Fracture Resistance of Aluminum Alloys
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CHAPTER **11**

Metallurgical Considerations in Fracture Resistance

11.1 Alloy Enhancement

THE APPLICATION OF toughness testing to alloy development has led to a number of high-strength aluminum alloys and special tempers of some alloys with outstanding combinations of strength and toughness. An underlying basis of such work arose from the findings of Staley et al. (Ref 2, 37, 51–54) that the presence of large amounts of impurity elements such as iron and silicon, in high-strength alloys provides sites for potential crack initiation and growth as well as paths for more rapid crack growth than would otherwise be expected. The elimination of these sites would be expected to improve the toughness of the nominal composition, a concept borne out by many experiments. The combination of this principle with other optimization of compositions and thermomechanical treatments has led to the development of high-toughness alloys 2124, 2324, and 2524, all superior to 2024, and of high-toughness alloys 7175 and 7475, both substantial improvements on 7075. Similar principles have been applied to the development of newer alloys such as 7050 and 7055.

The advantages these high-toughness alloys hold over the older, conventional compositions may be seen from the following illustrations from Ref 2 and 52:

- *2124-T851 versus 2024-T851:* Fig. 11.1 illustrates a comparison of K_{Ic} values for 2124-T851 plate with data for 2024-T851 plate from a consistent series of tests; K_{Ic} is 3 to 5 ksi $\sqrt{in.}$ higher for the 2124-T851

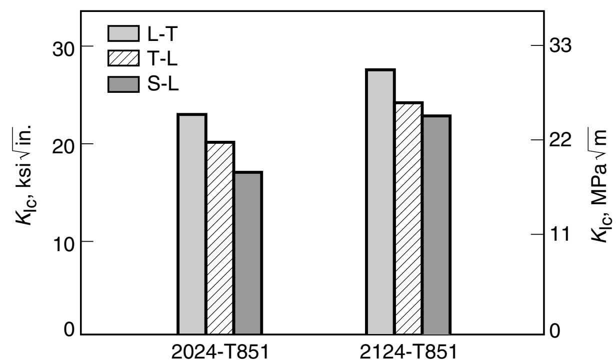


Fig. 11.1 Average plane-strain fracture toughness data for production lots of 4 to 5.5 in. thick 2024 plate

in all test orientations included, and the difference is greatest in the often-critical short-transverse (S-L) orientation.

- *2524-T3 versus 2024-T3:* A comparison of the crack resistance curves for these two alloys is presented in Fig. 7.6, demonstrating the advantages of the composition and processing controls for 2524-T3.
- *2419-T851 versus 2219-T851:* Fig. 11.2 illustrates a comparison of K_{Ic} values for 2419-T851 plate with data for 2219-T851 plate. K_{Ic} is about 3 to 5 ksi $\sqrt{in.}$ higher for the 2419-T851 in all test orientations included, and once again, the percentage difference is greatest in the short-transverse (S-L/S-T) orientations.
- *7050-T73651 (now T7451) versus conventional high-strength alloys:* Fig. 11.3 illustrates the range of K_{Ic} data for production lots of 7050-T73651 plate in the L-T orientation compared with a band of data for conventional high-strength aluminum alloys. The amount of

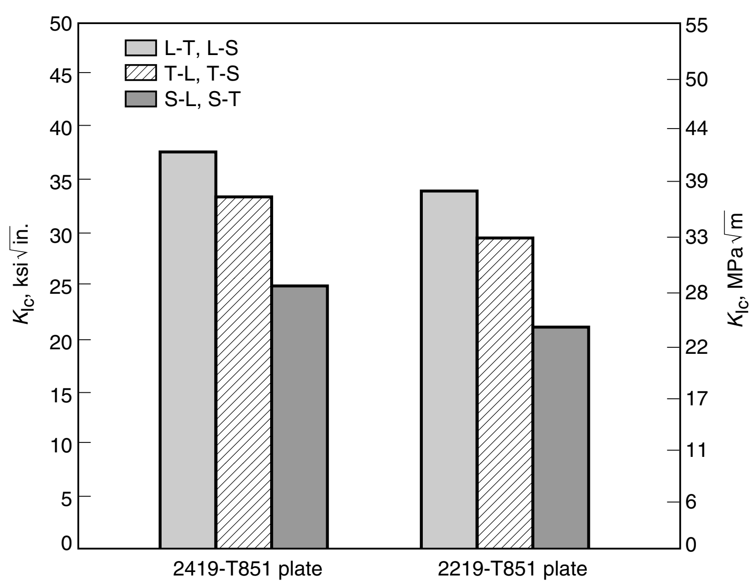


Fig. 11.2 Comparisons of K_{Ic} values for commercial production lots of 2419-T851 and 2219-T851 plate

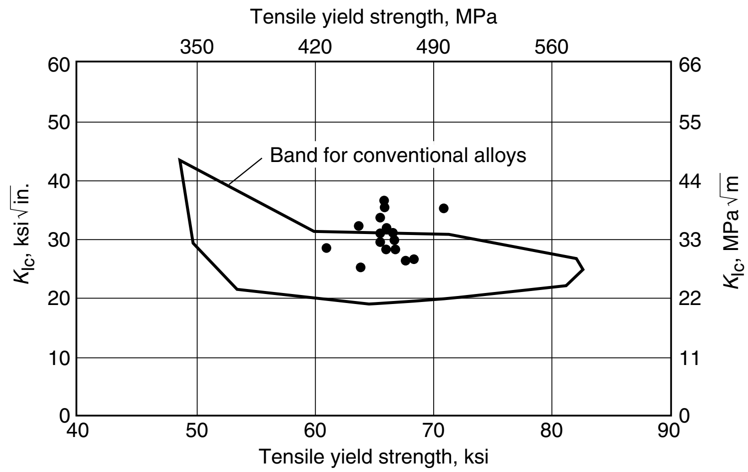


Fig. 11.3 Plane-strain fracture toughness, K_{Ic}, for production lots of 7075-T73651 plate in L-T orientation

Al_2CuMg content present in 7050 has a significant effect on the strength-toughness combination.

- *7175-T66 and T736 (now T74) versus 7075-T6 and T73:* Fig. 11.4 shows the results of comparison tests of die forgings of exactly the same configuration of 7175 and conventional alloy 7075. The 7175 data in both the T66 and T736 (T74) tempers consistently exhibit a superior combination of strength and fracture toughness.
- *7475 versus 7075:* Fig. 11.5 through 11.8 illustrate the advantages of 7475 sheet and plate in various tempers compared with 7075 and other alloys in comparable tempers. Figure 11.5 compares representative K_{Ic} data for production lots of 7475-T651 and T7651 with the range

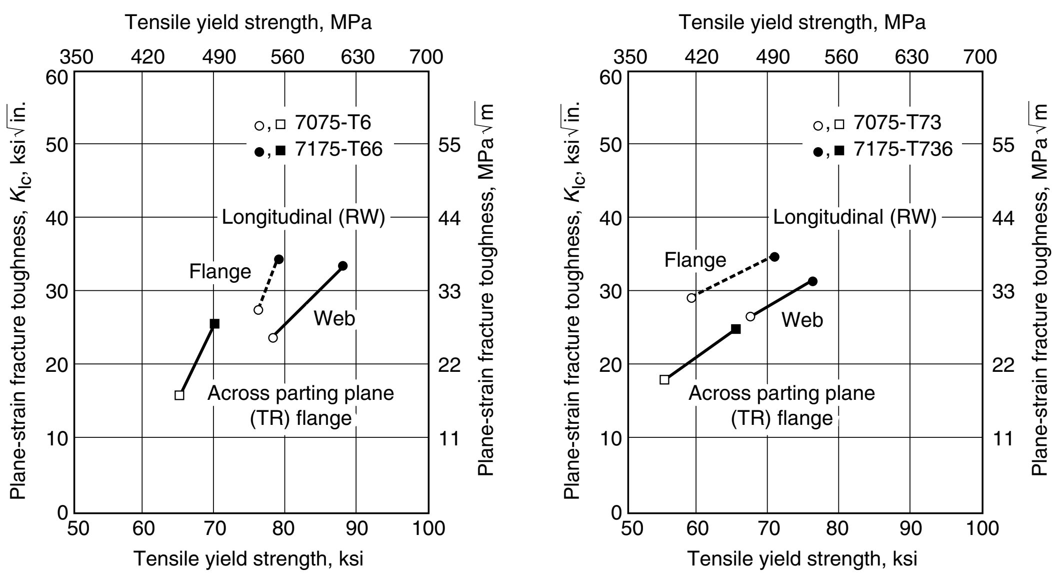


Fig. 11.4 Plane-strain fracture toughness of 7075 and 7175 die forgings of the same configuration

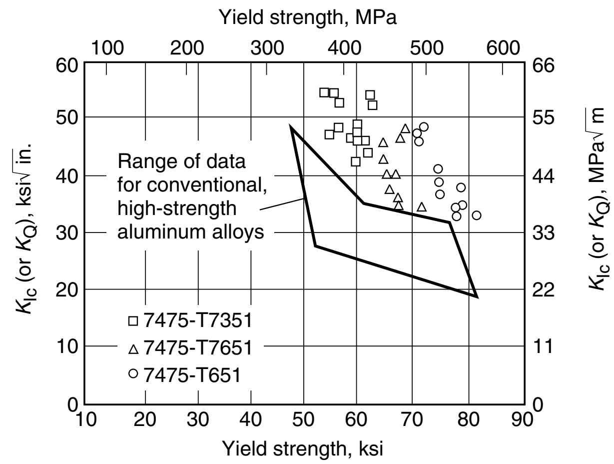


Fig. 11.5 Plane-strain fracture toughness, K_{Ic}, of 7475 plate compared to band of data for conventional high-strength aluminum alloys

of data for 7075 in comparable tempers. Fig. 11.6 shows a similar comparison for 7475 sheet, where the combination of toughness and strength of 7475 is greatly superior to those of a variety of aluminum alloys, including 2024-T3, long renowned for its high toughness. The significance of this comparison is seen in the stress-flaw-size graphs in Fig. 11.7; at any stress, 7475 will tolerate cracks three to four times

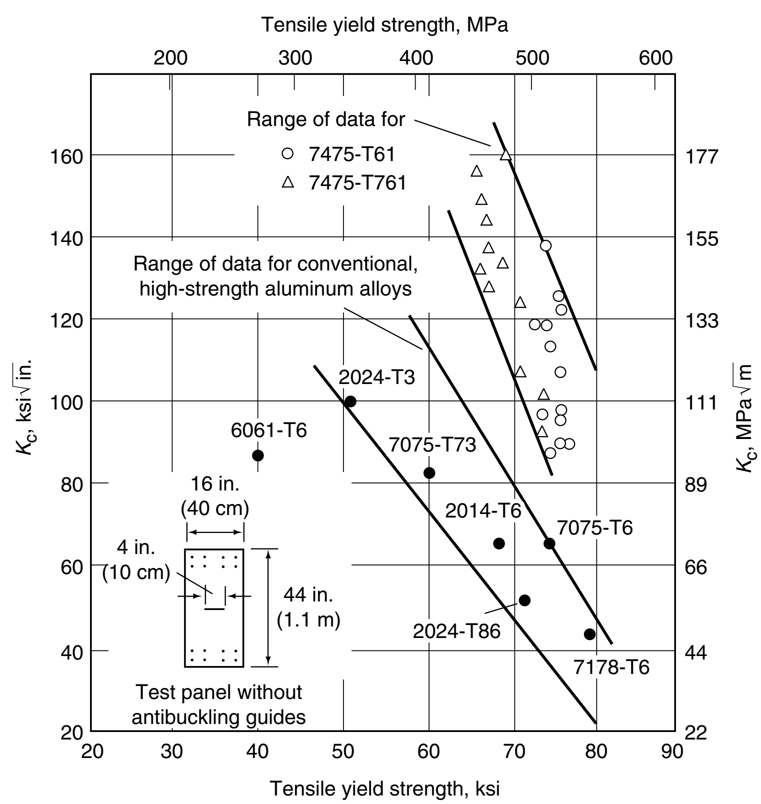
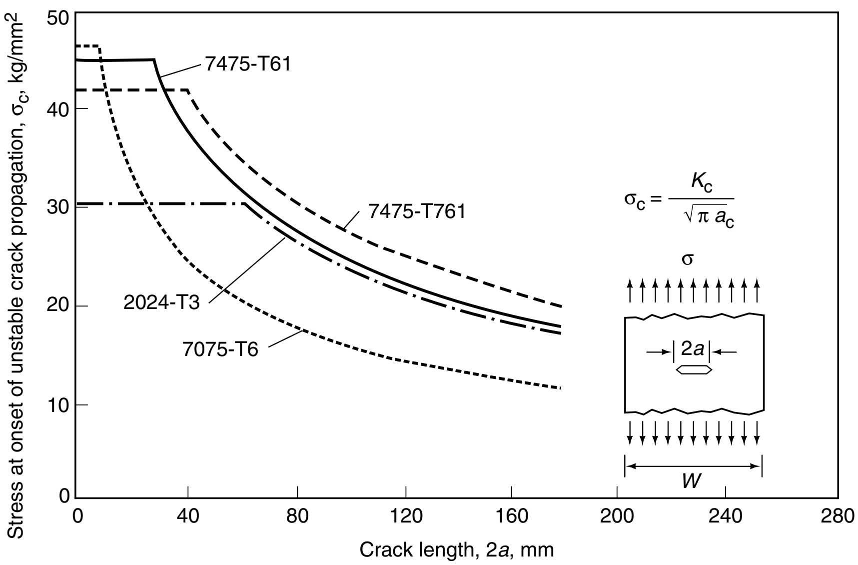


Fig. 11.6 Critical stress-intensity factor, K_c, vs. tensile yield strength for 0.040 to 0.188 in. aluminum alloy sheet



Alloy	K_c, ksi$\sqrt{\text{in.}}$	K_c, MPa$\sqrt{\text{m}}$
7075-T6	55	195
7475-T61	85	300
7475-T761	95	340
2024-T3	85	300

Fig. 11.7 Gross section stress at initiation of unstable crack propagation vs. crack length for wide sheet panels of four aluminum alloy/temper combinations. *W* is total panel width; σ is uniform applied stress.

longer than 7075-T6, and at a given flaw size, 7475 will safely tolerate almost twice the stress. The advantages shown in the crack resistance curves in Fig. 7.7 for 7475 are borne out in totally independent crack growth-resistance curve tests carried out by other investigators, shown in Fig. 11.8.

Several more general metallurgical trends regarding toughness have been confirmed by extensive fracture testing, including:

- Finer, recrystallized grain size leads to higher toughness in comparable products.
- As noted earlier, total iron + silicon content is directly related to the toughness of 2*xxx* and 7*xxx* alloys; the same effect leads to the toughness advantage that A356.0 sand and permanent-mold castings hold over 356.0 castings in corresponding tempers.
- While artificial aging 7*xxx* alloys past peak strength (i.e., “overaging”) leads to higher toughness, the strength-toughness relationship suffers; the strength of T73-type tempers is reduced to a greater extent than toughness is enhanced.
- Warm-water quenching of 7075-type alloys leads to an inferior combination of strength and toughness than cold-water or room temperature water quenching.

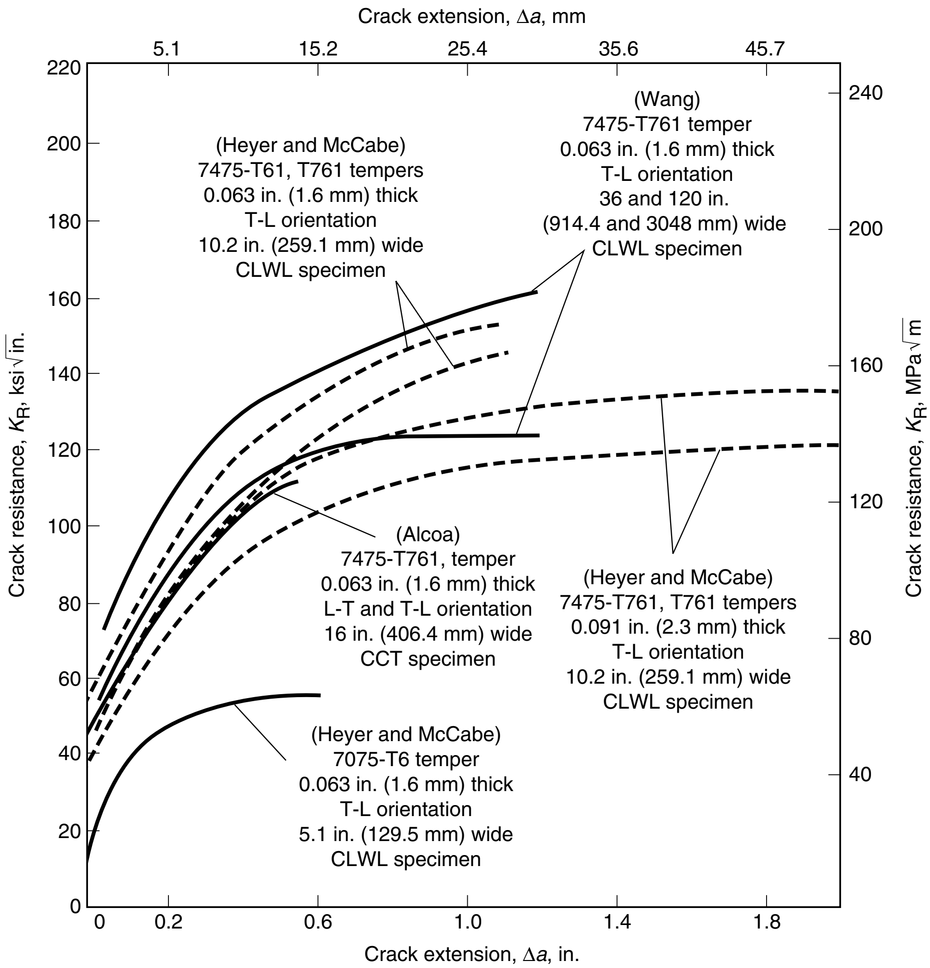


Fig. 11.8 Crack resistance curves for 7475 sheet. Specimen type: CLWL is crack line wedge loaded; CCT is center crack tension.

11.2 Enhancing Toughness with Laminates

The early recognition of the limitations of the toughness of traditional high-strength aluminum alloys for aerospace applications led to studies of the effect of interleaving layers of high-strength aluminum alloy sheet with polymers (Ref 68). Center-notched panels of 0.063 in., 0.125 in., 0.250 in., and 0.500 in. thickness 7075-T6 sheet and plate were tested in full thickness. Then panels of the various thicknesses were produced by laminating the sheets and plates together to produce comparable thicknesses to the monolithic samples and tested using identical procedures as for the monolithic panels. A two-part epoxy was used to produce the multilayered panels.

Center-slotted specimens of the type in Fig. A1.9(a) with very sharp notch-tip radii, and from each monolithic layer and each composite were tested. The specimens were instrumented, and both K_{Ic} and K_c values were measured. The K_{Ic} values were obtained using the loads observed at "pop-in" type of behavior; even with the thinnest sheet specimens, the pop-in and/or the initial deviation from elastic behavior was clear enough with high-strength alloy 7075-T6, T651 to permit comparative measurements of relative plane-strain behavior. The K_c values were generated using the crack lengths and loads at fracture instability.

The results of the tests of these center-slotted panels are summarized in Table 11.1 and are plotted in Fig. 11.9. The tests of the monolithic panels reflected the thickness insensitivity of the plane-strain K_{Ic} toughness level as well as the gradual decrease in stress/mixed mode toughness K_c values with increasing thickness, approaching the K_{Ic} values at the 0.500 in. thickness. These represent classic behavior for 7075-T6, T651. Most importantly, the tests of the laminated panels indicated clearly that the higher toughness of the individual thinner layers is retained in the multilayered panels, even when four layers of 0.063 in. material was used to produce 0.500 in. thick panels. The K_c values for the 0.500 in. thick, multilayered panel were about twice those of the monolithic panels of the same total thickness.

It is clear that for high-strength aluminum alloys, the metallurgical advantages of thin sheets of high-strength aluminum alloys may be retained in relatively thick panels by producing the required thicknesses of multilayered panels of the thinner sheet. The higher-level plane-stress or mixed mode toughness levels of the thinner sheet are retained in the thicker panel, provided that the layers are built up by a means (such as epoxy bonding) that permits the individual layers to deform plastically locally rather than acting monolithically in the thick panel. While the type of specimen design used in this study would not meet the desired rigor of the standard methods of today, the findings are unambiguous and meaningful.

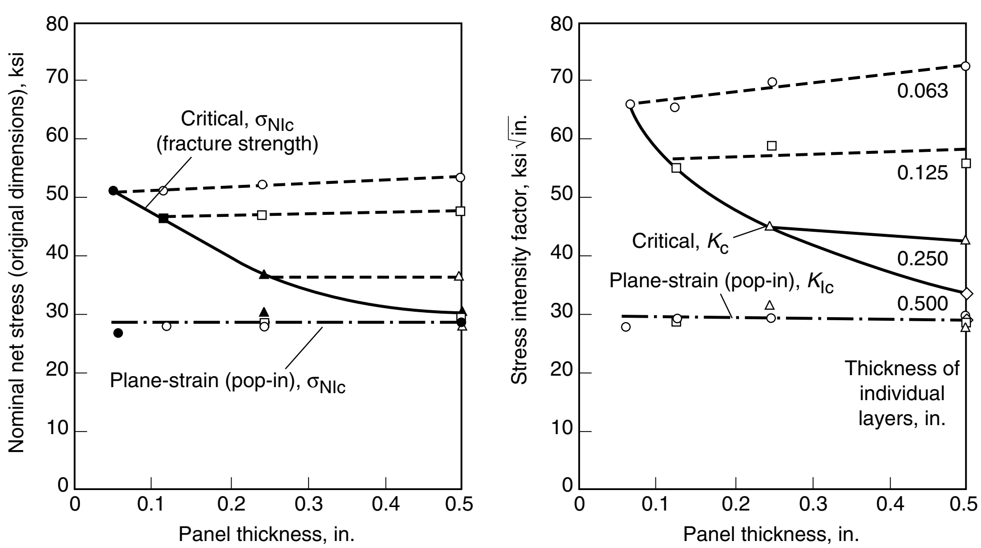


Fig. 11.9 Results of fracture toughness tests of plain and laminated panels of 7075-T6 and 7075-T651 sheet and plate (transverse). Solid symbols, single thickness; open symbols, multilayered

Table 11.1(a) Results of fracture toughness tests of 7075-T6 and 7075-T651 sheet, plate, and multilayered adhesive-bonded panels bonded with two-part epoxy, transverse direction (at initial pop-in instability)

Total nominal thickness, in.	Represented by	Width, W, in.	Thickness, t, in.: Includes adhesive	Thickness, t, in.: Net	Total crack length, in.: Original, $2a_o$	Total crack length, in.: Critical, $2a_c$	At pop-in instability: Load, P_{Ic}, lb	At pop-in instability: Stress, ksi: Gross, σ_{Ic}	At pop-in instability: Stress, ksi: Net(a) σ_{NIc}	Plane-strain stress-intensity factor, ksi $\sqrt{in.}$, K_{Ic}	Plane-strain strain-energy release rate, in.-lb/in.^{2} G_{Ic}
0.063	0.063 in. sheet	3.99	...	0.062	1.72	2.05	3,800	15.4	27.1	28.1	68
		4.00	...	0.062	1.72	2.08	3,800	15.3	27.0	28.0	68
		Average								**28.0**	**68**
0.125	0.125 in. sheet	4.00	...	0.122	1.72	1.96	7,950	16.3	28.6	29.8	77
		4.00	...	0.122	1.71	1.89	7,700	15.8	27.6	28.7	71
		Average								**29.2**	**74**
	Two layers of 0.063 in. sheet	4.00	0.131	0.124	1.71	1.96	7,500	15.1	26.4	27.5	65
		3.99	0.132	0.124	1.70	2.08	8,500	17.2	29.9	31.3	85
		Average								**29.4**	**75**
0.250	0.250 in. plate	3.99	...	0.253	1.70	2.06	18,220	18.0	31.5	32.8	94
		4.00	...	0.253	1.71	2.11	16,710	16.5	28.9	30.1	78
		Average								**31.4**	**86**
	Two layers of 0.125 in. sheet	4.00	0.254	0.244	1.70	1.96	15,900	16.3	28.3	29.5	76
		4.00	0.254	0.244	1.71	2.10	16,050	16.4	28.7	29.9	78
		Average								**29.7**	**77**
	Four layers of 0.063 in. sheet	4.00	0.268	0.248	1.71	2.07	15,050	15.2	26.5	27.6	66
		4.00	0.273	0.248	1.70	2.09	16,400	16.5	28.8	30.0	78
		Average								**29.8**	**72**
0.500	0.500 in. plate	4.00	...	0.500	1.71	1.86	31,700	15.8	27.7	28.8	72
		4.00	...	0.500	1.72	2.00	33,600	16.8	29.5	30.6	81
		Average								**29.7**	**76**
	Two layers of 0.250 in. plate	3.99	0.520	0.506	1.70	2.05	31,600	15.7	27.3	28.3	70
		4.00	0.517	0.506	1.71	2.00	31,200	15.4	26.9	28.0	68
		Average								**28.2**	**69**
	Four layers of 0.125 in. plate	4.00	0.526	0.488	1.71	1.94	31,300	16.0	28.0	29.2	73
		3.99	0.522	0.488	1.71	1.92	31,300	16.1	28.1	29.3	74
		Average								**29.2**	**74**
	Eight layers of 0.063 in. sheet	4.00	0.562	0.496	1.70	2.10	35,200	17.7	30.8	32.4	91
		4.00	0.562	0.496	1.72	2.11	31,200	15.7	27.6	28.8	71
		Average								**30.6**	**81**

Specimens per Fig. A1.9. (a) Based on original cross section, $(W-2a_o)t$; nominal net fracture strength

Table 11.1(b) Results of fracture toughness tests of 7075-T6 and 7075-T651 sheet, plate, and multilayered adhesive-bonded panels bonded with two-part epoxy, transverse direction (measurements at fracture instability)

Total nominal thickness, in.	Represented by	Width, W, in.	Thickness, t, in.: Includes adhesive	Thickness, t, in.: Net	Total crack length, in.: Original, $2a_o$	Total crack length, in.: Critical, $2a_c$	At fracture instability: Load, P_c, lb	Stress, ksi: Gross, σ_c	Stress, ksi: Net(a) (nominal), σ_{Nc}	Stress, ksi: Net(b) (actual), σ_N	Critical stress-intensity factor, ksi $\sqrt{\text{in.}}$, K_c	Critical energy release rate, in.-lb/in.^{2}, G_c	σ_N/σ_{ys}
0.063	0.063 in. sheet	3.99	...	0.062	1.72	2.05	7,250	29.4	51.8	60.3	67.1	437	
		4.00	...	0.062	1.72	2.08	7,250	29.2	51.4	60.5	67.3	440	
		Average								**60.4**	**67.2**	**438**	0.86
0.125	0.125 in. sheet	4.00	...	0.122	1.72	1.96	13,625	27.9	49.0	54.7	59.6	345	
		4.00	...	0.122	1.71	1.89	12,325	25.3	44.2	47.9	51.4	256	
		Average								**51.3**	**55.6**	**300**	0.69
	Two layers of 0.063 in. sheet	4.00	0.131	0.124	1.71	1.96	14,500	29.2	51.1	57.3	63.8	395	
		3.99	0.132	0.124	1.70	2.08	14,675	29.6	51.7	62.0	69.3	467	
		Average								**60.1**	**66.6**	**431**	0.85
0.250	0.250 in. plate	3.99	...	0.253	1.70	2.06	21,250	21.1	36.7	43.5	45.2	198	
		4.00	...	0.253	1.71	2.11	21,300	21.0	36.8	44.5	46.2	207	
		Average								**44.0**	**45.7**	**202**	0.59
	Two layers of 0.125 in. sheet	4.00	0.254	0.244	1.70	1.96	26,125	26.8	46.6	52.5	56.7	312	
		4.00	0.254	0.244	1.71	2.10	27,025	27.7	48.3	58.3	63.2	387	
		Average								**55.4**	**60.0**	**350**	0.75
	Four layers of 0.063 in. sheet	4.00	0.268	0.248	1.71	2.07	29,750	30.0	52.4	62.2	69.9	474	
		4.00	0.273	0.248	1.70	2.09	30,150	30.4	52.9	63.6	72.0	503	
		Average								**62.9**	**71.0**	**488**	0.88
0.500	0.500 in. plate	4.00	...	0.500	1.71	1.86	34,300	17.1	30.0	32.1	33.3	108	
		4.00	...	0.500	1.72	2.00	34,300	17.1	30.0	34.3	35.3	121	
		Average								**33.2**	**34.3**	**114**	0.45
	Two layers of 0.250 in. plate	3.99	0.520	0.506	1.70	2.05	41,550	20.6	35.8	42.4	43.9	187	
		4.00	0.517	0.506	1.71	2.00	41,200	20.4	35.5	40.7	42.4	175	
		Average								**41.6**	**43.2**	**181**	0.56
	Four layers of 0.125 in. plate	4.00	0.526	0.488	1.71	1.94	53,650	27.5	48.0	53.3	57.9	326	
		3.99	0.522	0.488	1.71	1.92	52,950	27.2	47.6	52.4	56.8	312	
		Average								**52.8**	**57.4**	**319**	0.71
	Eight layers of 0.063 in. sheet	4.00	0.562	0.496	1.70	2.10	61,550	31.0	53.9	65.3	74.5	539	
		4.00	0.562	0.496	1.72	2.11	61,250	30.8	54.2	65.3	74.4	537	
		Average								**65.3**	**74.4**	**538**	0.93

Specimens per Fig. A1.9. (a) Based on original cross section, $(W-2a_o)t$; nominal net fracture strength. (b) Based on cross section at onset of rapid fracture, $(W-2a_c)t$