Ultrasonic Characterization of Dissimilar Bonds

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ABSTRACT

Ultrasonic characterization of solid-state bonds between dissimilar materials is rendered very difficult by the fact that the relatively weak signals generated by boundary imperfections are often overshadowed by the much stronger specular reflection of the interface caused by acoustical impedance mismatch. A novel technique based on the symmetric (common) part of the interface reflections from the opposite sides of the bond is shown to improve flaw detectability by as much as a factor of ten. In this way, reliable quantitative information can be obtained even from the best, apparently flawless bonds, too, as is demonstrated by different inertia and friction welds.

KEYWORDS

Solid-state bonds; ultrasonic NDE; friction weld; boundary imperfections; dissimilar bonds.

ULTRASONIC FLAW DETECTION AT DISSIMILAR INTERFACES

Ultrasonic flaw detection at dissimilar interfaces is badly limited by the "blinding" effect of the strong reflections from the otherwise perfect boundary itself. Table I shows the acoustic impedance mismatch for different materials combinations.

Friction welds of similar materials, e.g. stainless steel-stainless steel joints, present no problem for ultrasonic flaw detection, but also do not usually contain gross defects. For slightly dissimilar joints, such as the stainless steel-precipitation hardened steel combination, the acoustical impedance mismatch is as small as 1%, therefore gross defects can be easily detected. Of course, more dissimilar joints are much more difficult to inspect for interface flaws. The impedance mismatch ranges from a low 5% in the case of stainless steel-copper to a very high 50% for stainless steel-aluminum. How do these inherent reflections compare to the backscattered signals from small defects to be detected? It is impossible to establish a

Table 1. Material combinations used in this study.

TYPE	MISMATCH*	MATERIALS
Similar	None	Stainless Steel 304L-304L
Dissimilar	Small (~1%)	Stainless Steel 304L-PH 13-8 Mo
	Medium (~5%)	Stainless Steel-Copper 304L-OFHC
	Large (~50%)	Stainless Steel-Aluminum 304L-AL1100 (TW1) 304L-AL6061-T6

*Acoustic impedance mismatch = $\frac{Z_1 - Z_2}{Z_1 + Z_2}$

general detection threshold for ultrasonic NDE of different solid-state bonds with widely different types of defects. Even on an individual basis, assessment of the adverse effect of a certain boundary imperfection on bond quality is greatly complicated by the large number of possible quality parameters and the lack of comprehensive experimental data. As an example, Fig. 1 shows the variation of eight strength-related parameters with lack of

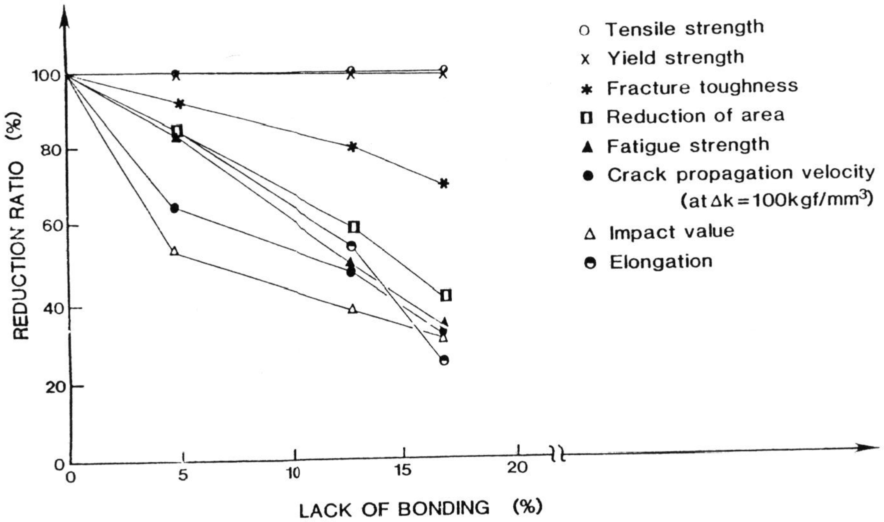

Fig. 1. Variation of eight strength-related parameters with lack of bond in titanium diffusion bond.

bonding in titanium diffusion bonds (Ohsumi et al., 1985). (To the best of our knowledge, similar comprehensive study has not yet been carried out for friction welds.) Different parameters are affected very differently. For example, tensile strength seems to be not affected at all by small partial lack of bond, while impact strength decreases by as much as 70% due to only 17% lack of bond. As an average, 2 - 3% lack of bond does appreciably reduce bond quality, therefore it should be detected by ultrasonic inspection.

Ultrasonic flaw detection in dissimilar solid-state bonds largely depends on the separation of weak boundary imperfections from the otherwise perfect boundary. The interface, which is the physical boundary between two different elastic domains, can be looked upon from two opposite directions. These two "pictures" can be easily combined into symmetric and antisymmetric parts in order to facilitate better separation between the boundary imperfections and the ideal boundary. The latter one is basically anti-symmetric since the step function in the elastic properties of a dissimilar bond exhibits different signs from the opposite directions, e.g. an effective softening from one side looks like an effective hardening from the other side. At the same time, most boundary imperfections, such as lack of bonding, porosity or inclusions, surface roughness, etc., look more-or-less the same from both sides, therefore they contribute to the symmetric component only.

Figure 2 shows the basic concept of the suggested signal processing technique. The feasibility of such a simple separation depends on the mostly symmetric nature of boundary imperfections. Unbonded areas and cavities are always softer than the softer part of the dissimilar bond, therefore they look "symmetrically" soft from both sides. Very dense

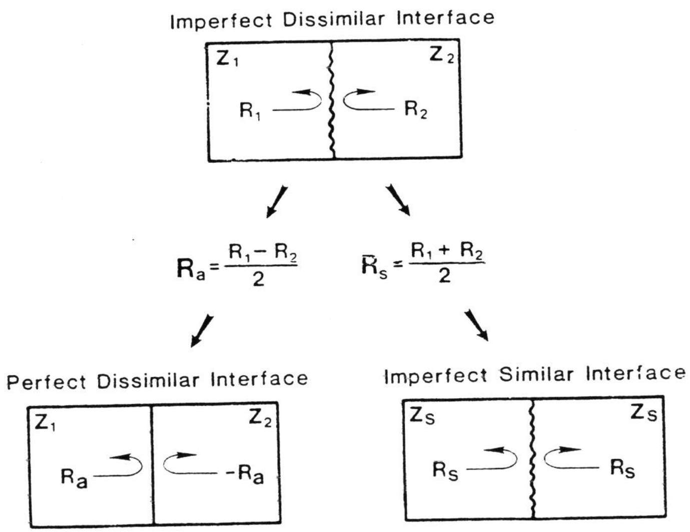

Fig. 2. Symmetric-antisymmetric separation of interface properties.

inclusions appear as a hardened region from both sides, therefore they introduce strong symmetric reflection, too. Sometimes, but not very often, the imperfect boundary region happens to be an intermediate transition causing reduced reflection from both sides. Even in such unusual cases, the imperfection often violates the true antisymmetric nature of the perfect interface and results in a measurable symmetric reflection.

Let us demonstrate the above technique through the widely used quasi-static model for imperfect interfaces (Baik and Thompson, 1985). For a plane wave incident normally on the interface, use of effective boundary conditions leads to a reflection coefficient

$$R_1 = \frac{\frac{Z_2 - Z_1}{Z_2 + Z_1}\left(1 - \frac{m\omega^2}{4\kappa}\right) + \frac{j\omega}{Z_2 + Z_1}\left(\frac{Z_2 Z_1}{\kappa} - m\right)}{1 - \frac{m\omega^2}{4\kappa} + \frac{j\omega}{Z_2 + Z_1}\left(\frac{Z_2 Z_1}{\kappa} + m\right)} \qquad (1)$$

where ω denotes the angular frequency, and m and κ are the effective mass per unit area and the interfacial stiffness, respectively. By changing the indices of Z_1 and Z_2, the antisymmetric and symmetric terms can be written as follows

$$R_a = \frac{Z_2 - Z_1}{Z_2 + Z_1}\,\frac{1 - \frac{m\omega^2}{4\kappa}}{1 - \frac{m\omega^2}{4\kappa} + \frac{j\omega}{Z_2 + Z_1}\left(\frac{Z_2 Z_1}{\kappa} + m\right)} \qquad (2)$$

and

$$R_s = \frac{\frac{j\omega}{Z_2 + Z_1}\left(\frac{Z_2 Z_1}{\kappa} - m\right)}{1 - \frac{m\omega^2}{4\kappa} + \frac{j\omega}{Z_2 + Z_1}\left(\frac{Z_2 Z_1}{\kappa} + m\right)} \qquad (3)$$

Equations 2 and 3 can be further simplified for low frequencies when $\omega^2 << 4\kappa/m$

$$R_a \simeq \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad (4)$$

and

$$R_s \simeq \frac{j\omega}{Z_2 + Z_1}\left(\frac{Z_2 Z_1}{\kappa} - m\right) \qquad (5)$$

or in a more convenient form

$$R_s \simeq \frac{j\omega}{\kappa}\,\frac{Z_2 Z_1 - m\kappa}{Z_2 + Z_1} \qquad (6)$$

Equation 4 confirms our expectation that the antisymmetric part of the reflection coefficient approximately equals the reflection coefficient of the perfect interface. More importantly, Eq. 6 shows that the crucial symmetric part measures the degree of imperfection. The principal first term is linearly proportional to frequency and inversely proportional to the interfacial stiffness which is infinite for a perfect interface, positive finite for cracks and pores, and positive or negative finite for inclusions. The second term on the right side of Eq. 6 is a weighting factor measuring the "symmetric" nature of the imperfect interface region. As we mentioned already, theoretically the boundary layer might act like an intermediate transition providing acoustical matching between the neighboring dissimilar media when $Z_1 Z_2 \simeq m\kappa$. In this highly unusual case, the detectability of the boundary imperfection is very low.

Figure 3 demonstrates the improved detectability of lack of bond at a stainless steel-aluminum interface by the double-sided symmetric method. In order to control the lack of bond area fraction, an increasing number of uniform scratches were made on the otherwise perfectly flat and smooth surface of an aluminum block. The stainless-steel counterpart was also carefully polished, and water couplant was used on the strongly compressed surfaces to approximate perfect bond over the flawless areas. This simple model experiment confirms our expectations that weak defects can not be reliably detected in the presence of the strong reflection from the dissimilar interface. More than 10% lack of bonding is necessary to produce a meager 3 dB (approximately 40%) increment in the reflected signal. This low contrast leaves much to be desired when we would like to detect small lack of bonds as weak as 1 - 2%. The results of the double sided symmetric method are also shown in Fig. 2. The relative contrast sharply improved from approximately 0.3 dB/percent to almost 10 dB/percent in the most important lower range of lack of bonding.

Figure 4 compares the symmetric and antisymmetric reflection coefficients measured in the same experiment. The antisymmetric part does not seem to be affected by the increasing lack of bond, and its absolute value is very close to the theoretically calculated value of 0.44 for perfect boundary conditions. The symmetric part is more-or-less linearly proportional to the strength of the boundary imperfection, in this particular case, to the number of scratches or to the area fraction of lack of bonding.

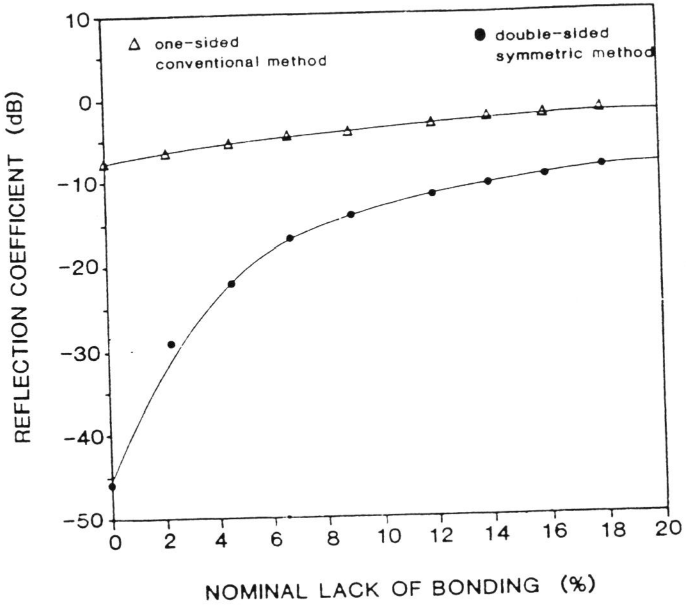

Fig. 3. Detectability of lack of bond at stainless steel-aluminum interface (one-sided measurement taken from the steel side).

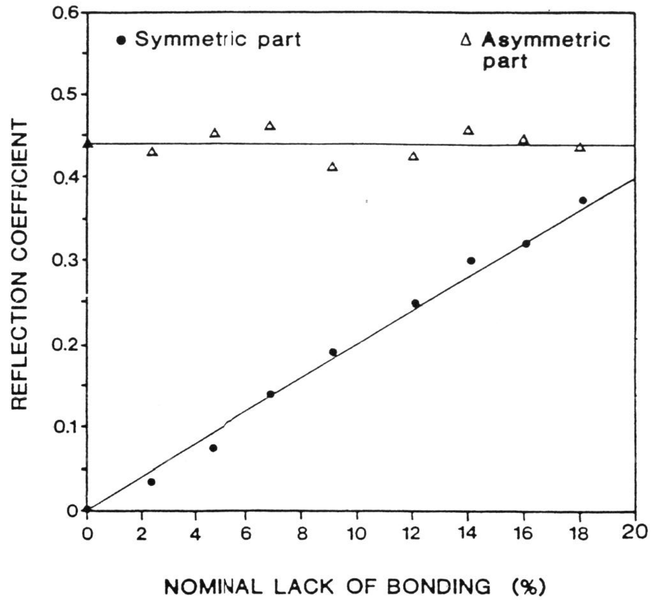

Fig. 4. Symmetric and antisymmetric reflection coefficients as a function of lack of bond at a stainless steel-aluminum interface.

Let us see a few examples of real dissimilar inertia and friction welds in order to assess the sensitivity of the suggested technique in such demanding applications. The stainless steel-copper combination is one of the most important dissimilar pair used in inertia and friction welding. Since their acoustic impedances are unusually close, even relatively small boundary defects can be easily detected. Figure 5 shows the ultrasonic reflection spectra from a stainless steel-copper inertia weld made at 1800 psi pressure. The average value of the reflection coefficients over the measuring frequency range between 3 and 10 MHz was found to be +2.6% and -4.2% from the copper and steel sides, respectively. The antisymmetric term gives 3.4% which is fairly close to the 3.3% ideal value calculated from the material densities and sound velocities. The symmetric term turns out to be -0.8%, a considerable effective softening. It should be mentioned that these data were taken by a small 1/4" diameter contact transducer close to the perimeter of the 1" diameter sample. The dominantly antisymmetric nature of the interface becomes even more symmetric at the center where the bond was found to be much worse.

The crucial symmetric part is calculated as the sum of reflection coefficients of opposite signs. Such a subtraction type of operation is naturally very sensitive to the accuracy of the two measured parameters. In practice, ±0.5 dB or ±5% relative errors can be expected from the amplitude measurements. In a stainless steel-copper relation this means approximately ±0.17% uncertainties in the reflection coefficients, and ±0.25% combined

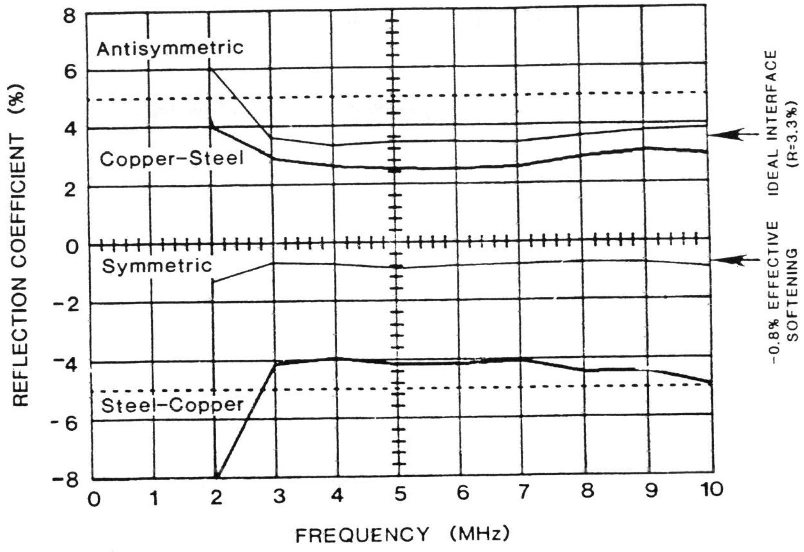

Fig. 5. Ultrasonic reflection spectra from a stainless steel-copper inertia weld made at 1800 psi (diameter 1", rotational speed 2000 rpm, flywheel energy 20 ft. lb.).

error in the symmetric part of -0.8%. Since this weld was found to be apparently flawless at the perimeter, the above accuracy seems to be sufficient. Obviously, our ability to detect interface imperfections is more limited in other dissimilar combinations, let us say in stainless steel-aluminum bonds, when the reflection coefficient of the perfect boundary is as high as 48%. Unless we manage to improve the measuring accuracy, the uncertainty of the symmetric term becomes a fairly high ±3.4%.

Further improvement can be expected from precision measurements using e.g. spatial averaging. Figure 6 shows the ultrasonic reflection spectra from a 304L stainless steel-1100 aluminum friction weld provided by The Welding Institute, Abington, England. The 3" diameter weld was made after careful surface preparation by optimal welding parameters. Each reflection measurement was repeated ten times at different, but statistically identical positions in order to improve accuracy to approximately ±0.15 dB which results in close to ±1% uncertainty in the symmetric term. The average reflection coefficients were found to be +0.46 and -0.498 from the aluminum and steel side, respectively. Again, the antisymmetric term comes out to be very close to the calculated reflection coefficient of the ideal interface, and the symmetric one turns out to be -1.9%. This value corresponds to an effective softening higher than the experimental uncertainty.

Accurately measuring elastic parameters of the bond is one thing, correlating the results to weld quality is another. At this point, we have not yet accumulated sufficient destructive information on these samples to

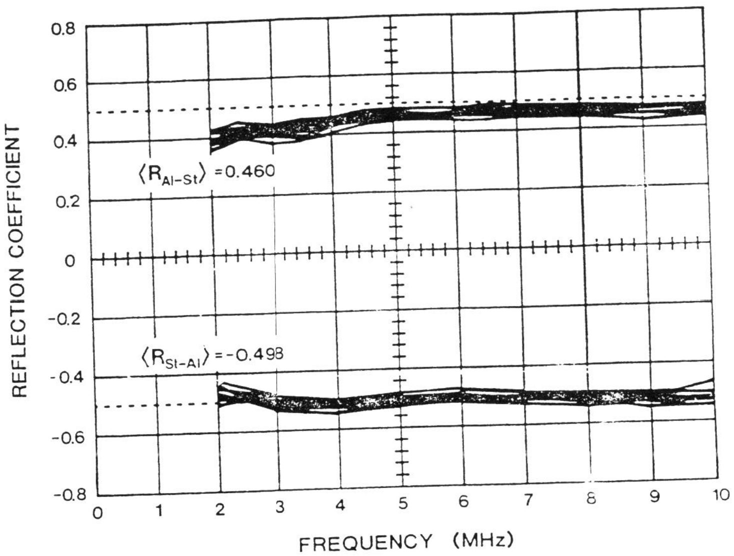

Fig. 6. Ultrsonic reflection spectra from a stainless steel-aluminum friction weld (sample #LA13, diameter 3", rotational speed 250 rpm, touch down load 20 kN, friction force 150 kN, forge force 300 kN).

address this important problem in its full complexity. As a first step, we can compare the ultrasonic results to the principal welding parameter used to control bond quality. Fig. 7 shows the good correlation between the measured symmetric reflection coefficient and the welding pressure between 1500 - 2200 psi for stainless steel-copper inertia welds. Each data point represents the average of eight different locations around the perimeter of the 1" diameter welds. In this way, the absolute error in the symmetric reflection coefficient is expected to be less than ±0.1%. Below 1600 psi, the otherwise flawless perimeter of the weld starts to deteriorate very sharply, and at 1300 - 1400 psi large cracks can be observed even by conventional one-sided ultrasonic inspection.

The negative symmetric reflection corresponds to the effective softening of the interface. We can not be absolutely sure whether the 1% overall effect was caused by, let us say, 100% softening, i.e. lack of bond, over 1% of the total interface area or by an evenly distributed 1% softening over the whole cross-section, or by some combination of these limiting cases. On the other hand, fracture surfaces of these apparently flawless inertia welds indicate that failure occurs always in the softer (copper) material, but very close to the interface. The presence of this seemingly continuous weak boundary layer indicates that the measured effective softening is due to a relatively evenly distributed effect rather than to lack of bond at a small fraction of the interface.

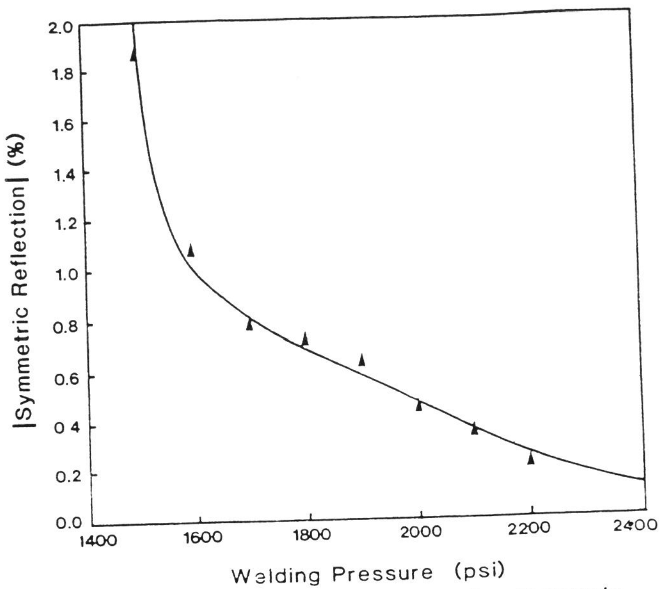

Fig. 7. Correlation between the symmetric ultrasonic reflection coefficient and the welding pressure for stainless steel-copper inertia welds.

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