INTRODUCTION

This paper discusses two special ultrasonic NDE problems of particular interest to dissimilar solid-state bonds. The first problem is the so-called "cold weld" effect which is a lack-of-bond type defect, but as opposed to other common types of defects in this category, it is very difficult to detect by ultrasound. The other problem, to be addressed in the second part of this paper, is the "blinding" effect of the strong interface reflection caused by acoustical impedance mismatch between dissimilar materials. Ultrasonic characterization of such bonds is rendered very difficult by the fact that the relatively weak signals generated by possible boundary imperfections are often overshadowed by this inherent reflection. A novel technique based on the symmetric part of the interface reflections from the opposite sides of the bond will be introduced to obtain quantitative information even from very good, apparently flawless bonds.

COLD WELD EFFECT

Cold weld is a fairly common type of defect in inertia and friction welds and, to a smaller degree, in diffusion bonds and resistance welds as well. It occurs as a combined result of strong compressive stresses and insufficient heating when the elevated interface temperature is not high enough to produce good metallurgical bond, but at least one of the contacting parts is softened enough by the heat to reach plastic deformation at that particular pressure. The resulting intimate mechanical contact between the compressed surfaces causes small reflection and high transmission, i.e. the bond appears to be flawless for ultrasonic inspection, but the joint strength is zero in this cold welded region [1].

Fig. 1 shows the schematic diagram of the axial cross-section of a defective inertia weld. The friction heat is generated mainly at the perimeter of the sample where the relative velocity between the parts is maximum. The center part is heated via conduction only and the interface temperature lags behind that of the periphery. At sufficiently high welding pressures, the bond is very good at the circumference of the joint, but usually contains a large cold weld spot at the center. What happens is that the best part of the heated material is extruded from the
welded region and the motion stops in a very short time, therefore there is not enough heat conducted to the center part to raise the interface temperature to the necessary level.

In order to demonstrate the difficulty of inspecting such a cold welded interface, Fig. 2 shows the typical ultrasonic reflection and transmission profiles of a 1" diameter stainless steel-copper inertia weld made at 2000 psi axial pressure. The fracture surface of this weld revealed that there was no metallurgical bond whatsoever at the center within a 5 mm radius, while the bond was apparently flawless in an approximately 5 mm wide ring at the circumference of the joint. The shaded areas in Fig. 2

![Figure 2: Typical ultrasonic transmission and reflection profiles from an inertia weld with a cold welded region at the center (taken at 10 MHz by a 1/2" diameter, 2.5" focal length transducer).](image)
indicate the deviation of the measured ultrasonic profiles from the expected ones due to the called weld effect. The ultrasonic transmission is greatly enhanced and the reflection drops to $-20 \text{ dB}$ at the center.

From the numerous imperfect boundary models, Haines' model for plastic deformation of contacting rough surfaces seems to be the best suited for addressing the cold weld problem [2]. According to this approach, the initial contact area between flat rough surfaces increases via plastic flow of the softer material (or both if they are similar) at the contacting peaks of the surfaces with increasing compressive pressure. Haines' results can be summarized by the following very simple formulae for the ultrasonic reflection $R$ and transmission $T$ coefficients.

$$ R = \frac{R_0 - i\omega/\Omega}{1 + i\omega/\Omega} $$ \hspace{1cm} (1)

and

$$ T = \frac{T_0}{1 + i\omega/\Omega} $$ \hspace{1cm} (2)

where $R_0$ and $T_0$ denote the reflection and transmission coefficients of the perfect interface. The frequency dependence of these coefficients is given by a single characteristic frequency $\Omega$ which increases by compressional pressure. Fig. 3 shows the frequency dependent reflection and transmission coefficients of contacting stainless steel surfaces for different compressive pressure to flow pressure ratios. As can be expected from simple physical considerations, the reflection increases while the transmission decreases with increasing frequency, and the turning point of the spectra moves upward with increasing compressive pressure.

It is well known that extremely high compressive pressures are needed to achieve good ultrasonic contact between dry solid surfaces [3]. This

$$ h = 10 \mu m \text{ rms} $$

![Graph showing calculated reflection and transmission coefficients for different compressive pressures](image)

**Fig. 3.** Calculated reflection (solid lines) and transmission (dashed lines) spectra from contacting stainless steel surfaces for different compressive pressure to flow pressure ratios (after Haines [1]).
is in good accordance with predictions based on Fig. 3 indicating that at as high as 10% of the flow pressure the interface is still rather poorly transmitting and strongly reflecting. So, how is it possible that welding pressures around 2 ksi can result in almost perfect ultrasonic contact between materials with flow pressures of 30 ksi or even higher? The answer is, of course, that the temperature of the interface increases to a maximum just below the melting point where the flow pressure drops to the level of the applied compressive stress.

![Graph](image-url)

**Fig. 4.** Experimental reflection spectra from cold welded center parts of stainless steel-copper inertia welds made at different compressive pressure.

Due to certain approximations used in the quantitative evaluation of Haines' model, the above simple formulae for the reflection and transmission coefficients of contacting rough surfaces are valid for relatively weak plastic deformations only when the compressive pressure does not exceed 10 - 20% of the flow pressure. Fig. 4 shows the measured reflection spectra from cold welded center parts of stainless steel-copper inertia welds made at different compressive pressures. In spite of the considerable plastic flow during the welding process, these spectra still exhibit the main features predicted by Haines. In particular, from low to high frequencies, the curves rise from the low reflection coefficient of a perfect interface to the full reflection of total misbond, and the transient frequency moves upward with increasing pressure. At 1500 psi this turning point is below the measuring frequency range and the cold weld looks like a strong misbond. At the other end of the scale, at 2200 psi, the turning point is above 20 MHz, therefore this very strong cold weld cannot be detected in the applied frequency range.
**SYMMETRIC INTERFACE PROPERTIES**

Ultrasonic flaw detection in dissimilar solid-state bonds largely depends on the separation of weak boundary imperfections from the strong elastic discontinuity at the otherwise perfect boundary. In theory, the solution is quite simple: one should subtract the reflection of the ideal interface from the measured one to get the sought component caused by imperfections. In practice, inevitable uncertainties in the assessment of the ideal reflection badly limit the detectable smallest imperfection. In the following we are going to introduce a novel version of this basic technique which takes advantage of certain symmetric properties of imperfect dissimilar interfaces.

Fig. 5 shows the basic concept of the suggested signal processing technique. First, we measure the reflection coefficients $R_1$ and $R_2$ from both sides of the interface then we combine them into antisymmetric and symmetric components. Our working hypothesis is that the antisymmetric part approximates the reflection coefficient of the ideal interface without any imperfections, while the symmetric part approximates the reflection from the imperfections without the additional elastic discontinuity, i.e. as if they were at a similar boundary. These assumptions are justified by the fact that a perfect dissimilar interface looks just the opposite from the two different sides, and any imperfection will destroy this ideal antisymmetric nature.

Let us demonstrate the ability of the suggested signal processing technique to separate weak boundary imperfections from much stronger inherent reflections through a simple model experiment. In order to control the lack of bond area of an aluminum-stainless steel interface, an increasing number of uniform scratches were made on an 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. Fig. 6 compares the symmetric and antisymmetric reflection coefficients measured in the same experiment. The antisymmetric part does not

$$\text{Imperfect Dissimilar Interface}$$

$$\begin{align*}
Z_1 & \rightarrow R_1 \rightarrow Z_2 \\
R_a &= \frac{R_1 - R_2}{2} \\
R_s &= \frac{R_1 + R_2}{2}
\end{align*}$$

$$\text{Perfect Dissimilar Interface} \quad \text{Imperfect Similar Interface}$$

$$\begin{align*}
Z_1 & \rightarrow R_a \rightarrow Z_2 \\
Z_s & \rightarrow R_s \rightarrow Z_s
\end{align*}$$

$$\text{Imperfect Dissimilar Interface}$$

Fig. 5. Symmetric-antisymmetric separation of interface properties.
Fig. 6. Symmetric and antisymmetric reflection coefficients as a function of lack of bond at a stainless steel-aluminum interface.

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 the area fraction of lack of bonding.

Let us see a few examples of real dissimilar inertia welds, too. The stainless steel-aluminum combination is one of the most demanding dissimilar pairs because of the very different acoustical impedances of these materials. Fig. 7 shows the ultrasonic reflection spectra from a 304L stainless steel-1100 aluminum friction weld. This 3" diameter weld was made after careful surface preparation and by optimal welding parameters. Each reflection measurement was repeated ten times at different positions in order to improve accuracy by averaging. The spectra were found to be fairly flat from 2 - 10 MHz, which indicates that there were no fully or partially resolved flaws at this interface. The average reflection coefficients were found to be +0.460 and -0.498 from the aluminum and steel side, respectively. Again, the antisymmetric term turns out to be very close to the calculated reflection coefficient of the ideal interface, while the symmetric component is -1.9%. This value corresponds to an effective softening (lower acoustic impedance) in the interface region. As a matter of fact, in all of our experiments the symmetric term appears to be negative, i.e. the interface region has lower effective impedance than those of the neighboring solids.

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 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. 8 shows the good correlation between the measured symmetric reflection coefficient and the welding pressure between 1500 - 2000 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. 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.

CONCLUSIONS

Ultrasonic detection and characterization of cold welds are discussed in the first part of the paper. The low ultrasonic contrast of such defective bonds can be attributed to the intimate mechanical contact between the surfaces due to substantial plastic flow in the heated parts under high compressive pressure. Strong qualitative correlation was found between the characteristic transition frequency of the reflection spectra from cold welded interfaces and the compressive pressure applied during the welding process. Quantitative evaluation of the measured spectra
Fig. 8. Correlation between the symmetric ultrasonic reflection coefficient and the welding pressure for stainless steel-copper inertia welds.

necessitates the further development of Haines' model to include stronger plastic deformations as well.

A novel signal processing technique was suggested for quantitative evaluation of weak boundary imperfections at dissimilar interfaces. We showed that the symmetric part of the interface reflection coefficient is a sensitive measure of boundary imperfections and it is sufficiently independent from the usually very strong specular reflection. Strong correlation was found between the symmetric reflection of apparently flawless inertia welds and principal welding parameters, such as axial pressure. Further investigation of the relationship between the measured parameter and actual bond quality must be carried out on a case-by-case basis.

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