. The roll bonded 7475 Al/1100 Al and 7075 Al/7072 Al laminates possessed average critical fracture toughness values that were 33% and 35% higher than corresponding monolithic 7475 Al and 7075 Al plate of the same thickness.

4. The explosive bonded 7075 Al/7072 Al laminate had an average critical fracture toughness value that was 50% higher than monolithic 7075 Al plate of the same thickness.

5. Laminates having 7475 Al as the primary alloy were found to have considerably higher crack divider fracture toughness than similar laminates having 7075 Al as the primary alloy (an average of 63% for roll bonded laminates).

6. The single layer sheet toughness of the primary 7475 Al and 7075 Al alloys was retained in all Al/Al laminates tested.

7. Diffusion bonded laminates exhibited "adhesive" bondline failures. Roll bonded laminates showed a combination of "adhesive" and "cohesive" interleaf failure. The explosive bonded laminate displayed 100% "cohesive", ductile interleaf failure. "Cohesive" interleaf failure is considered the preferable failure mode for efficient metal/metal laminate design.

Ti/Al Laminate Properties

1. The diffusion bonded Ti-6Al-4V/6061 Al laminate possessed an average critical fracture toughness that was 117% higher than the baseline monolithic Ti-6Al-4V alloy plate of the same thickness.

2. Laminate primary/secondary bondline failures were observed to be "adhesive" in character.

3. The single layer fracture toughness of the primary Ti-6Al-4V alloy was essentially retained in the Ti/Al laminate panel. The average K_c value for the laminate was only 12% less than that for single layer Ti-6Al-4V sheet of the same thickness as the primary titanium layers in the laminate.

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