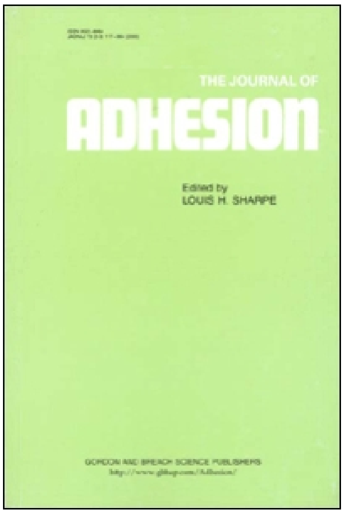

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Fatigue Crack Initiation and Propagation in Bonded Sheets†

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The initiation and propagation of fatigue cracks in bonded sheets are investigated. Two sheets of 2024 T346 aluminum alloy are bonded together either with CC15 or Epoxy adhesive and a center notch is created in one of them. The bonded second sheet tends to reduce the stress intensity factor at the tip of the notch in the first sheet, thereby retarding both crack initiation and propagation. The experiment is compared with calculated reductions in stress intensity factor and the crack growth results show reasonable agreement.

INTRODUCTION

An adhesively bonded structure is expected to have a greater damage tolerance capability than an identical monolithic structure, when the failure involves crack extension in one of the adherends. Furthermore, the rate of fatigue crack growth in an individual layer of the bonded structure may be less than the rate of growth for a crack of the same length in the monolithic structure.

A recent paper by Erdogan and Arin [1] considers the calculation of stress intensity factor for a sandwich plate with a part-through and a debonding crack, where the materials of the sandwich plate consist of an isotropic sheet and an orthotropic sheet which are held together by an adhesive layer. Their method requires the solution of an integral equation over the area of the *intact* adhesion region.

Keer, Lin and Mura [2] calculate the stress intensity factor at the crack tip for adhesively bonded sheets, one of which is cracked; the adhesive in this case does not debond, and the stress intensity factor calculated will be a

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somewhat less conservative estimate. According to the theoretical results, the stress intensity factor is reduced from that of the monolithic case, and the reduction of the fatigue crack growth rate due to adhesive bonding can be attributed to the reduction of the stress intensity factor.

In this paper experimental results of fatigue are reported on the crack initiation and propagation for bonded sheets and compared with the theory obtained by Mura and Lin,[3] where the stress intensity factor calculated by Keer *et al.*[2] is used.

EXPERIMENTAL PROCEDURE

The material used in the experiment is commercial 2024 aluminum based alloy with T356 heat treatment. The chemical composition of the alloy is Cu 4.5, Mn 0.6, Mg 1.5 in weight percent. The rectangular sheet specimens, shown in Figure 1, were prepared by taking the longitudinal direction in the rolling direction in the alloy. The surfaces of the specimens were polished with 1 μ diamond paste. A center notch of 1 mm length and 0.2 mm width was introduced by electro-discharge machining. The center notched sheet was bonded with adhesive to the undamaged second sheet. The completed, three layer composite specimen is called a bonded sheet. The thickness of adhesive and length of notch and crack were measured using a 100× telemicroscope, which can measure accurately a length of about 1/500 mm.

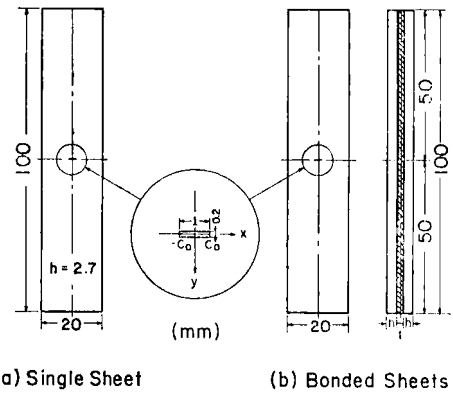

FIGURE 1 Geometry of the bonded sheet.

Two different adhesives, CC15 and Epoxy, were used to observe the effect of the adhesive property. The mechanical properties of these adhesives are listed in Table 1. These adhesives were applied by 1 kg weight at room temperature and cured for seven days for Epoxy and three days for CC15, respectively.

TABLE I

Mechanical properties of the adhesives

Adhesive material	Brand name	Maker	Tensile strength MN/m²	E MN/m²	G MN/m²	ν
α-cyanoacrylate	CC15	Toagosui Chemical Co.	186	784	271	0.45
Epoxy	Araldite AW-106	Ciba Co.	235	1471	506	0.45

The fatigue tests were conducted using a closed loop electrohydraulic MTS fatigue machine at 30 Hz. The R ratio (minimum stress/maximum stress) was 0.05. The length of the propagating crack was measured with a 100× telemicroscope for given fixed number of cycles.

CRACK INITIATION

The experimentally observed numbers of cycles needed for crack initiation, N_i, and failure, N, at three different levels of stress amplitude are shown in Figure 2 for single and bonded sheets with CC15 adhesive and bonded sheets with Epoxy adhesive. Their theoretical curves which will be explained later in this section are also shown in Figure 2 by A_i, B_i, C_i, and A_f, B_f, and C_f. The geometry of the single sheets is the same as that of the notched sheet in the bonded sheets as shown in Figure 1. It is observed that the bonded sheets always have larger values of N_i and N than the single sheets for the

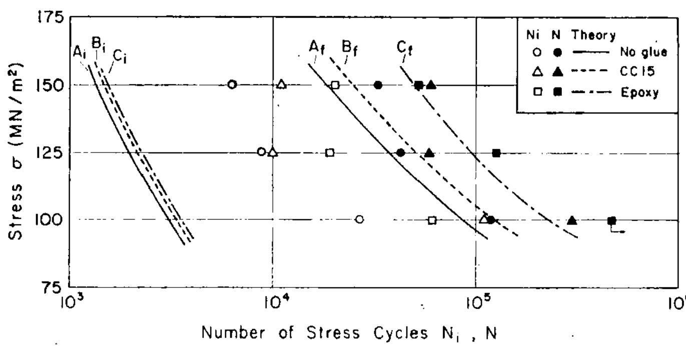

FIGURE 2 Experimental data and theoretical curves for numbers of stress cycles needed for crack initiation and failure at various stress levels. (*No glue*: — theory, ● N, ○ N_i; *CC15*: --- theory, ▲ N, △ N_i; *Epoxy*: — - — theory, ■ N, □ N_i).

same stress level. Clearly, the bonding improves the fatigue property of the structures, because the presence of the second sheet (unnotched sheet) reduces the stress intensity factor of the crack in the notched sheet. The reduction of stress intensity factor of the crack was calculated in Ref. 2, and the result for infinitely extended medium is shown in Figure 3. Here, K and K^* are the stress intensity factors of the bonded sheet and the single sheet, respectively; c is the half length of the crack; and $s = 2G/\mu th$, where G and μ are the shear modulus of the adhesive and the sheet, respectively, t and h are the thickness of the adhesive and of each of the two sheets, respectively. The reduction of stress intensity factor for a finite width is also shown in Ref. 2. For simplicity, however, in this paper the effect of width is introduced by Ishida's correction since it has been found that the difference is negligibly small.

According to Mura and Lin,[3] the number of cycles for crack initiation at the tip of a notch with stress intensity factor K is expressed by

$$N_i = \frac{8\mu U_0}{1+\kappa} K^{-2} \tag{1}$$

where $\kappa = (3-\nu)/(1+\nu)$ for plane stress, $\kappa = 3\text{–}4\,\nu$ for plane strain, and ν, μ are Poisson's ratio and the shear modulus of the single sheet, respectively. U_0 is the effective surface energy for crack formation. For the bonded sheet the modified K is used, as shown in Figure 3; namely, the effect of the second sheet is included through the reduction of the stress intensity factor. Thus we put

$$K = \sqrt{\pi c}\,\sigma f(c) g(cs^{\frac{1}{2}}) \tag{2}$$

where $f(c)$ is Ishida's correction term [4] for finite width of the specimen and $g(cs^{\frac{1}{2}})$ is the value of K/K^* shown in Figure 3. The substitution, Eq. (2), will be used again later, and when it is used for (1), c is taken as the half length of the notch.

The following numerical values are taken:

$$\begin{aligned} \mu &= 26410\ \text{MN/m}^2, & \nu &= 0.33, & \kappa &= 2.0 \\ G &= 271\ \text{MN/m}^2,\ \text{for CC15}, & & & t &= 0.05\ \text{mm} \\ G &= 506\ \text{MN/m}^2, & &\text{for Epoxy}, & t &= 0.05\ \text{mm} \\ U_0 &= 0.7\times 10^6\ \text{J/m}^2. \end{aligned}$$

The resulting curves from Eq. (1) for N_i are shown by A_i, B_i and C_i in Figure 2 for the single sheet, the bonded sheet with CC15 adhesive, and the bonded sheet with Epoxy adhesive, respectively. The corresponding theoretical values of N, which will be explained in the following section, are shown by A_f, B_f, and C_f and are obtained by using the same numerical values as listed above. The value of U_0 was chosen so that these curves fit reasonably well with experiments. The experimental observation of N_i depends upon the accuracy of the telescope used. If the initiation of a crack can be detected in early stages, the data will be shifted to the left in Figure 2. Thus the discrepancy between the theoretical curves and experimental data is understandable.

CRACK PROPAGATION

The rates of crack propagation were measured for a single sheet and two bonded sheets with different types of adhesives. Figure 4 shows data for the stress amplitude of 125 MN/m^2. Similar data were obtained for other stress levels. Data are given for the single sheet and for the bonded sheets with CC15 and Epoxy adhesives, respectively, where the stress intensity factor has been taken as $\sqrt{\pi c}\sigma f(c)$. When the stress intensity factor for the bonded sheets is modified according to Ref. 2, the data points for the bonded sheets are shifted to the left as shown. If the theory that modifies the stress intensity factor is correct, then the modified points for the bonded sheets should be on the same line as the data for the single sheet. The solid line in Figure 4 is drawn from the theoretical result of Mura and Lin:[3]

$$\frac{dc}{dN} = \frac{\pi(1+\kappa)}{256\,\mu\,U_0\sigma_y'^2}K^4 \tag{3}$$

where σ_y' is the cyclic yield stress and is taken as 300 MN/m^2.[5] The other values of μ, κ, U_0 are the same as listed before. For a constant σ, K is a function of c. If we integrate (3) with respect to c from the initial value (half length of the notch) to the final value of the half width of the specimen, we have the cycle number for failure, N.

The results for N are shown by curves A_f, B_f, C_f for the single sheet and for the bonded sheets with CC15 and Epoxy adhesives, respectively. The

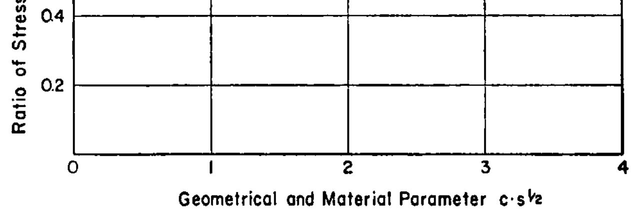

FIGURE 3 Ratio of the stress intensity factors for a bonded sheet and a single sheet. c is the half length of a crack and s is proportional to the strength of the adhesive.

theory is in reasonable agreement with the experiment. It is also noticed that 80% of the fatigue life is spent for propagation of the crack and 20% for initiation of the crack.

In the process of comparison of the theory and experiment, the only assumed value was U_0. The agreement between the theory and experiment

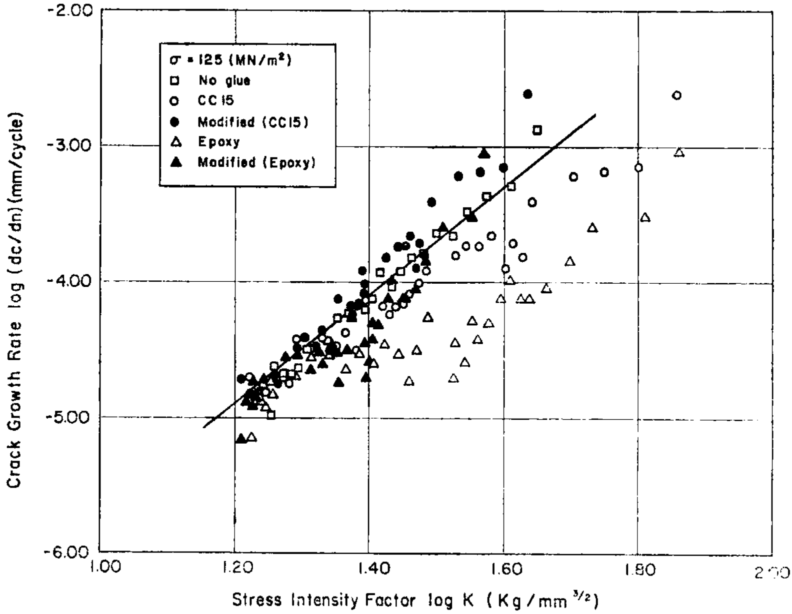

FIGURE 4 Crack growth rates versus the stress intensity factor, stress level $\sigma = 125$ (MN/m^2) (□ No glue; ○ CC15, ● Modified (CC15); △ Epoxy, ▲ Modified (Epoxy)).

is rather remarkable considering that only one parameter was available for adjusting the agreement. Moreover, the value assumed for U_0 is of the same order as the magnitude reported for the effective surface energy by others: $U_0 = 2.0 \times 10^6$ J/m^2 by Weertman,[6] 1.1×10^7 J/m^2 by Rice,[7] and $0.54 \sim 1.20 \times 10^6$ J/m^2 by Ikeda *et al.*[8]

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