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FRACTURE RESISTANCE OF ADHESIVELY-BONDED 7075-T6 ALUMINUM ALLOY LAMINATES

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INTRODUCTION

Thickness effects in the fracture of high strength alloys are well known. In general, greater fracture toughnesses are measured in thin sections, down to some limit, with smaller thicknesses required for the development of high toughness in alloys of greater strength [1]. In the past, most thin-section fracture results have been presented in terms of "plane stress" fracture toughness, K_c. Unfortunately, the K_c values measured in a given alloy for a given thickness also depend significantly on other features of specimen geometry, particularly width, W, and crack aspect ratio, a/W [2]. In addition, testing machine characteristics and the degree of out-of-plane buckling permitted may affect the measured toughness. When the usual variability due to metallurgical differences is included, the result can be a near-total masking of the thickness effect by scatter in K_c caused by these other variables[3]. For tests carried out under closely similar conditions, however, the thickness effect becomes more apparent; fracture toughnesses of about $3K_{Ic}$ can be measured in some cases.

Use of K_c values in engineering analysis and design is difficult because of the uncertainties introduced by the sources of variability mentioned above. An alternative, the crack growth resistance curve, introduced in its present form by Krafft, Sullivan and Boyle [4], is potentially more useful. The postulated equivalence between crack extension force, G or K, and resistance to crack growth, R or K_R, while stable crack growth proceeds, provides a method of presenting fracture data from which much of the specimen-dependence is removed [5]. While its ultimate value as a technique of engineering analysis is less obvious, the R-curve does provide a rational means for comparing fracture behaviours in the same material as a function of, for instance, thickness, or for comparing different materials. This can be done by examining complete R-curves or by comparing R or K_R values for a specific amount of crack extension, Δa. More meaningful studies of the effect of thickness on fracture toughness are in this way possible.

LAMINATES

The increases in toughness observed in high strength alloys at low thicknesses suggest the fabrication of "crack divider" laminates made by joining thin layers with relatively weak interfacial bonds [6]. Each lamina can then fracture independently, exhibiting the same fracture resistance it would have in single sheet form. For aluminum alloys, adhesive bonding provides a satisfactorily weak interface, Kaufman [7] having measured K_c values of the order of $2K_{Ic}$ in laminates made by bonding together 1.6 mm thick 7075-T6 sheets.

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Fabrication of laminated elements by adhesive bonding thus allows, in principle the design of structural members in any thickness having the toughness of the original sheet. In addition to the higher fracture toughness, somewhat better fatigue resistance can be achieved, due primarily to the redundancy of the laminate, with crack initiation and growth occurring more-or-less independently in the several laminae. It is also possible to combine layers of different thicknesses, as well as various alloys and tempers of a given family, to achieve a desirable combination of properties; if thermal strains are compensated for, alloys of several families can be combined. The present study, however, was concerned solely with the effect of lamina thickness in a particular alloy, 7075-T6 aluminum.

Previous work [8] has demonstrated the practicality of deriving resistance curves for adhesively bonded 7075-T6 laminates using relatively small (6.35 cm x 6.1 cm) compact tension specimens. In determining the laminate R-curve, in effect an average R-curve for the particular lamina thickness, the problem of out-of-plane buckling is also avoided, as the crack grows at slightly different locations in each layer. This is a simple way of preventing buckling in thin sheet fracture tests.

In this work 8 layers of 0.84 mm thick clad 7075-T6 were used. When compared with monolithic material of comparable overall thickness (6.5 mm), toughnesses about 50% higher were measured for the laminates. Similar tests have now been conducted using both thinner and thicker 7075-T6 laminae.

EXPERIMENTAL PROGRAMME

One set of laminates had a layer thickness of 0.292 mm -- below the range for which fracture toughness data have been commonly acquired. The thicker 7075-T6 laminae were 1.54 mm, for which ample data from single sheet tests are available for comparison.

As in previous tests [8], the laminates were machined to standard compact specimen form (H/W = 0.6, W = 5.08 cm). The laminate configurations, together with their tensile properties, are given in Table 1. In all cases the loading axis was parallel to the rolling direction of the sheet. The layers were joined with Hysol EA 9410 epoxy; bondline thicknesses were 0.05 mm for the 22-layer laminates, 0.12 mm for those with 4 layers.

Fatigue cracking was used to give a range of initial crack lengths. Maximum stress intensity for the last increment of fatigue crack growth was less than 20 MPa•m$^{1/2}$. Fracture tests were then conducted under load-control with a standard fracture mechanics clip gage sensing the displacement across the crack mouth. Effective crack lengths were determined using Roberts' [9] analysis for the compact specimen. Newman's [10] K-calibration was employed.

RESULTS AND DISCUSSION

Crack growth resistance curves for the 22-layer and 4-layer laminates are shown in Figure 1. Average curves for the 8-layer laminates (lamina thickness 0.84 mm) and for monolithic material (6.5 mm thick) previously tested [8] are also given. The relatively larger divergences between R-curves for laminates of the same type at small crack extensions are attributed to slightly different fatigue crack lengths in the several layers; as the cracks extend, becoming more nearly uniform in length in all layers, the R-curves approach one another more closely. Typical fracture surface appearances are shown in Figure 2.

Laminates with 22 layers gave K_R values comparable to those for 8-layer laminates at small crack extensions (Figure 1); however for greater Δa_{eff} the 22-layer R-curves are lower. Figure 1 also indicates that considerably greater amounts of stable crack extension occurred in the previously tested 8-layer and monolithic material. Evidently the smaller values of Δa_{eff} at instability for both the 22-layer and 4-layer laminates result from the lower slopes of their resistance curves, particularly evident when comparing 22-layer laminates to those with 8-layers. Consideration of the tangency condition for instability, $\partial K_R/\partial a = \partial K/\partial a$, indicates that the slope of the R-curve will have a major effect on the extent of stable growth. This is particularly true for compact specimens where the slopes of the applied stress intensity curves, $\partial K/\partial a$, are also shallow. At least part of the reason for the differences in the slopes of the R-curves of Figure 1 appears to lie in variations in strain hardening rate in the various materials. In none of these tests was the initial crack length, ranging from 20 to 26 mm, found to influence Δa_{eff} at instability.

Concerning the overall toughness levels exhibited in Figure 1, it has frequently been hypothesized that K_c increases with decreasing sheet thickness until reaching a maximum, beyond which it falls off to zero at zero thickness. However, because of the geometry-dependence of K_c values in thin sheet material, it is better to examine such behaviour in terms of the K_R corresponding to a fixed amount of crack extension [11]. In Figure 3, K_R values for 1.5 mm of crack extension for 7075-T6 alloy in several different thicknesses are shown. This figure includes averages from the present work as well as Reference [8] (Figure 1) and several other studies. Of these, Kaufman's [7] results encompass both monolithic panels and adhesively bonded laminates. Kaufman did not present R-curves; the K_R values in Figure 3 were found by plotting K_c as a function of Δa for the several specimens of each thickness that he tested and extrapolating back to $\Delta a_{eff} = 1.5$ mm. In all cases in Figure 3 the crack extensions are effective--determined from displacement measurements--but both LT and TL orientations with respect to rolling are represented. This accounts for some of the variation, particularly evident for thicknesses of 1.6 mm. The lowest point for this thickness, from Freed et al [13], for example, is for a TL orientation, which generally gives lower toughness than the LT case. Although the 4-layer R-curves in Figure 1 were initially thought to be rather low, perhaps as a result of the unusually high strength level of the particular sheet from which they were fabricated (Table 1), Figure 3 indicates that these laminates are not abnormal.

Figure 3 does show a more pronounced trend for increase in fracture toughness with decreasing thickness than plots based on K_c which similarly include data from a number of sources--see, for example, Figure 6 in Reference [3]. How much of the scatter in Figure 3 might represent the effect of different specimen types is impossible to say, although it does seem that R-curves are at least nominally specimen-independent [5, 14].

Figure 3 also indicates that the greatest toughness in 7075-T6 alloy is reached at thicknesses of about 1 mm. This is in accord with the results of Weitzmann and Finnie [15], obtained using a single test specimen of varying thickness. However, their peak toughness value, 125 MPa•m$^{1/2}$, is much higher than has been found here using R-curve methods. Weitzmann and Finnie's results also show a very rapid rise to peak toughness followed by a correspondingly steep drop as the thickness continues to decrease. However at least some of this precipitate variation in toughness with thickness is attributed to the peculiarities of their specimen, which is face-grooved as well as tapered [15].

Figure 2 shows that full slant fractures result even in the 1.54 mm material which is below peak toughness. Thus models which attempt to account for toughness variations with thickness on a simple shear lip width basis--the peak toughness being supposed to result when a full slant fracture just developes [16, 17]--must be considerable oversimplifications.

CONCLUSION

Peak toughnesses in adhesively-bonded 7075-T6 aluminum laminates are developed when the lamina thickness is about 1 mm. In the absence of buckling, single sheets of the same thickness range would be expected to exhibit similar toughnesses. The actual magnitude of the fracture toughness depends on the extend of stable crack growth; for the laminated compact tension specimens of 7075-T6 alloy tested, the amount of slow crack growth observed depends on the slope of the R-curve, not on the initial crack length.

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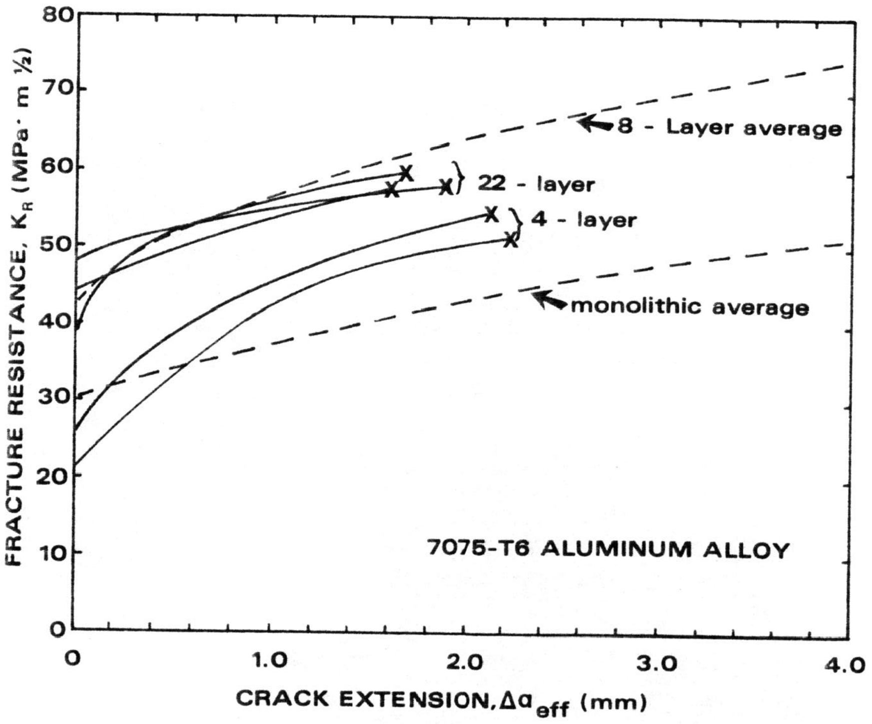

Figure 1 Resistance Curves for 22-Layer (Layer Thickness 0.292 mm) and 4-Layer (Layer Thickness 1.54 mm) Laminates. Results from Reference [8] for 8-Layer (Layer Thickness 0.84 mm) and Monolithic (6.5 mm thick) Clad Material Also Shown

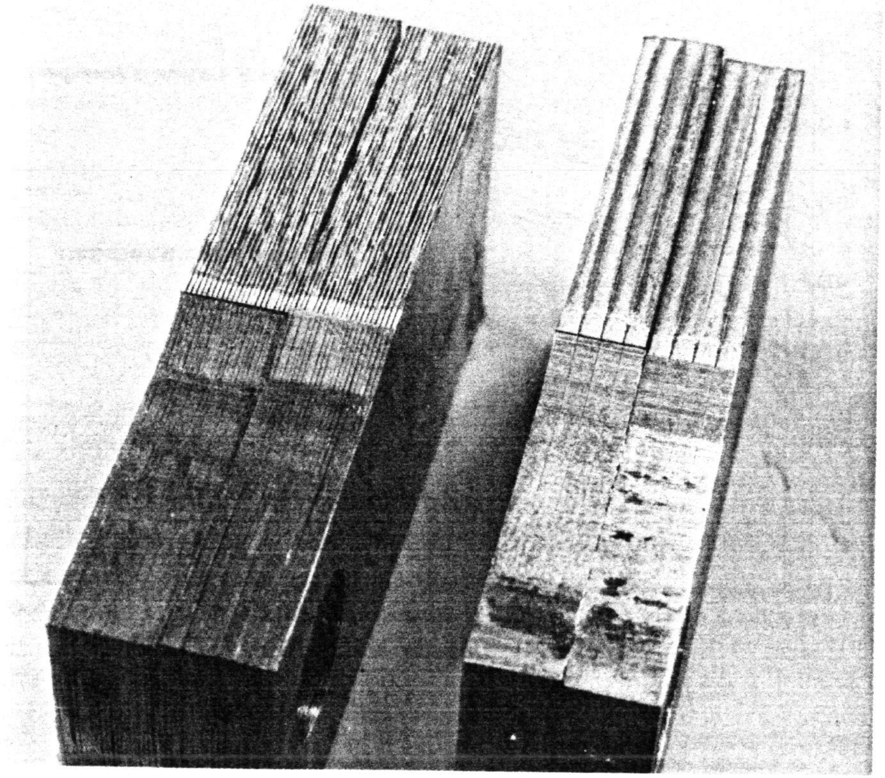

Figure 2 Fracture Surfaces of 22-Layer and 4-Layer 7075-T6 Laminates

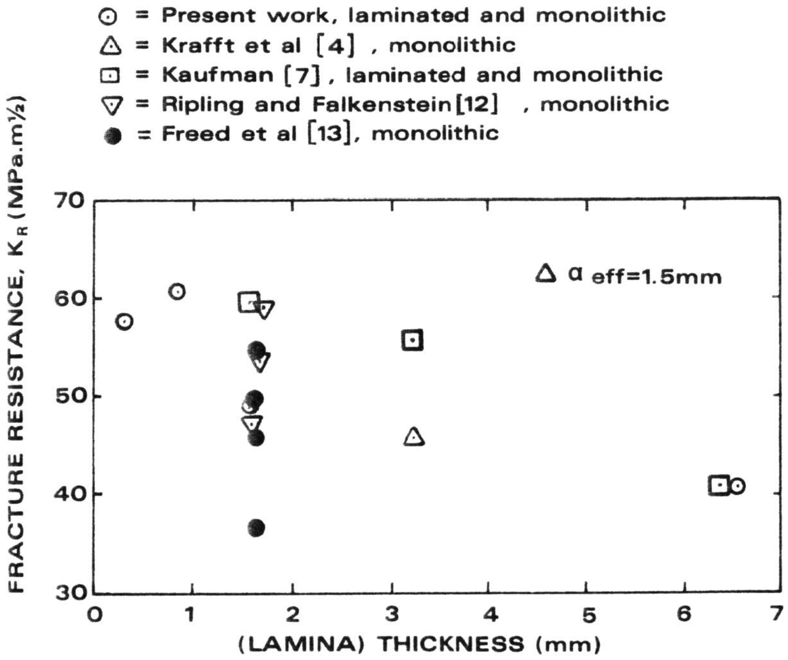

Figure 3 Fracture Resistance for Δa_{eff} = 1.5 mm in Laminated and Monolithic 7075-T6 Aluminum Alloy

Table 1 7075-T6 Laminates Tested

Lamina Thickness (mm)	Number of Layers	Average Tensile Properties		
		0.2% Offset Yield Str. (MPa)	Tensile Str. (MPa)	Elong. in 2.5 cm (%)
0.292	22	496	545	16
1.54	4	551	594	18