KISSING BONDS IN DIFFUSION BONDED PARTS

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INTRODUCTION

The widespread application of diffusion bonding has been hindered, in part, by concerns over kissing bonds. Kissing bonds are generally considered to be conditions where a bond has little or no strength and the concern is that such conditions might escape detection. At Rohr we differentiate between an intimate contact disbond (which has no bond between the surfaces but is detectable by careful ultrasonic testing) and a kissing bond (which also has no bond between the surfaces but is not detectable using current ultrasonic technology). These definitions will be used throughout.

While this work was prompted by concern over the possibility of kissing bonds in solid state diffusion bonds, concern also exists over the possibility of such conditions in other bonded structures such as liquid interface diffusion (LID™) bonded parts, brazed structures and polymeric composite components. These bonding methods are used for solid-solid bonds and in the manufacture of honeycomb sandwich structures.

THE EFFECT OF PRESSURE ON INTERFACES

Modeling

As two similar surfaces are brought together, small asperities on the two surfaces start to contact each other. As the fraction of the total interface area that is actually contacting at a microscopic level is very small, the yield strength of the material is soon exceeded at the points of contact and the asperities start to deform plastically. Deformation increases but the rate slows as the fraction of the interface that is contacting increases and the local stress at the asperities decreases. If the surfaces can be brought into perfect contact then the interface should become ultrasonically transparent [1]. The field of kissing bonds is centered on the exact nature of the microscopic contact between the surfaces and the ensuing ultrasonic behavior of the interface. This work modeled small gaps filled with air or solid material and predicted the dependence of the ultrasonic reflection coefficient on the separation of the surfaces as illustrated in Figure 1. Some of the limited experimental work in this field [2] indicated that this simple theory overestimates the reflectivity of interfaces under these conditions and that significant ultrasonic transparency starts when the face separation is little less than 0.001 inches (25 μm).

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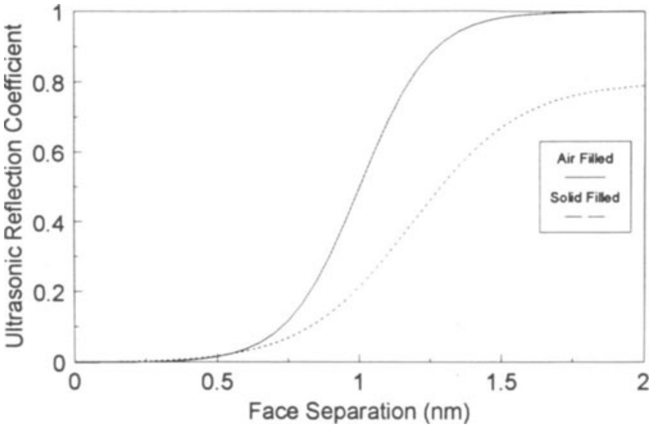


Figure 1 Modeling the effect of surface separation on ultrasonic reflection coefficient.

Other models have been developed to include the effects of pressure on an unbonded interface [3, 4, 5] and have predicted a decrease in reflection coefficient of up to a factor of three. Other models [6] have predicted the reflection and transmission coefficients as a function of frequency and an example of such a calculation is shown in Figure 2(a). A characteristic frequency, Ω, can be defined at which the reflection and transmission coefficients are equal and the ratio of these coefficients for compression and shear waves can be expressed in terms of Poisson's Ratio, ν :

$$\frac{\Omega_T}{\Omega_L} = \frac{2-\nu}{2}\sqrt{\frac{2(1-\nu)}{1-2\nu}} \tag{1}$$

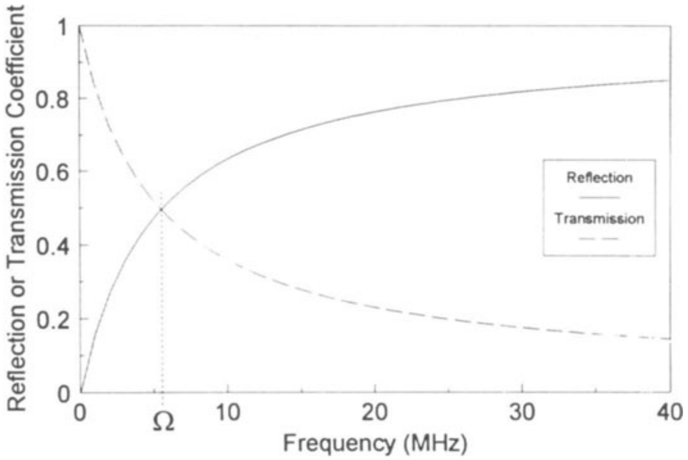
For titanium 6-4, ν is approximately 0.31 and the ratio of characteristic frequencies is 1.61. This indicates that stronger reflections will be obtained with compression waves than with shear waves. If we assume that we have a kissing bond with no strength, the ratio of characteristic frequencies is given by [7] :

$$\frac{\Omega_T}{\Omega_L} = \frac{1}{2(1+\nu)}\sqrt{\frac{2(1-\nu)}{1-2\nu}} \tag{2}$$

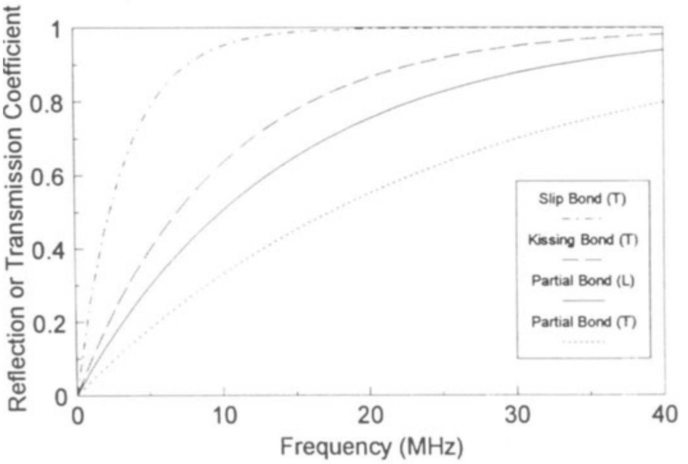
In this case the ratio of characteristic frequencies for titanium is 0.73 and slightly stronger reflection will be obtained by the use of shear waves. The literature often refers to a slip bond as one that allows easier transmission of shear across an interface that a kissing bond. A partial or intermittent bond is one in which there are discrete disbonds in an otherwise well bonded interface. This is commonly modeled as a regular array of bonded and unbonded regions [8]. Predicted reflection coefficients for all these different types of interfaces are shown in Figure 2(b). This and other modeling indicates that high frequencies are the most effective for detecting a wide range of defects. While a few published works have examined the effect of pressure on the ultrasonic behavior of interfaces, none have done so at pressures representing more than a few percent of the yield strength of the materials concerned. In one study of interfaces in aluminum [6], reductions in reflection coefficients of around 15 dB were measured when a pressure of 8 ksi was applied to the interface.

Experimental Measurements

A compression test fixture (shown in Figure 3) was constructed from stainless steel to allow the ultrasonic measurement of the interface between two titanium plates under high loads. The faying surfaces of 4 pairs of titanium 6-4 plates were prepared to have surface finishes bracketing those typically used in diffusion bonding. The plates were ground very flat and parallel and were then abraded in pairs on sheets of carborundum paper to produce the required surface finishes. The surface finishes (R_a values) obtained were as shown in Table 1. The surface finishes achieved with the 220, 120 and 80 grit Carborundum were very similar for each of the pairs of test plates. With the 60 grit Carborundum, it proved impossible to match the surface finishes on both plates.



(a) Generalized interface.



(b) Differing imperfect interfaces.

Figure 2 Ultrasonic reflection and transmission coefficients for interfaces.

Table 1 Surface finish measurements on test plates

Plates	Carborundum Grit #	Surface Finish A (μ") Mean ± SD	Surface Finish B (μ") Mean ± SD
1 & 2	220	7.0 ± 2.2	8.3 ± 3.0
3 & 4	120	11.0 ± 1.4	11.5 ± 2.4
5 & 6	80	30.8 ± 3.2	27.8 ± 1.7
7 & 8	60	53.8 ± 14.4	24.3 ± 6.5

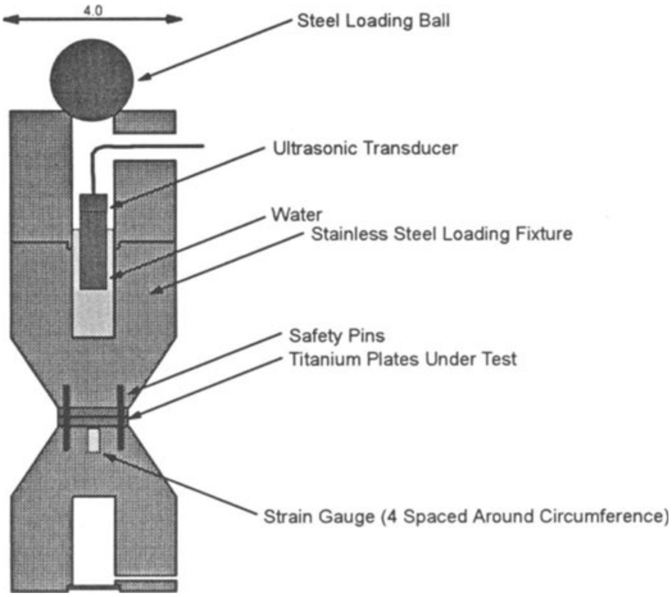
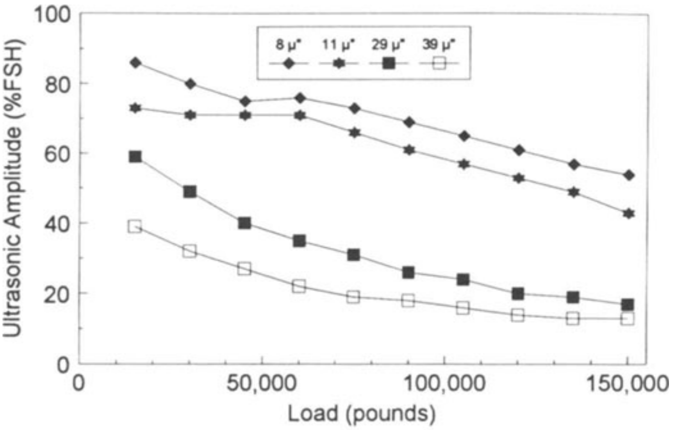


Figure 3 Compression test fixture.

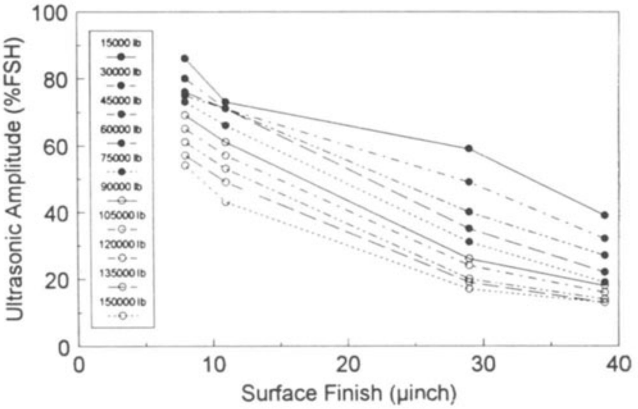
The pairs of plates were very evenly matches in surface finish except for the coarsest combination (#7 and #8). Each pair of plates was installed in the test fixture along with a 10 MHz, 0.25 inch element, unfocused, wideband transducer coupled to the fixture with water. The transducer was connected to a portable flaw detector with a digital readout. The gain was selected such that the interface echo between the two plates was a little less than full scale. The test plates were ultrasonically coupled to the rest of the fixture using Panametrics SWC (Shear Wave Couplant). A large stainless steel ball was used at the top of the fixture to try to keep all the loads axial and four strain gauges were mounted on the outside of the loading fixture to check that the loading was axial.

The assembly was installed in a standard test machine and incrementally loaded in 15,000 pound steps to 150,000 pounds (approximately 60% of the compressive yield strength of titanium 6-4). Prior to each loading sequence, a small load was applied and then removed to settle all the interfaces and ensure good ultrasonic coupling.

The amplitudes of the interface echo as a function of applied load are shown in Figure 4(a). It can be seen that the amplitude (and therefore the reflection coefficient) decreased monotonically with increasing load. It should be noted that the amplitude did not fall below 30% of its initial value and never fell below 10% Full Screen Height (FSH).



(a) Plotted against load.



(b) Plotted against surface finish.

Figure 4 Ultrasonic amplitudes during compression loading.

In Figure 4(a) it can be seen that the ultrasonic amplitude (and therefore the reflection coefficient) decreases as the surface finish becomes rougher (the numerical value increases). This can be seen more clearly in Figure 4(b) which demonstrates that this effect occurs at all pressures and at approximately the same rate. Intuitive assessment of the mechanics of this experiment would suggest that rougher surfaces should give higher reflection coefficients as they should have smaller area fractions in contact due to the larger asperities. The opposite effect noted here is attributed to the rougher surface finishes resulting in more local yielding as the local pressures are higher. This effect cannot continue indefinitely as the surfaces become finer as the reflection coefficient for perfectly flat surfaces must be zero.

ULTRASONIC EXAMINATION OF BONDED METALLIC STRUCTURES

There are four major types of bond in metallic structures - solid state diffusion bond, liquid interface diffusion (LID™) bond, brazed bonds and adhesive bonds. Most of the data presented are applicable to the first three of these bond types and some will also apply to adhesive bonds. One of the problems in investigating intimate contact disbonds or potential kissing bonds is that the very act of cutting samples to metallographically determine the nature of the bond will often separate the faces of any intimate contact disbond or kissing bond that might be present.

LID™ Bonded Titanium Structures

There is anecdotal evidence of kissing bonds in LID™ bonded parts inspected in through transmission that subsequently were found to have no bond strength. In recent years there has been a move towards the more widespread use of pulse echo inspection as this is thought to be more effective at detecting any possible intimate contact disbond condition. The reason for the superior capability of pulse echo testing lies in signal to noise ratio considerations.

If an intimate contact disbond were present in a through transmission test, its amplitude would be very similar to that from a good bond for it to remain undetected. This would be consistent with the data presented above for interfaces under pressure having significantly reduced reflection coefficients. If that same defect is present in a pulse echo test, the signal to noise ratio is considerably better than in the through transmission case and it is easier to distinguish the intimate contact disbond from the good bond. In the case of honeycomb sandwich parts, this is particularly true as the through transmission inspection has a particularly low signal to noise ratio due to the very high attenuation in the honeycomb core.

An example of different bond conditions is illustrated in Figure 5 which shows metallographic sections of four core to skin bonds in a LID™ bonded titanium alloy honeycomb sandwich part. In the good bond, perfect bonding is observed between the core and the skin. In the case of the partial bond, part of the interface is bonded and the remainder is completely disbonded. In the disbonded case, there is total separation between the core and the skin. In the potential intimate contact disbond case, there is a very small separation between the core and the skin and it is possible (although unprovable) that the two surfaces were in intimate contact before the part was sectioned.

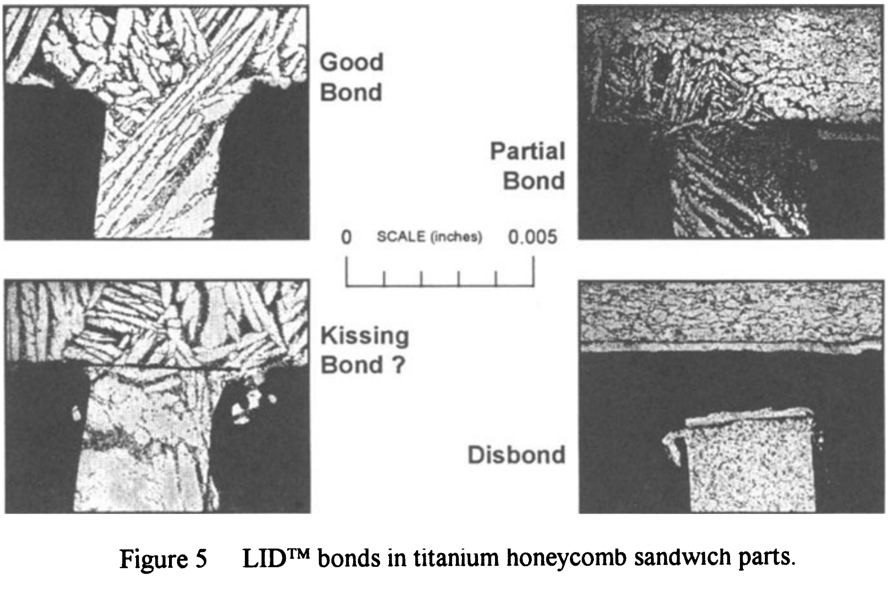


Figure 5 LID™ bonds in titanium honeycomb sandwich parts.

Table 2 Pulse echo and through transmission in LID™ bonded titanium

Sample Number	Detected in Pulse Echo	Detected in Through Transmission
1	81	25
2	47	31
TOTAL	128	56

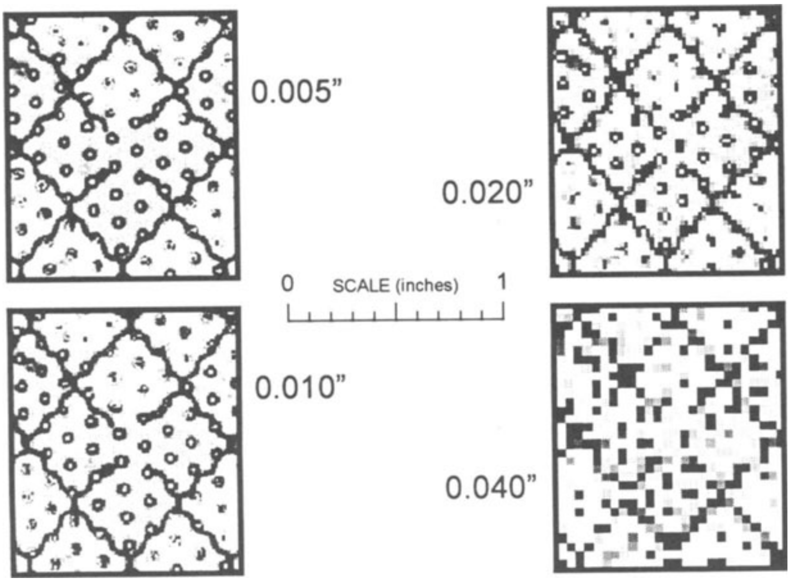


Figure 6 The effect of resolution on image quality for honeycomb sandwich parts.

Table 2 shows the result of performing pulse echo and through transmission inspection on LID™ bonded titanium honeycomb sandwich parts. The parts could not be destructively examined but it is assumed that pulse echo detected all the defects. It can be seen that pulse echo testing detected significantly more defects than through transmission inspection. Assuming that pulse echo found 100% of the defects, through transmission only detected 44% with the correct size, although an additional 8% were detected but undersized. The size of the defects did not appear to be a factor in their detection (or lack of detection).

An important feature of any form of ultrasonic testing is the spatial resolution employed. This is a function of many parameters including the pixel size and many transducer characteristics. The effect of resolution is particularly marked for the inspection of honeycomb sandwich structures, as illustrated in Figure 6. The core to skin bonds can be clearly seen at 0.005 and 0.010 inch pixel sizes but become less clear at 0.020 inches and almost impossible to see at 0.040 inches (a common pixel size in the aerospace industry).

Brazed Inconel Structures

A similar assessment of pulse echo and through transmission inspection to that described above was carried out on brazed Inconel honeycomb sandwich parts which were destructively examined after inspection. The data are shown in Table 3.

Table 3 Pulse echo and through transmission in brazed Inconel

Sample Number	Found Metallographically	Detected in Pulse Echo	Detected in Through Transmission
1	47	47	10
2	93	93	33
3	35	35	8
4	23	23	0
TOTAL	198	198	51

The parts were destructively examined after inspection to determine the position and size of all core to skin defects. Pulse echo testing detected all 198 defects and correctly sized each one (within ±0.05 inches). Through transmission inspection only detected 26% with the correct size, although an additional 10% were detected but undersized. The defects that remained undetected with through transmission encompassed the entire range of sizes and did not have a size limit.

CONCLUSIONS

Interfaces under pressure have reduced ultrasonic reflection coefficients compared to those not under pressure and the reflection coefficient decreases as the pressure is increased. The reflection coefficient does not fall to zero, even when the yield strength of the material is approached. The effect of increasing surface roughness of the faying surfaces is to decrease the reflection coefficient. If ultrasonic inspection is carried out correctly, there should never be an instance where an intimate contact disbond remains undetected.

Experimental assessments of pulse echo and through transmission ultrasonic testing were performed on both LID™ bonded titanium and brazed Inconel honeycomb sandwich structures. In Inconel, pulse echo identified and correctly sized all defects but through transmission failed to detect many defects and undersized others. In titanium, pulse echo detected a significantly greater number of defects and, on occasions, indicated larger sizes. Pulse echo inspection is clearly superior and appears to detect all defects in these structures.

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