PREPRINT UCRL- 81201

CONF-780650--3

Lawrence Livermore Laboratory

ULTRASONIC MEASUREMENTS OF THIN METALLIC INTERFACIAL REGIONS

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MAY 31, 1978

THIS PAPER WAS PREPARED FOR SUBMISSION TO:
FIRST INTERNATIONAL SYMPOSIUM ON ULTRASONIC MATERIALS CHARACTERIZATION
JUNE 7-9, 1978, NATIONAL BUREAU OF STANDARDS, GAITHERSBURG, MARYLAND

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A typical braze joint consists of a metallic region which wets the surface of the two metals being joined, thereby achieving a bond of good mechanical integrity. An ultrasonic signal reflected from this bond can normally distinguish between bonded and unbonded regions but gives little information about the strength of such a region. For some brazes (and other bonding operations), there is a good correlation between thickness and bond strength in that a bond falling within a specified thickness range can be shown to perform adequately while both thinner and thicker bonds exhibit degraded performance. For a 50 μm thick braze, ultrasonic reflections are "separated" by roughly 16 nsec. For any real transducer, this means that there is significant overlap of the front and back surface reflections. We have studied a model system consisting of thin (12 to 50 μm) aluminum bonded to the back surface beryllium. By computer fitting the time dependence of the elastic distrubance reflected from the beryllium-aluminum region to a two-plane wave reflector model and allowing for multiple reflection, we correctly predict the interface separations. Details of the data acquisition and analysis, including the fitting procedure and an error analysis, are given.

Accuracy depends upon the separation; a 50 μm thick (2 mil) bond can be determined with an accuracy of about 20%. The thickness of highly graded joins, consisting of two different braze materials, can be determined with an accuracy of about 30%.

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Work performed under the auspices of the U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48

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INTRODUCTION

The joining of metals, especially dissimilar ones, can pose many difficult problems, particularly in some high-technology areas where materials are often chosen in order to exploit certain special characteristics and not for ease of joining and assembly. For instance, metals that have their strength or other features by virtue of a heat treatment cannot subsequently be heated above some transformation or annealing temperature during any bonding operation without degrading performance. (In some cases, rapid heating followed by rapid cooling is permissible without significant reduction in material strength.) For some complex assemblies, it can be desirable to limit the temperature and/or temperature gradients during joining. There are also materials that are metallurgically incompatible, at least if joins of even modest strengths are to be achieved.

Although there is no universal means for solving these joining problems, one general approach has proven quite effective. Each surface to be joined is coated with a metal to which it will adhere easily and strongly. Coating materials are chosen so that they can also be joined to each other under whatever bonding constraints that have been imposed. For example, a low temperature, high strength bond between two stainless steel components can be achieved by depositing silver on each surface and then applying low heat and pressure (stresses well within the elastic limit) to effect a silver-silver diffusion bond.

A more complex problem involves attaching beryllium (Be) to stainless steel. Beryllium forms a solid solution with aluminum (Al) well below the melting point of Be. Stainless steel can be coated with many metals, silver (Ag) is chosen in

this case because Al-Ag intermetallics can form a strong bonding layer. In a Be-stainless steel join, it is sometimes desirable to prevent the Be from contacting the stainless steel; consequently the coating layers are often made rather thick, about 50 μm (2 mils).

Actual bonding parameters, such as the best coating thickness and optimum temperature, are determined empirically through correlation of these parameters with nondestructive and destructive tests and metallographic studies. For some Be-stainless steel joins, bond layer thickness turns out to be an important parameter. For one of our problems, a thickness of about 80 μm was chosen. It was necessary to measure the final bond thickness to insure that a strong joint was achieved. Ultrasonics was chosen as the best method.

EXPERIMENTAL APPROACH

There are several practical problems associated with the ultrasonic measurement of interfacial regions less than a few hundred microns thick. Attenuation places a practical upper limit or the frequency. The compressional wave transit time in aluminum is 0.16 nsec/μm. A thickness determination requires measuring the time between front and back surface reflections. This was to be accomplished with existing commercial transducers which are available with pulse widths (full width at half-maximum voltage level) ranging down to 50 nsec. Hence, such a measurement requires separating reflections that overlap substantially.

It is important to determine, under the best possible conditions, just how close two reflectors can be and still yield reflections that can be separated reliably. To accomplish this, the test specimen shown in Fig. 1a was fabricated. Aluminum was vacuum melted just above its melting point onto the pre-machined Be form and then faced on a lathe to produce the final test block. Prepared in this way, the Al alloys with the Be yet produces a sharp boundary.

The Be/Al test specimen is supported in a water bath (see Fig. 1b) at a few points around the rim. A nominal 25 MHz, focused transducer with its axis normal to the surface directs compressional elastic energy to a region about 1 mm in diameter at the Be/Al interface as shown in Fig. 1b. The same transducer is used to detect the reflected signal. Mode conversion due to the converging focused beam also generates shear waves at both the upper and lower surfaces.

The transducer is excited using a rectangular pulse about 30 nsec wide. Figure 2 shows a typical reflection from the Be/Al interface, the two smaller signals resulting from mode conversion and shear wave propagation in the Be. This waveform is recorded using a transient recorder (Biomation 6500) sampling once every 2 nsec. In order to facilitate curve fitting (data interpretation), 64 consecutive signals are summed to increase the signal-to-noise ratio. Data is input to a computer for analysis as described in a later section.

THE MODEL

A simple yet physically reasonable model expresses the reflected signal, $u(t)$, in terms of a reference signal, $u_R(t)$, which is a measure of the incident elastic waveform; namely

$$u(t) = \sum_{i=1}^{N} a_i f(t - \tau_i) \qquad (1)$$

$$u_R(t) = f(t) + n(t) \qquad (2)$$

where $n(t)$ is the noise that is invariably superimposed upon the incident and reflected elastic wave responses. The function $u_R(t)$ is obtained experimentally by measuring the reflection from a single, sharp interface. For example, the

beryllium-water reflection near the rim of the specimen can be used for this purpose. The interfacial signal is then expressed as the sum of amplitude-scaled and time-shifted responses to account for both primary and secondary or multiple reflections. One obvious disadvantage of this method is that some a priori knowledge of the bond structure is required. This is, however, usually available from metallographic studies.

The best values of the model parameters, (a_i, τ_i), are obtained by minimizing the sum of the squared differences between u(t) and $u_R(t)$; namely, one minimizes

$$I = \int \left[u(t) - u_R(t)\right]^2 dt \qquad (3)$$

DATA ANALYSIS

There are numerous practical problems in obtaining a sufficiently accurate fit to allow thickness changes as small as 5 μm to be detected reliably. A distance of 5 μm corresponds to a round-trip transit time of about 2 nsec, the sampling interval. Thus, samples at a 2 nsec interval do not, for our purposes, define a continuous function, especially in the presence of noise. Since f(t) is basically the transient response of a damped resonator, it is inherently smooth in the absence of noise. An *interpolation scheme was developed*[1] to obtain intermediate points such that their fast Fourier transform matched as closely as possible the full integral transform of the signal. Actual system noise is included on a statistical basis for each point (any noise spectrum can be incorporated in the analysis). In this way, one obtains a continuous function for curve fitting.

Reflections from regions B,C,D,E and F (see Fig. 1a) were analyzed for a reflected signal of the form

$$u(t) = (1-\alpha)f(t) + \alpha(2-\alpha)\sum_{n=1}^{\infty}(1-\beta)^n\,(1-\alpha)^{n-1}e^{-nk\tau v}\,f(t-n\tau) \qquad (4)$$

where $(1-\alpha)$ is the Be-to-Al reflection coefficient, $(1-\beta)$ is the Al-to-water reflection coefficient, v is the compressional wave velocity in Al, κ is a damping factor, τ is the round trip transit time in Al and n indexes the number of reflections within the Al. Factors α and β are used as fitting parameters but should not be much different from their expected values of $\alpha = 1.15$, $\beta = 1.84$, if a reliable fit has been achieved. Curve fitting is not very sensitive to the damping factor, κ, as long as it is sufficient to allow for more than two weakly damped reverberations.

RESULTS

The curve fitting procedure just described determines the time between reflections caused by abrupt changes in the acoustic impedance. For the test specimen, the Al thickness is determined directly from $d = 0.5\ v\tau$, where $v = 6.4 \times 10^{3}$ m/sec. Table I summarizes our results when only two reflectors are assumed with no reverberations. For each round trip transit time, an estimate of the fitting accuracy is tabulated. This estimate results from a rather complex computation. To each reflection amplitude is added a random signal representative of the system noise. A spectrum of transit times is then calculated to arrive at the error estimate quoted in Table I. Obviously, as the reflections become closer, any given noise level creates a greater uncertainty in the transit time. The calculated and actual thicknesses are within the uncertainties established by our error

analysis procedure for all except region C. A reason for this difference has not yet been found.

For n = 1 in Eq. (4), the two reflections should have an amplitude ratio of -5.6. Table I shows that for the largest transit time (region B), the amplitude ratio is indeed -5.5 but, as the transit time decreases, this ratio also decreases. Thus, to some extent, the curve fitting can compensate for transit time changes by amplitude changes and vice versa.

Thickness determination for the Be-stainless steel join is much more difficult for several reasons. First, the compressional sound velocity in silver is 3.7×10^3m/sec, much different from Al. Metallography of a section bond shows regions of Al near the Be interface and of Ag near the stainless-steel interface. Between the Al and Ag is a mixture of varying composition. When averaged over the beam area (about 1 mm), however, the sound travels through roughly equal amounts of Al and Ag; consequently an average velocity given by $v_a = 0.5\ (6.4+3.7) \times 10^3$m/sec $= 5.05 \times 10^3$m/sec is used for thickness determination. Results of measurements on a Be-stainless steel braze joint are summarized in Table II. Accuracies are somewhat less than that achieved with the Be-Al test specimen.

SUMMARY

A number of different procedures have been used to analyze results of the type presented in this paper. Spectrum or Fourier analysis can work well for essentially noise-free signals but the accuracy of any inversion or transform can be influenced dramatically by the presence of noise. Our fitting procedure requires a reference signal that is a faithful reproduction of the incident elastic disturbance. In practice, this requirement does not differ significantly from the Fourier transform approach where a "good" reflection must be available in order to determine the transducer response. The interpolation scheme that we use to obtain a continuous function could be used to obtain a more accurate transform. It is our experience, however, that the fitting procedure described yields more accurate results.

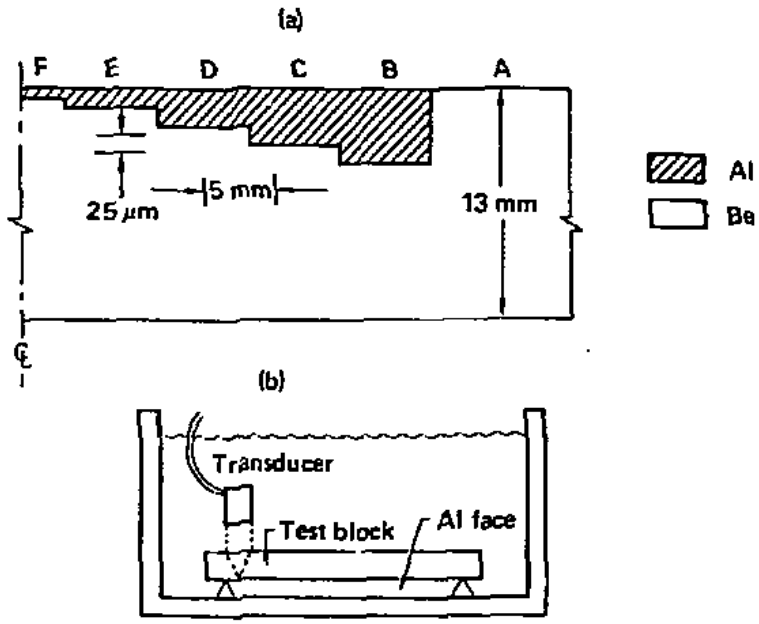
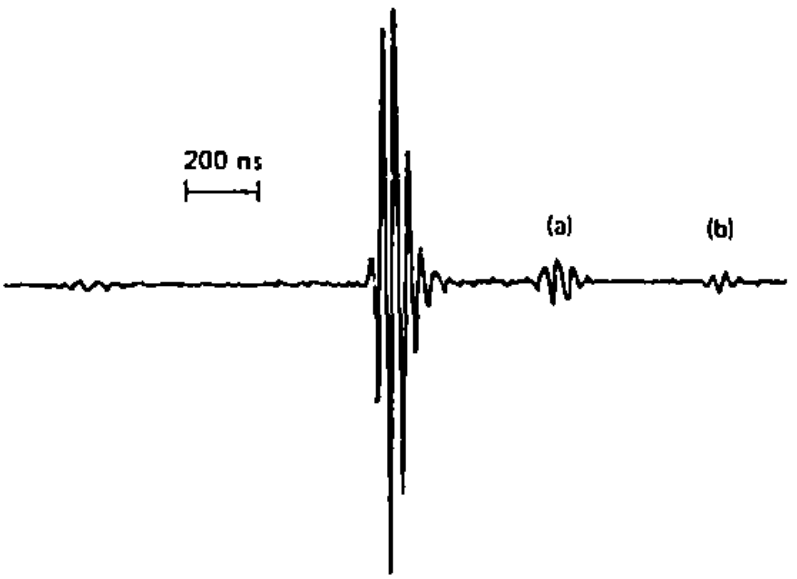


FIG 1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(a)
(b)