Nondestructive Characterization of the Mechanical Strength of Diffusion Bonds. II. Application of a Quasi-Static Spring Model

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Received January 7, 1988; revised October 31, 1988

It has been shown that the acoustic response of imperfect interfaces may be described by a quasi-static spring model. In the present paper, experimental data on the geometry of the contacts between two diffusion-bonded blocks have been used to determine the “spring stiffness” of such interfaces which have been correlated with experimentally determined ultrasonic reflection coefficients. The correlation between the theoretical reflection coefficient and the “spring stiffness” was found to be in excellent agreement with experimentally-observed values, if the disbonds are of infinitesimally small thickness. For disbonds of finite thickness, the agreement is less satisfactory. Reasons for the discrepancy in the latter case are unknown at the present time.

KEY WORDS: Bond strength; contacts; diffusion bonds; disbonds; distributed spring model; fractional bonded area; fractography; ultrasonic reflection coefficient.

1. INTRODUCTION

In attempting to join two pieces of metal by diffusion bonding, the possibility exists that the process will be incomplete. In this case, bonded as well as disbonded areas are produced. The disbonded areas then reduce the tensile strength, or bond strength, of the interface, with the extent of this loss of strength being mainly a function of the fraction of disbonded area. The correlation between strength and extent of bonding was experimentally determined on diffusion bonds of copper to copper with variations in bond quality.1 Furthermore, an imperfect bond causes a partial reflection of an ultrasonic wave whose amplitude can then be correlated to the strength of the bond achieved.

The present paper deals specifically with the problem of quantitatively explaining a subset of the experimental results obtained1 in terms of a model2 in which an imperfect interface (in this case, an imperfect diffusion bond) is represented by a distributed spring. The “spring stiffness” is a function of the contact geometry and, therefore, affects the reflection coefficient of a longitudinal acoustic wave impinging on the interface. Thus, the model is ideally suited to be tested against experimental observations of the relation between the contact geometry and the acoustic reflection coefficient. The model, however, does not provide information on the bond strength. To obtain such information, fracture mechanics may be invoked and a failure criterion estab-
lished, based on disbond geometry and certain materials parameters. This topic is discussed in a separate paper. The initial results indicate that a full theory on the correlation between reflection coefficient and bond strength will eventually be available.

The quasi-static spring model to be applied to diffusion bonds, assumes that when a tensile load is applied, the presence of voids at the interface increases the far-field displacement due to local deformation at the interface. Several cases in which this model has proven useful to the interpretation of ultrasonic measurements include friction, fatigue crack closure, adhesive bonding, and shrink-fit couplers.

This paper summarizes the important points of the quasi-static model for imperfect interfaces and reviews the application of this model to the case of diffusion bonds, using experimentally-obtained results from Cu–Cu diffusion bonds. Two extreme cases are developed and used to explain the experimental results. First, the case of a periodic array of strip-like disbonds is examined and applied to diffusion bonds on which fractography indicated strip-like contact or disbond areas. Second, the cases of penny-shaped as well as circumferential disbonds are discussed and used on diffusion bonds which, after fractographic analysis, showed random distributions of contact or disbond areas.

2. THE QUASI-STATIC MODEL

The inputs for the quasi-static model of imperfect interfaces are shown in Fig. 1. When an ultrasonic stress is applied, the far-field displacement is increased due to local deformation at the interface. The total displacement, $\Delta_x$, consists of a standard displacement, $\Delta_p$, of the bulk material (no interface is present) plus an additive displacement, $\Delta_f$, due to local deformation at the interface. In other words, $\Delta_p$ is an elastic displacement and $\Delta_f$ is a (dynamic) crack-opening displacement. The cases of cracks or voids at the interface, $\Delta_f > 0$. For the case of inclusions, $\Delta_f$ can be either positive or negative, depending on their shape and elastic moduli. Figure 1b shows a sketch of the geometry of the ultrasonic measurements as was used in the actual experimental setup. An incident ultrasonic wave is transmitted through points of contact along the interface and reflected from the disbonded regions. If the acoustic wavelength is large compared to both the thickness of the interface as well as the contact spacing, the case shown in Fig. 1c applies. In this case, the interface can be assumed to consist of an array of springs with individual interfacial stiffnesses $\kappa$ which, in actuality, are stiffnesses per unit area defined as

$$\kappa = \sigma / \Delta_f$$

where $\sigma$ is the ultrasonic stress and $\Delta_f$ is the added displacement previously discussed. The mass per unit area at the interface, $m$, which takes into account the change in density due to the presence of pores or inclusions at the interface, may be defined as

$$m = \int_{-l/2}^{l/2} \left( \rho(x) - \rho_0 \right) dx$$

where $\rho_0$ is the density of the matrix metal, $\rho(x)$ is the average density of the discontinuous region of the interface (including the voids or inclusions), and $l$ is its thickness. $m$ may be either positive or negative for volumetric imperfections such as voids or inclusions; however, for an array of infinitely thin cracks, $m = 0$.

After proper application of the boundary conditions, i.e., in stress and displacements, the transmission and reflection coefficients can be determined. For similar materials on either side of the interface and acoustic waves at normal incidence, the results are

$$R = \frac{\frac{j\omega (Z/2\kappa - m/2Z)}{1 - m\omega^2/4\kappa} + j\omega (Z/2\kappa + m/2Z)}{\left(1 + m\omega^2/4\kappa\right) + j\omega (Z/2\kappa + m/2Z)}$$

where $\omega$ is the angular frequency of the acoustic