A COMPARISON OF THE DETECTABILITY OF DRY CONTACT KISSING BONDS IN ADHESIVE JOINTS USING LONGITUDINAL, SHEAR AND HIGH POWER ULTRASONIC TECHNIQUES

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ABSTRACT. This paper details a study on the detectability of dry contact kissing bonds in adhesive joints using three ultrasonic inspection techniques. Conventional normal incidence longitudinal and shear wave inspection were conducted on dry contact kissing bonds using a standard immersion transducer and an EMAT respectively. The detectability of the dry contact kissing bonds was assessed by calculating the reflection coefficient of the interface at varying loads for a number of surface roughnesses. A high power ultrasonic method was also employed to determine the non-linear behavior of the adhesive interface. The non-linearity of the interface was determined by the ratio of the amplitudes of the first harmonic and fundamental frequencies of the transmitted waveform. It was found that the high power technique showed the greatest sensitivity to kissing bonds at low contact pressures, however at high loads conventional longitudinal wave testing was more sensitive. It was also noted that a combination of two or more techniques could provide enhanced information about the kissing bond compared to a single technique alone.

INTRODUCTION

A large amount of literature has been published on the subject of kissing bonds[1-4], however not all definitions are consistent which has lead to confusion regarding exactly what a kissing bond is and how they are formed. This paper concerns dry contact kissing bonds which are adhesive disbonds in which the disbonded surfaces are compressively loaded thereby providing intimate kissing contact.

Conventional longitudinal wave [5, 6] and shear wave [7] techniques have both been used to inspect imperfect interfaces in metal-metal contacts, whilst recent years have seen an increase in the interest surrounding the use of high power ultrasonic techniques to determine the non-linear behavior of structures [8-10]. This paper looks at the ultrasonic response of dry contact kissing bonds with respect to determining their detectability. The detectability of dry contact kissing bonds will be assessed for both longitudinal and shear wave inspection by determining the degree of reflection from the disbonded interface. For the high power inspection of the kissing bonds, the detectability is determined by comparison of the non-linearity of the disbonded interface to that of a perfectly bonded interface. The detectability of the kissing bonds using all three techniques is then compared.
EXPERIMENTAL SET-UP

Longitudinal Wave and Shear Wave Inspection

The experimental set-up for both the longitudinal (Figure 1a) and shear (Figure 1b) wave tests was based on the experimental technique used by Drinkwater et al [6] for the study of aluminum-aluminum contact. Both experiments were conducted in pulse-echo looking at the adhesive bondline from the disbonded side.

Longitudinal wave testing was conducted using a 10MHz wideband immersion probe with a spherical focal length of 76.2mm in water. The longitudinal wave ultrasound was coupled to the bond using a water bath with the standoff set to focus on the first aluminum-adhesive interface which was where the disbond was created. Shear wave testing was conducted using a 4MHz Electro-Magnetic Acoustic Transducer (EMAT). The EMATs used produced normal incidence radially symmetric shear waves. The adhesive bond samples were loaded in compression using a Zwick 1478 mechanical testing machine. The time traces were converted to the frequency domain using a Fast Fourier Transform (FFT) and then divided through by a reference trace. The reference trace is obtained by capturing the reflection from an aluminum-air interface for which the degree of reflection is known to be 100%. The Reflection Coefficient (RC) of the interface is therefore determined by equation 1.

\[ RC = \frac{U_{\text{exp}}}{U_{\text{ref}}} \]  

where \( U_{\text{exp}} \) and \( U_{\text{ref}} \) are the amplitudes of the reflection from the kissing bond at a given load and the reference traces respectively.

The same experimental technique used for the longitudinal wave testing was used for the shear wave inspection. The amplitude of the shear waves produced was found to be highly sensitive to the standoff of the EMAT from the surface of the aluminum disc.

FIGURE 1. Loading test experimental set-up. Longitudinal (a) and shear (b) wave loading apparatus schematic diagrams.
The effect of the signal amplitude variation was reduced by dividing each of the signals, both reference and for each load increment, by the signals obtained from the second reverberation within the lower aluminum disc. The reflection coefficient therefore becomes,

\[ RC = \frac{U_{\text{exp} 2}/U_{\text{exp} 1}}{U_{\text{ref} 2}/U_{\text{ref} 1}} \]

where the numerical subscripts refer to the first and second reverberations within the lower aluminum disc.

**High Power Ultrasonic Inspection**

For the high power ultrasonic inspection, through transmission was used requiring the addition of an upper loading cylinder to accommodate a second transducer for reception of the through transmitted signal (Figure 2).

To obtain the large amplitudes of oscillation necessary to create non-linear behavior at the adhesive-aluminum interface a narrow band ultrasonic transducer was manufactured using a 20mm diameter PZT8 focal bowl element with a spherical focal length of 80mm in water. Input to the high power transducer was a 6 cycle gated burst at 1.85MHz from a RITEC RAM10000 high power amplifier. The peak-to-peak amplitude of the signal input to the transducer was 300V. The signal transmitted across the bond was received by an off-the-shelf 5MHz wideband ultrasonic immersion transducer and fed through an amplifier and captured by a digital oscilloscope. An FFT was then performed on the signal and the non-linearity of the system calculated by taking the ratio of the amplitudes of the first harmonic and fundamental frequencies \( A_1/A_0 \).

**EXPERIMENTAL RESULTS**

**Longitudinal Wave Inspection**

Figure 3 shows loading curves for three dry contact kissing bond tests inspected using longitudinal wave ultrasound. The graph shows the reflection coefficient plotted against contact pressure for the three bonds. Also plotted is the reflection coefficient loading curve for a perfectly bonded joint.
It can be seen from Figure 3 that, for all roughnesses of interface, as the contact pressure at the interface is increased the reflection coefficient reduces. This reduction in reflection coefficient is due to an increase in the physical contact area. The increase in the actual contact area increases the interfacial stiffness and hence increases the percentage of ultrasound transmitted. It can also be seen that for the smooth interface the reflection coefficient tends towards that of the perfect contact bond at lower contact pressures than for the two rougher interfaces.

**Shear Wave Inspection**

Figure 4 shows the multiple loading cycle plots for both a longitudinal and shear wave test. Both samples were produced to the same nominal roughness and the two loading curves calculated for an interrogating frequency of 5MHz. Although not the center frequency of either the longitudinal or shear wave transducers, both have sufficient bandwidth for the 5MHz point to lie within their -6dB points. It can be seen from Figure 5 that the essential form of the two loading curves is the same. It is however noticeable that because of the much lower signal amplitudes produced by the EMAT shear wave transducers, the loading curve shows a much “noisier” response than the longitudinal wave immersion transducer.

Figure 5 shows the plot of contact pressure against Reflection Coefficient Ratio (RCRatio) for three surface roughnesses of sample. The RCRatio is defined as the ratio of the shear wave reflection coefficient to the longitudinal wave reflection coefficient.

$$RCRatio = \frac{RC_{\text{Shear}}}{RC_{\text{Long}}}$$  \hspace{1cm} (3)

It can be seen from Figure 5 that the RCRatio at low contact pressures is very similar. As the contact pressure is increased, the RCRatios for the separate interfaces become different. The RCRatio of the smoother interfaces tends to be larger for a given contact pressure indicating a larger degree of shear wave reflection for a given longitudinal reflection. This suggests that dry contact kissing bonds with smoother surfaces tends towards the case of a slip bond in which the shear interfacial stiffness is much reduced.
FIGURE 4. Comparison of shear and longitudinal loading tests.

FIGURE 5. RCRatio plotted against contact pressure for 3 roughnesses. Surface roughness given in $R_a$.

due to the ability of the surfaces to slip across one another. In contrast the larger asperities of the rougher surfaces will tend to give a higher shear stiffness due to interlocking of the surface asperities.

High Power Ultrasonic Inspection

An example of the high power ultrasonic response of a dry contact kissing bond is shown in Figure 6. The plot shows the non-linear ratio plotted against contact pressure for a two cycle loading test. It can be seen from the plot that the non-linear ratio of the system is at a maximum at very low loads. This can be attributed to clapping behavior of the interface. At low loads the interface will have large areas which are only just or very nearly in contact. When the large amplitude of oscillation is incident on these contact areas, their localized stress-strain curve may look something akin to that in Figure 7. The large difference between the tensile and compressive stiffnesses results in a highly non-linear system creating large amplitude harmonics in the transmitted signal. As the contact pressure is increased, the percentage of contact area that is only lightly loaded will decrease and hence the non-linearity of the interface will also decrease.
FIGURE 6. High power ultrasonic response from dry contact kissing bond.

FIGURE 7. Non-linear stress-strain response of clapping contact.

Comparison of Shear, Longitudinal and High Power Inspection Techniques

Figure 8 shows the sensitivity of each of the three techniques to the presence of three roughnesses of interface. The sensitivity is determined by the percentage of the perfect contact value for each technique. In the case of longitudinal and shear wave inspection, this is determined by percentage change in the reflection coefficient from the disbonded interface relative to the reflection coefficient for the perfectly bonded interface. In the case of the high power inspection, this has been measured by the percentage change in the non-linear ratio of the disbonded interface relative to the non-linearity of the entire inspection system when inspecting a perfectly bonded joint.

It can be seen from Figure 8a and Figure 8b that the sensitivity of the high power technique drops off very quickly with load. Once a small degree of pressure is applied to the system the contact non-linearity reduces. Because the non-linearity of the system is also influenced by any non-linearity in the equipment and measuring technique, there may still be some contact non-linearity at higher pressures but it may be overwhelmed by the inherent system non-linearity.

Although the longitudinal wave sensitivity to this type of kissing bond is less at low pressures than for the high power inspection technique, it can also be seen that the sensitivity is spread over a much larger range of pressures. This suggests that longitudinal wave inspection is more sensitive to dry contact kissing bonds at high pressures.
CONCLUSIONS

Longitudinal wave, shear wave and high power ultrasonic inspection has been carried out on dry contact kissing bonds. Comparison was made between dry contact kissing bonds with different interface roughnesses using all three techniques. It was found that at very low contact pressures the greatest sensitivity is gained by use of the high power inspection technique. As the contact pressure increases, the sensitivity of this technique reduces rapidly making it less effective at higher contact pressures. For higher contact pressures, conventional longitudinal wave inspection offers the greatest contrast between kissing bonds of different surface roughness and contact pressures, thereby showing the greater potential for their detection.
Although each single technique shows promise for detection in certain circumstances, a combination of two or more ultrasonic techniques could potentially provide enhanced information about the quality of an adhesive bond.

REFERENCES