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Intermetallic Bonding as an Alternative to Polymeric Adhesives in Ultrasound Transducers

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***Abstract*— Common ultrasound transducers utilize epoxy for bonding the active piezoelectric to the rest of the acoustic stack. This paper explores some of the potential benefits of replacing this soft epoxy layer with a harder metallurgical bond. The influence of varying the bond layer thickness was evaluated for epoxy- and intermetallic bonding layers in an ultrasound transducer, as was the effect of voids and delamination that may occur during fabrication of intermetallic bonds. It was found that the intermetallic bond could be made much thicker than an epoxy bond without degrading the transducer performance, and the influence by thickness variations was less. Small voids in the intermetallic where shown to cause a downshift in resonance frequency, whereas regions with delamination will cause reflections that degrade the performance of the transducer.**

Keywords— Ultrasound, Transducers, Modelling, Bonding Techniques, Intermetallics

I. Introduction

A. Background

An ultrasound transducer should function as designed for many years and endure challenging environments. For a medical ultrasound transducer, this means several hours use every day, over years with rough handling, cleaning, and sterilization procedures that may involve high temperatures. For downhole oil and gas investigations, the transducer will be exposed to the high pressures and temperatures in an oil well. This may contribute to degradation of transducer performance over time, and delamination in the acoustic stack is one possible source of this. Fleury et. al. reported 18% reduction in pulse-echo amplitude after exposure to a high temperature and high pressure tests [1]. Hence, there is a demand for investigation into new materials and fabrication methods that can increase the robustness and longevity of transducers.

B. Limitations in Transducers

Common ultrasound transducers use a piezoelectric element to convert between electrical and mechanical energy. To maximize energy transfer and bandwidth, acoustic matching and backing layers need to be bonded to the piezoelectric material. This is commonly done using a polymer adhesive, e.g. epoxy resin. The characteristic acoustic impedance of the polymer bonding layer is typically much lower than that of the piezoelectric material and the innermost matching layer. Such a low-impedance, or soft, layer between two harder layers influences the acoustic performance of the transducer unfavorably, by creating extra resonances, typically resulting in a longer pulse. The normal way to mitigate this is by making this bonding layer very thin compared to the acoustic wavelength. This can be difficult to achieve, especially for high frequencies: Above 10 MHz, the short wavelengths makes even a few micrometer thick layer noticeable. Despite this, the use of polymeric adhesives is a well-established method for bonding the layers in an acoustic stack, and decades of experience verify that it functions excellently in many ultrasound transducer applications. The drawbacks associated with the polymeric layer are most evident in either harsh conditions, i.e. high temperatures and pressures, and at high frequencies. If the bonding were done using a hard material, i.e. a material with higher characteristic acoustic impedance, the bonding layer would have less influence on the acoustic performance. This allows for a thicker bonding layer where the acoustic performance would be less influenced by inhomogeneities and thickness variations between and in each element.

C. SLID Bonding

SLID (Solid-liquid interdiffusion) bonding, also called TLP (transient liquid phase bonding), isothermal solidification and off-eutectic bonding, is an alternative for creating hard metallurgical bonds. The system was first developed as a die attach and interconnection technology for high temperature electronics and offers a well-defined, reliable metallurgical bond line with excellent mechanical strength and electrical conductivity [2]. The technique combines a high- and low-melting temperature metal (hereafter referred to as HTM and LTM, respectively) processed above the melting temperature of the LTM. The heating process allows the metals to interdiffuse to create an intermetallic compound (IMC) which is stable at temperatures above the melting temperature of the LTM. Nguyen et. al. investigated this in the first work utilizing the SLID technique for fabrication of ultrasound transducers [3]. Manh et. al. [4] followed up the work by Nguyen by bonding PZT to a Tungsten carbide (WC) dematching layer using an eutectic 80 wt% Au- 20 wt% Sn preform.

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The aim of this study is to investigate the effects of such metallurgical bonds on the acoustic performance of the transducer, using FEM simulations. The influence of the bond layer thickness was studied, especially the influence on the bandwidth of the transducer, as were the influence from voids and delamination in the bond line. Results were compared to bond lines using a typical polymeric epoxy material.

II. Method

COMSOL Multiphysics 5.3a was used to model transducer-structures with epoxy and intermetallic bonds. Two separate studies were performed. First, the influence of the thickness of the epoxy and intermetallic bond layer were compared. Second, the influence of voids and delamination in the intermetallic bond was evaluated. The models for the two studies had some differences, which will be discussed in the following sections.

A. *Common for Both Models*

The transducers were designed with PZT and WC dematching. Layer thicknesses are listed in Table 2. The boundary condition "Roller" was applied to all side-edges while the top and bottom boundaries were "Free". The domains were defined as "Piezoelectric Material" for the piezoelectric layer and "Linear Elastic Material" for the remaining domains. The electric ground and voltage terminal were applied to the top and bottom boundaries of the piezoelectric domain, respectively.

The intermetallic bond in these models consists of a three-layered structure consisting of gold (HTM) on top and bottom, with an intermetallic Gold-Tin (Au-Sn ζ' phase) intermetallic layer (LTM) between the gold layers.

Fig. 1 shows the general model. Material properties and thicknesses of the passive materials are listed in Table 1. Table 2 lists the material properties of the piezoelectric material.

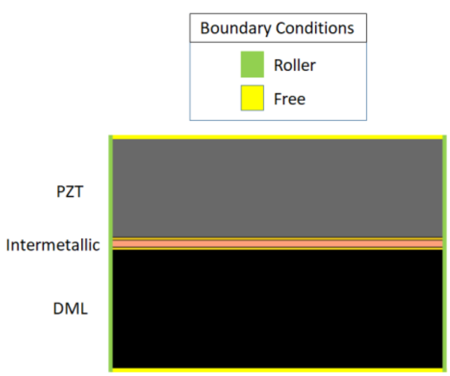

Fig. 1 - Enlarged view of the general model. From the top: PZT, Upper HTM, Intermetallic, Lower HTM, WC dematching.

TABLE 1 – PROPERTIES OF THE PASSIVE MATERIALS

Property	Z MRayl	c m/s	Thickness µm
WC	103	6895	287
Intermetallic (Au-Sn ζ' phase)	47.5	2912	13
Gold	62.5	3240	5
Epoxy	2.8	2450	2

TABLE 2 – PROPERTIES OF THE PIEZOELECTRIC MATERIAL

Property	$\frac{\varepsilon_{33}^{T}}{\varepsilon_0}$ (-)	Z MRayl	c m/s	k_t (-)	Thickness µm
PZT	1200	31.06	4034	0.51	360

B. *Thickness Variation Model*

The model used to evaluate the thickness variation of the bond layer, see Fig. 2, was extended from the basic model, Fig. 1, by adding two matching layers, ML1 and ML2, with a 2 µm thick epoxy layer between each matching layer.

The matching layer thicknesses were kept constant as the bond line thickness between PZT and WC was increased. The thicknesses of the matching layers were optimized for the minimum bond line thickness of each bonding material (2 µm and 13 µm for epoxy and intermetallic, respectively), see Table 3.

Water was used as the acoustic load with a "Perfectly Matched Layer" on top to absorb the propagated acoustic energy.

The performance of the transducer was calculated as the electro-acoustic transfer function $H_{tt}(f)$, defined as:

$$H_{tt}(f)=\frac{U(f)}{V(f)} \tag{1}$$

where U(f) is the normal velocity amplitude at the transducer surface, and V(f) is the voltage amplitude over the electrodes of the piezoelectric. $H_{tt}(f)$ was used to evaluate the bandwidth of the transducer structures as the bond thickness between PZT and WC was varied.

Realistic values for the thickness of the bonds were used. For the metallurgical bonds, the gold layers were kept at 5 µm, while the intermetallic layer was set to 13, 15 and 26 µm. The values were chosen to study the effect of a small, 2 µm change in thickness, and the effect of doubling the thickness. For comparison, conventional epoxy bond lines with thicknesses 2 and 4 µm were also studied.

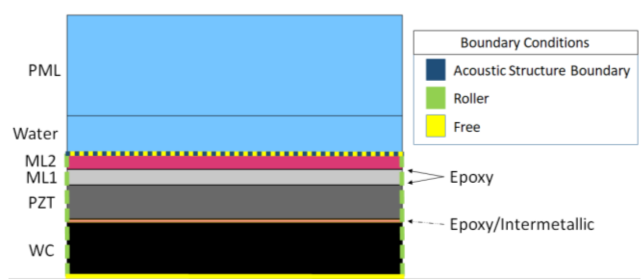

Fig. 2 – The model used to study the effects of varying the thickness of the epoxy/intermetallic layer. Water was used as the acoustic load with a perfectly matched layer on top. The transducer was made similar to the general model but now with two matching layers towards the front.

TABLE 3 – MATCHING LAYER PARAMETERS AND BOND LINE THICKNESSES

Property	Z	c	Thickness	
			Epoxy bonding	Intermetallic bonding
	MRayl	m/s	µm	µm
ML2	2.8	2450	100	95
ML1	8.36	2290	96	85
Bond Layer Thicknesses				
	Epoxy µm			**Intermetallic µm**
	2 4			13 15 26

C. *Void and Delamination Models*

The models used to evaluate the influence of voids and delamination in the intermetallic layer were essentially the same structure as the basic model, Fig. 1. Air was used as the acoustic load in order to get undamped resonance peaks, which are easy to identify by studying electrical impedance spectra. A 13 µm thick intermetallic bond line was used for both models.

The model with voids had an array of voids evenly distributed over the entire bond line, Fig. 3. The void fraction was varied by letting the voids grow in size to occupy up to 20% of the intermetallic volume. The delamination model had one large void centered in the bond line and occupying the full height of the bond. The effect of a growing delamination was studied by increasing the width of the delamination up to 15% of the length of the bond line.

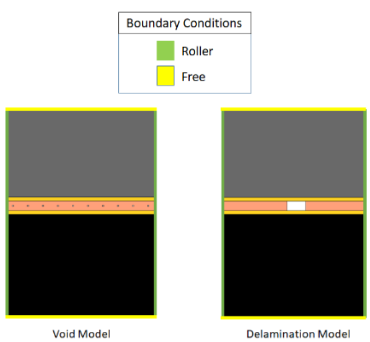

Fig. 3 – Enlarged view of how the voids and delamination were modelled. The left structure shows an array of voids evenly distributed over the entire bond line. The diameter of the voids grow in size from 0-20% volume fraction of the bond. The right structure shows a delamination occupying the entire height of the intermetallic bond. The delamination grow in size from 0-15% length fraction of the bond.

III. RESULTS AND DISCUSSION

A. *Thickness Variation in Bondline*

The influence of varying the bond layer thickness in the interface between PZT and WC is shown in Fig. 4. The transducers with 13 µm intermetallic bond and with 2 µm epoxy bond both have a bandwidth of 58%, but the amplitude of the intermetallic bonded transducer is 1 dB higher. A minimal, 0.3%, variation in bandwidth is observed as the intermetallic bond thickness is increased to 15 µm, and doubling the bond thickness from 13 µm to 26 µm gives a 3% reduction in bandwidth. Comparatively, when the epoxy bond line is increased from 2 µm to 4 µm a 9% reduction in bandwidth is observed.

When 15% volume fraction of voids are introduced in the intermetallic layer the bandwidth decreases 0.3%, the same influence as increasing the intermetallic layer by 2 µm. A delamination that occupies 15% of the length of the bond line gives a 5% reduction in bandwidth.

These results indicate that a harder, metallurgical bond with higher characteristic impedance is less influenced by thickness variation, despite the bond thickness being several times greater than the soft epoxy bond. Voids are proven tolerable whereas a delamination will degrade the acoustic performance of the transducer.

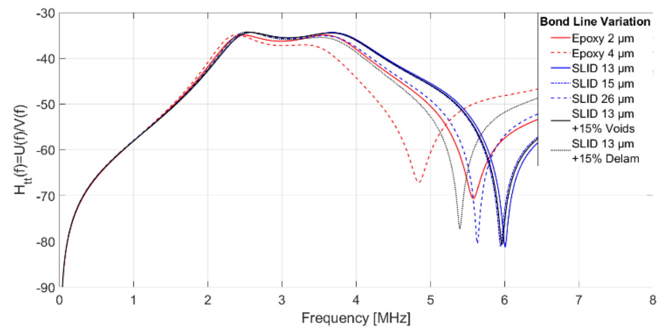

Fig. 4 – The influence of varying the bond line thickness. An epoxy bond shows a large reduction in bandwidth as the thickness is increased from 2 µm to 4 µm (shown in red). An intermetallic bond (shown in blue) is less influenced by doubling the bond thickness from 13 µm to 26 µm. Increasing the bond line thickness from 13 µm to 15 µm has negligible influence on the bandwidth. A 13 µm intermetallic bond with 15% volume fraction of voids has an insignificant impact on the bandwidth of the transducer. A delamination occupying 15% of the length of the bond line will degrade the bandwidth significantly.

TABLE 4 – BANDWIDTH VALUES FOR BOND LINE THICKNESS VARIATION

Bond Line	-3 dB Bandwidth
Epoxy 2 µm	58.2%
Epoxy 4 µm	49.4%
SLID 13 µm	58.2%
SLID 15 µm	57.9%
SLID 26 µm	55.2%
SLID 13 µm +15% Voids	57.9%
SLID13 µm +15% Delamination	53.1%

B. *Void Evaluation*

Fig. 5 shows the electrical impedance of the transducer as the voids increase in size. Voids in the bond line will cause the resonance frequency to downshift and this effect becomes more noticeable for higher frequencies.

It is believed that the reason for the downshift is a reduction in the effective characteristic acoustic impedance in the metal bond due to the presence of voids. These voids are not necessarily destructive to a single element transducer where the volume fraction of voids is constant. However, an array transducer is more susceptible to a variation in the void fraction between elements, which may cause the electro-acoustic performance to vary between the elements.

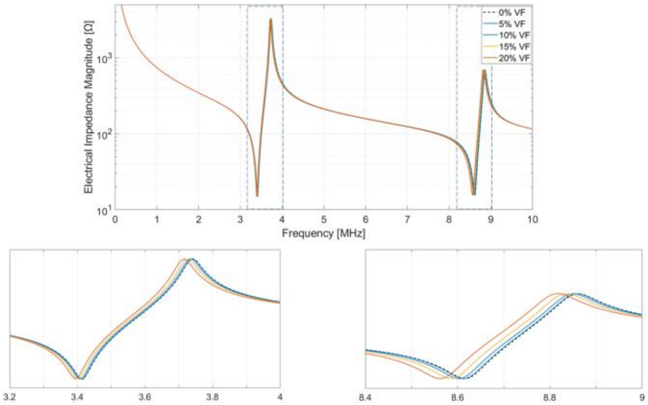

Fig. 5 – Influence of voids on the electrical impedance. The resonance frequency shifts down as the voids increase in size, but no other effect is seen. Voids occupy 0%, 5%, 10%, 15% and 20% of the volume of the intermetallic.

C. Delamination Evaluation

Fig. 6 shows the electrical impedance of a transducer with an intermetallic layer with a growing delamination. A 100% delaminated structure has been included for reference; this resembles a PZT plate in air, i.e. a half-wave resonator.

The delamination causes the first harmonic to downshift, whereas the third harmonic will show increasing reflections as the size of the delamination grows. At 15% delamination of the length of the bond line, the half wave resonance of the PZT becomes visible.

A delamination in the metallurgical layer is considered undesirable, as reflections will cause a reduction in the bandwidth as well as loss of transmitted and received signal amplitude. It is also reasonable to assume that the mechanical strength of the bond will be compromised if delamination is present.

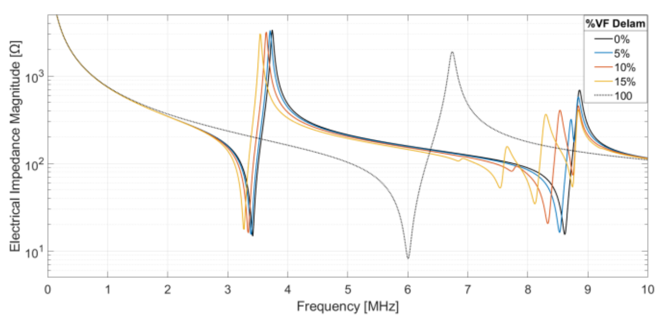

Fig. *6* - The structure with delamination occupying the full height of the intermetallic bond (as shown in Fig. 3) and covering from 0% to 15% of the length of the bond line. The delaminated area will induce reflections which become more apparent as the delamination grows and occupy larger sections of the length of the bond.

IV. Conclusion

A FEM model was built to evaluate and compare the performance of intermetallic bonds to epoxy bonds in an acoustic transducer stack. From the results, it can be concluded that hard metallic bonds are less influenced by the bond line thickness than the epoxy bond. A 2 µm increase of the epoxy bond thickness was found to reduce the bandwidth of the transducer considerably in comparison to a 13 µm increase of the metallurgical bond.

Voids may occur in intermetallic bonds. These were found to shift the resonance frequency down, presumably by lowering the effective characteristic acoustic impedance. If the distribution of voids is homogeneous, the effect may be compensated by optimizing the matching layer thicknesses accordingly.

Delamination, defined as a single void of larger lateral extent, was found to cause ringing in the transducer, reducing the bandwidth. The effect of this single delamination-type void was dramatically different compared to the same volume fraction of voids distributed evenly over the aperture.

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