NONDESTRUCTIVE CHARACTERIZATION AND BOND STRENGTH OF SOLID-SOLID BONDS

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INTRODUCTION

With increasing demand in industry to produce solid-solid bonds, the need for their quantitative characterization, particularly with respect to their strength, becomes more urgent. In the present paper, restricted to diffusion bonds in metallic systems, we define strength as the ultimate engineering stress achieved in a uniaxial tensile test at slow strain rate. It is assumed that the reduction of strength is basically determined by a lack of metallic bonding over a fraction of the total area to be bonded, with metallically bonded areas being separated by crack-shaped voids. In the present paper, these voids are considered to contain a vacuum or, at most, a low pressure gas. In principle, they could be filled with some form of a solid contaminant (oxide, e.g.) which increases the complexity of the analysis[1]. Furthermore, the present paper concentrates on a situation where self-diffusion, necessary to achieve bonding, is the only metallurgical effect considered. Any phase transformations, precipitate reactions and grain growth during the bonding process are ignored. In addition, the materials on either side of the bond are identical. At present, it is not anticipated that the case of dissimilar materials will adversely complicate the following analyses too much, particularly in the case of materials of complete mutual solid solubility and having similar work hardening behavior in the two materials. Certainly, the acoustic impedance mismatch at such an interface has to be taken into account, however[1].

The bulk of the paper reviews the present status of our efforts on diffusion bonds: (i) to describe such interfaces using a "spring" model[1,2] which provides a description of the contact topology and predicts its ultrasonic response, (ii) to predict the strength of the bonds based on the contact topology using a failure model, and (iii) to determine experimentally the ultrasonic response and the strength of the bonds to test the theoretical models. Copper was bonded to copper[3,4] under a flowing hydrogen atmosphere and uniform pressure over a range of temperatures and times to achieve a homogeneous distribution of the metallically bonded areas. The bond interfaces were characterized by means of acoustic pulse-echo measurements using broadband focused transducers and by a determination of the bond strength in a tensile test. After bond failure, further characterization was performed by optical fractography from which the fractional bonded area and the mean distance between bonded or disbonded areas was determined[3,4]. It was concluded that actually two independent acoustic measurements will be necessary to determine the contact topology nondestructively[4]. So far, complete sets of two independent acoustic measurements have only been performed on partially closed fatigue cracks[2,5] which happen to have contact topologies quantitatively similar to those in diffusion bonds. In addition, partially closed fatigue cracks have taught us[2,5] that the acoustic experiments are capable of dealing with spatially varying (nonhomogeneous) contact topologies. This is a problem often encountered in bonding of large sections where the bonding pressure may not always be completely uniform, leading to such nonhomogeneous contact topologies.

MODELLING AND EVALUATING THE CONTACT TOPOLOGY

The bond plane is viewed as consisting of sections of well-bonded material with matrix properties interrupted by crack-like voids which act as scatterers of an elastic wave. The theory of the scattering is based on the electromechanical reciprocity theorem[6] which has been applied to the experimental conditions of normal incidence, shown in Fig. 1. The approximation yields the field scattered

$$\Gamma = \frac{jw}{4P} \int_{A+} (2u_i^I - \Delta u_i^T)\, \tau_{ij}^R \, n_i^+ \, dA \qquad (1)$$

where P is the electrical power incident on the transmitting transducer, w is the angular frequency of the signal, u_i^I is the displacement field of the incident acoustic illumination, Δu_i^T is the crack opening displacement due to u_i^I, and τ_{ij}^R is the stress field that would be produced if the receiving transducer illuminated a defect-free material. Integration is performed over the surface A of the scatterer which has a normal n_i^+. The major problem in evaluating Eq. (1) is in selecting an appropriate description of Δu_i^T. At present, it is assumed[1] that the random distribution of crack-like objects can be modelled as a periodic array of either penny-shaped or circumferential cracks.

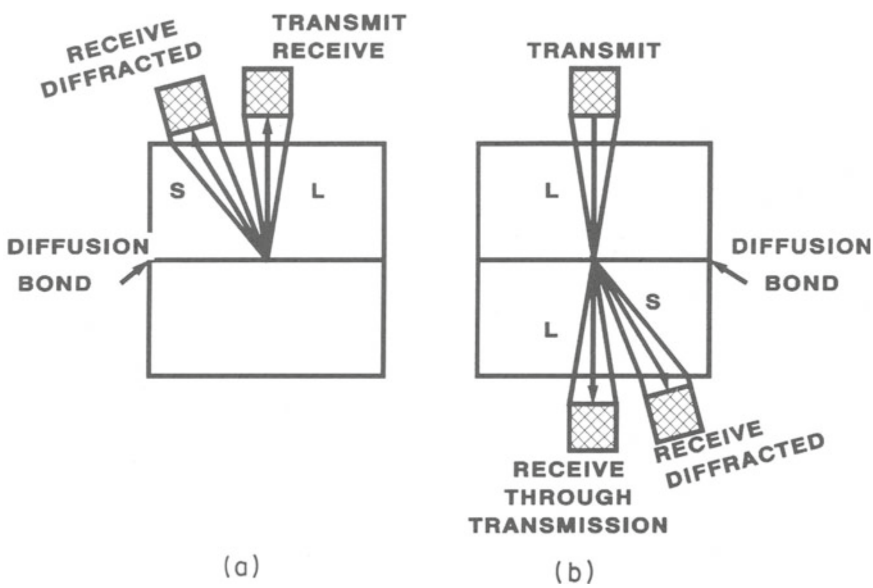

Fig. 1. Experimental arrangements (a) Reflection, (b) Transmission.

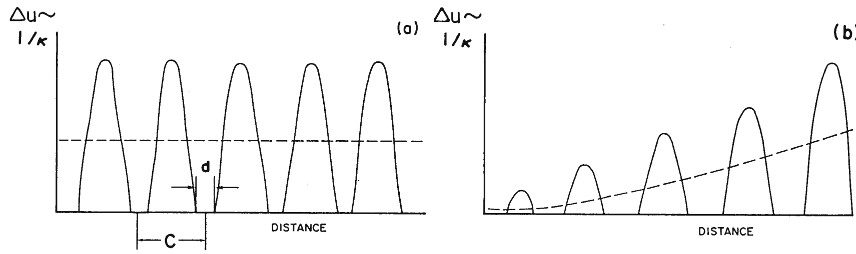

Fig. 2. Dynamic interface opening displacements. (a) Homogeneous and (b) nonhomogeneous distribution of contacts.

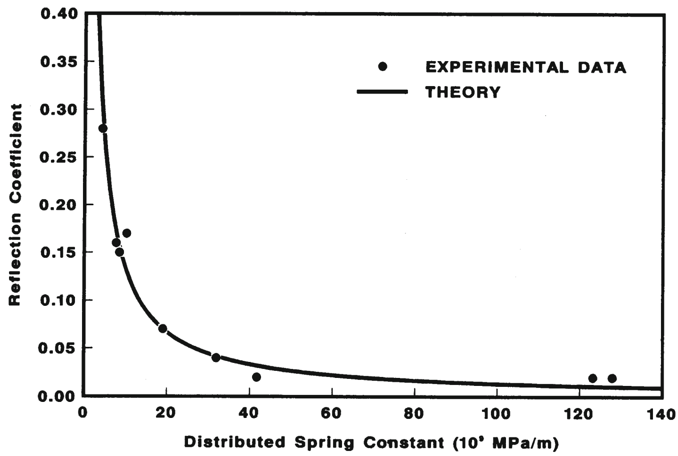

Fig. 3. Reflection coefficient versus distributed spring constant for diffusion bonds of various qualities.

A quasi-static distributed spring model describes the strength of the contact leading to a spring constant κ which is mainly a function of contact diameter d and separation C. The dashed lines in Fig. 2 schematically show $1/\kappa$ for homogeneous and nonhomogeneous spatial contact distributions. Since $1/\kappa$ is directly proportioned to $\overline{\Delta u_i^T}$[1], the spatial average of Δu_i^T, evaluation of Eq. (1) leads to a direct prediction of the experimentally determined signal in terms of κ. Excellent agreement of the measured reflection coefficient and the distributed spring constant κ for a set of diffusion bonds of widely varying quality[3], have been obtained, as shown in Fig. 3.

In order to account for the large diffracted signals observed[2,8] discrete contacts have to be introduced, however. Their effect on the dynamic interface opening displacement is indicated by the full lines in Fig. 2. For a given "distributed" κ, one may now adjust C (or d) such that the calculated amplitude of the diffracted signal matches the measured one, as shown in Fig. 4[2] for a partially closed fatigue crack. Knowing κ and C, the average diameter d of the contacting areas can then be calculated[5]. Thus two independent acoustic measurements are needed to provide a full description of the contact topology. All experimental evidence obtained thus far indicates, however, that the model works equally well for homogeneous[3,4] and nonhomogeneous[2] contact topologies. An example of the latter case is shown

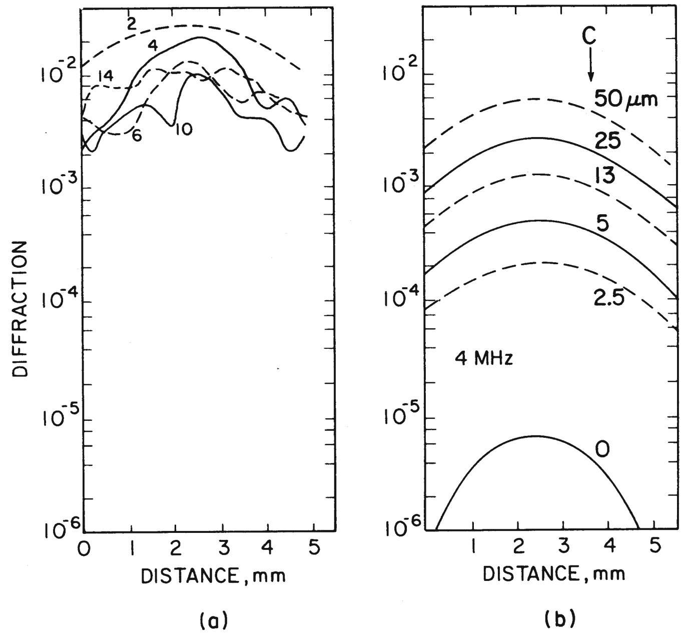

Fig. 4. Diffracted shear wave signals. (a) Experimental results at various frequencies. (b) Theory, as a function of C.

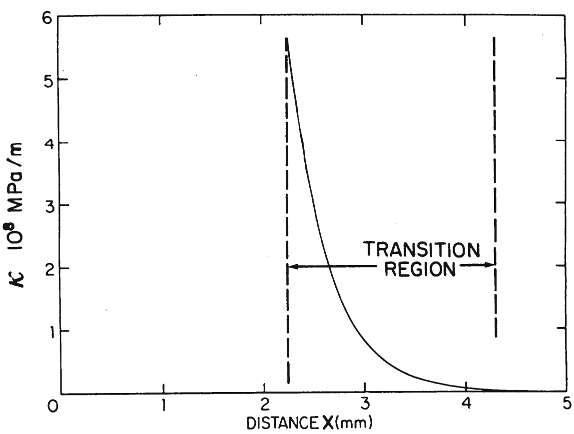

Fig. 5. Distributed spring constant for a nonhomogeneous distribution of contacts.

in Fig. 5 where κ decays exponentially with distance in qualitative agreement with the dashed line in Fig. 2b. Although the result in Fig. 5 was obtained on a partially closed fatigue crack, the result would look qualitatively similar for a nonhomogeneous diffusion bond with a transition from a perfect bond on the left to a totally unbonded section on the right hand side. Other examples of nonhomogeneous κ distributions have also been observed[9].

Another feature of Eq. (1) is that it predicts the frequency dependence of the scattered signal. Such an analysis has been performed on diffusion bonded samples. An example is given in Fig. 6, indicating

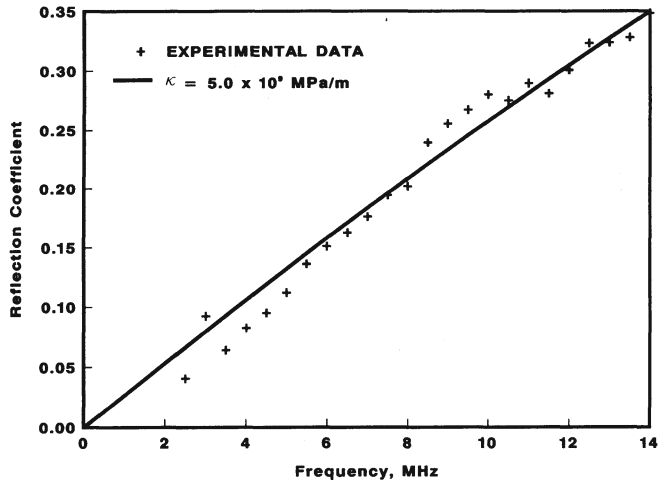

Fig. 6. Reflection coefficient versus frequency of a Cu-Cu diffusion bond.

good agreement between the experimentally determined reflection coefficient and that predicted by Eq. (1), shown as the dashed line.

Overall, we now have evidence[10,11] that demonstrates that two acoustic measurements provide the information necessary to deduce the contact topology of diffusion bonds nondestructively if the contacts are distributed randomly[4]. Table I provides a comparison of d, C, and κ as determined in the closure region of a fatigue crack[5] and on diffusion bonds[4]. Also included are the fractional contact area A/A_0 and a "normalized" spring constant κ^*[1], related to κ by

$$\kappa^* = C\kappa(1-\nu^2)/E \qquad (2)$$

where E is the Young's modulus and ν is Poisson's ratio. It was found[1] that κ^* depends on the ratio d/C (or A/A_0) only and not on the material. A comparison of κ^* and A/A_0 then shows that their values in the closure region are almost the same as those of a low quality bond. This is important since the values for d and C, which determine κ and κ^*, have been obtained differently. In the case of the fatigue crack, d and C were determined based on transmission and diffraction studies, while fractography provided the data for the diffusion bonds. Yet they yield, for similar A/A_0, about the same normalized spring constant κ^*. This supports the accuracy of the acoustic determinations of C.

Table I. Comparison of Contact Topology and Spring Constant of a Fatigue Crack and Diffusion Bonds of Different Qualities.

	Fatigue crack in Al[5]	High quality DB in Cu[4]	Low quality DB in Cu[4]
$d(\mu m)$	35	148	12
$C(\mu m)$	70	150	26
$\kappa\left(10^8 \frac{MPa}{m}\right)$	5.3	1,280	42
$A/A_0(\%)$	25	97	22
κ^*	0.5	135	0.8

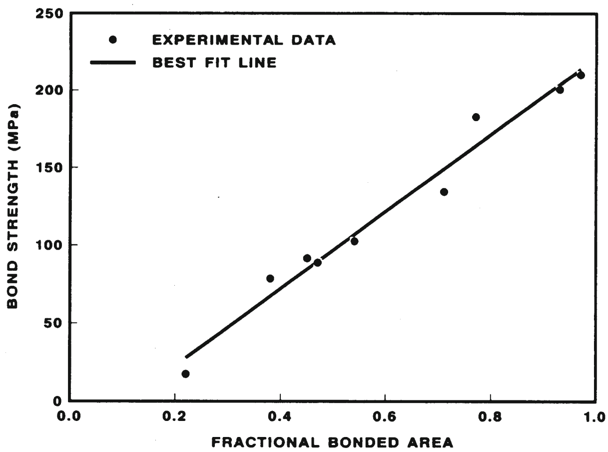

Fig. 7. Bond strength as a function of A/A_o in Cu.

STRENGTH OF A DIFFUSION BOND

Inadequate bonding conditions result in a reduction of the fractional bonded area A/A_o which is given by C and d. From this information, one would like to know at what tensile stress the bond will fail. First experimental results indicate that the bond strength, here defined as the ultimate strength at which the bond fails in tension, increases with A/A_o, as shown in Fig. 7[4]. Note that the range of A/A_o achieved in a series of diffusion bonds of copper against copper varied from about 22% to 97%[3,4]. Up to about 80% fractional bonded area the bonds failed[4] with little indication of ductility (strain-to-failure < 1%). Viewing the disbonded areas either as penny-shaped or as circumferential cracks[11], one may attempt to employ linear elastic fracture mechanics (LEFM) to determine the stress intensity factor K_I at which the specimens fail in uniaxial tension. Under this assumption, for penny-shaped cracks[12]

$$K_I' = \sigma_{bond}[A_o/A]\sqrt{\pi d/2}f'(d/C)\sqrt{1-d/C} \quad (3)$$

and for circumferential cracks[12]

$$K_I'' = \sigma_{bond}\ [A_o/A]\ \sqrt{\pi(C-d)/2}\ \ f''(d/C)\sqrt{d/C} \quad (4)$$

where $f'(d/C)$ and $f''(d/C)$ depend on A_O/A only and are both related to the spring constant κ.

Application of Eqs. (3) and (4) yields the surprising result that $K_I' \approx K_I'' \approx 0.5$ MPam$^{1/2}$ over a wide range of A/A_O except at low (≈25%) and high (>90%) values[11]. At the low end, the model probably becomes inaccurate because the largest disbonds in the distribution begin to dominate the failure. In specimens with large A/A_O, as in the case of high quality Cu-Cu diffusion bonds, the ductility is quite large (strain-to-failures up to 20%) so that LEFM is clearly no longer valid.

These findings are now under further investigation since it is concluded that the model may indeed be appropriate, even at large A/A_O, for materials with low ductility of the bulk material. On the other hand, for diffusion bonds in materials with high ductility of the bulk material and large A/A_O, plasticity will have to be taken into account. The present results indicate, however, that two acoustic measurements to evaluate the contact geometry and a knowledge of K_I as a function of the contact topology does allow a calculation of the bond strength, using Eqs. (3) or (4), respectively, with a comparison of measured and predicted bond strength shown in Fig. 8. Basically, all necessary ingredients are therefore available to predict the bond strength versus reflection coefficient relation such as shown in Fig. 9 [3,4]. In view of the above discussions, it has to be kept in mind that the

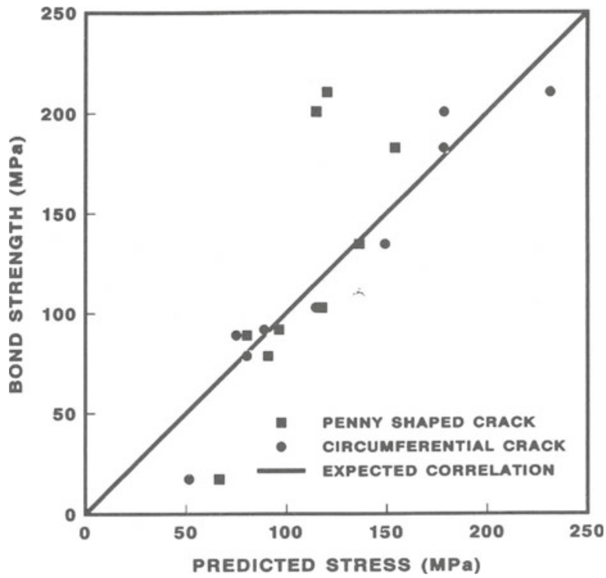

Fig. 8. Measured versus predicted bond strength in Cu.

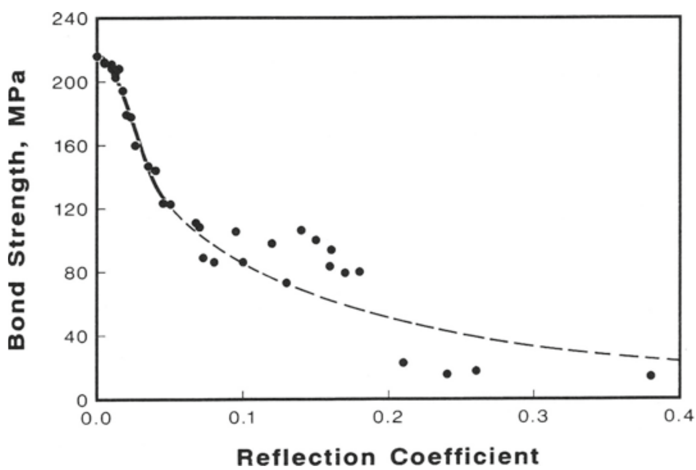

Fig. 9. Bond strength versus reflection coefficient-experimental results.

correlations of such quantities, as shown in Fig. 9, are not unique functions since the bond strength does not only depend on κ, which determines the reflection coefficient, but also on one of the other topological parameters, such as C. We would also like to point out again that the presence of solid contaminants in the interface certainly adds to the complexity of the above analyses. The spring model[1] reconciles the effects of such contaminants by adding a mass term, which can be either positive or negative. So far we have not had any experience in the application of this expansion of the model, however.

CONCLUSIONS

The present paper summarizes briefly experimental results and the analysis of Cu-Cu diffusion bonds. The analysis is based on a modified quasi-static spring model which takes into account the discreteness of the contacts achieved during the bonding process to account for the large diffracted signals observed. Two independent acoustic measurements are necessary to determine the contact topology nondestructively. All indications are that this acoustically deduced contact topology agrees well with the actual topology if the contacts are randomly distributed[4]. Spatial variations in the contact topology can also be quantified, posing no particular problem. Based on the assumption that linear elastic fracture mechanics determines the failure of the bonds we have used information on the contact topology, and the experimentally determined bond strength, to determine a critical stress intensity factor. Its application over a large range of bonds of different qualities predicts the measured strength reasonably well.

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