11017 BANDOL PLACE
LAS VEGAS, NV 89141
805.386.8299 FAX 805.386.8289

Case Study: Bonding Integrity in Bimetallic Steel Tubing

.060" diameter .006" total wall thickness
.155" diameter .010" total wall thickness

A number of samples were provided in 4 groups for evaluation of the interlayer bond integrity of stainless steel- tantalum-stainless steel tubing. These samples were examined with two types of RM-EMATs (resonance mode electromagnetic acoustic transducers) each of several configurations; toroidal axially polarized shear wave and through thickness radially polarized shear wave transducers. The different transduction techniques provided the ability to introduce different types of stress fields into localized areas in the samples. This higher frequency resonance's produced by the flat or through thickness transducer introduces larger strains through the cross section thus providing information on the density or dimensional information and with more formal calculations the elastic constants of the composite core.

Shear resonance modes for the through thickness and toroidal transducers were calculated for the .155" and the .060" diameter samples. Toroidal transducers were constructed in 2,3,4 and 5 wavelength (increasing magnet count) configurations. Presented is data taken with 5 wavelength and 3 wavelength transducers for the .155" and .060" samples respectively.

Shear plate type resonant modes for the .155" were calculated at 413 kHz, 916 kHz, 1.295 MHz and 1.680 MHz. Measured resonant frequencies for the 4th order resonance were as follows:

Frequency = wavenumber x velocity of shear wave / 2 x thickness
1.679 MHz = (4 x 125,984) / (2 x .150)

36" sample nominal diameter is .1581" resonates at 1.7051 MHz. Calculated at 1.703 MHz
18" sample nominal diameter is .1557" resonates at 1.740 MHz
17" sample nominal diameter is .1559" resonates at 1.755 MHz. Calculated at 1.7337 MHz

These plate resonances were of consistent Q (this is a description of the shape of the resonant response) and amplitude throughout each sample. The difference in the short samples of over 10 kHz is a function of materials properties indicative of differences in hardness, given all of the other variables are of equal magnitude. The lower frequency of the 18"` sample representing the harder material.

The tests were also performed with an N: 5 or 5 wavelength 227 " diameter toriodal transducer. The axial shear resonant frequency for this wavelength transducer was calculated at 1.337 MHz for a pure stainless steel tube of these cross-sectional dimensions. The measured resonant frequencies for the first order axial shear mode are as follows:

36" sample nominal diameter of .1581" is 1.2974 MHz
18" sample nominal diameter of .1557' is 1.34450 MHz
17" sample nominal diameter of .1559" is 1.358700 MH

Consistent with the plate transducer output the long sample has a slightly larger diameter (.003) larger diameter sample has a lower resonant frequency consistent with prediction. The 17" and 18" samples have a slightly higher resonant frequency as expected due to their diameter but the 18' sample has a lower resonant frequency than it's shorter slightly larger diameter counterpart thus the frequency difference indicates the hardness difference. Of note the resonant characteristics of the 18" sample utilizing the toroidal transducer were rather poor with a low amplitude and a broad Q, a characteristic of certain materials properties as previously observed in certain highly worked steels.

The .060" samples prepared for the determination of the performance of the ARIS technique for the determination and location of delaminations are presented in the groups as they were sent. These samples were tested with both transducer configurations however for the purpose of brevity the data from both test regimes is presented in a format to show detection sensitivity and the differences between the two test techniques.

The six samples supplied as at the outset of the evaluation were marked in two groups these short pieces were too short for length vs. frequency plotting so the frequency was recorded at three points along each sample and the data averaged. These samples were tested with a three wavelength N: 3 .110" diameter toroidal transducer. The resonant frequency's are as follows:

- Three samples marked "acceptable" exhibited a first order resonant frequency at 1.75500MHz with a spread of approximately +/- 3.25 kHz between samples. This is a data spread of +/- .21%

- The samples marked "unacceptable" primarily resonated at 1.7330 MHz with a similar data spread across and between two of these samples. The mean frequency difference is approximately 22kHz or slightly in excess of 1.25%. One of these samples generated a resonance with near normal frequencies (approaching 1.745 MHz) along the center of its length.

The next set of samples were tested blind with the samples marked "A", "B", "C" and "D". These pieces were tested with both types of transducers. The plate type transducer data is presented. The 1st-3rd order resonant frequencies were calculated at 1.049 MHz, 2.333 MHz and 3.4MHz, respectively. The 2nd order resonances are:

"A":	2.312 MHz	.06185" dia.
"B":	2.304 MHz	.06175" dia.
"C":	2.305 MHz	.06185" dia.
"D":	2.313 MHz	.06180" dia.

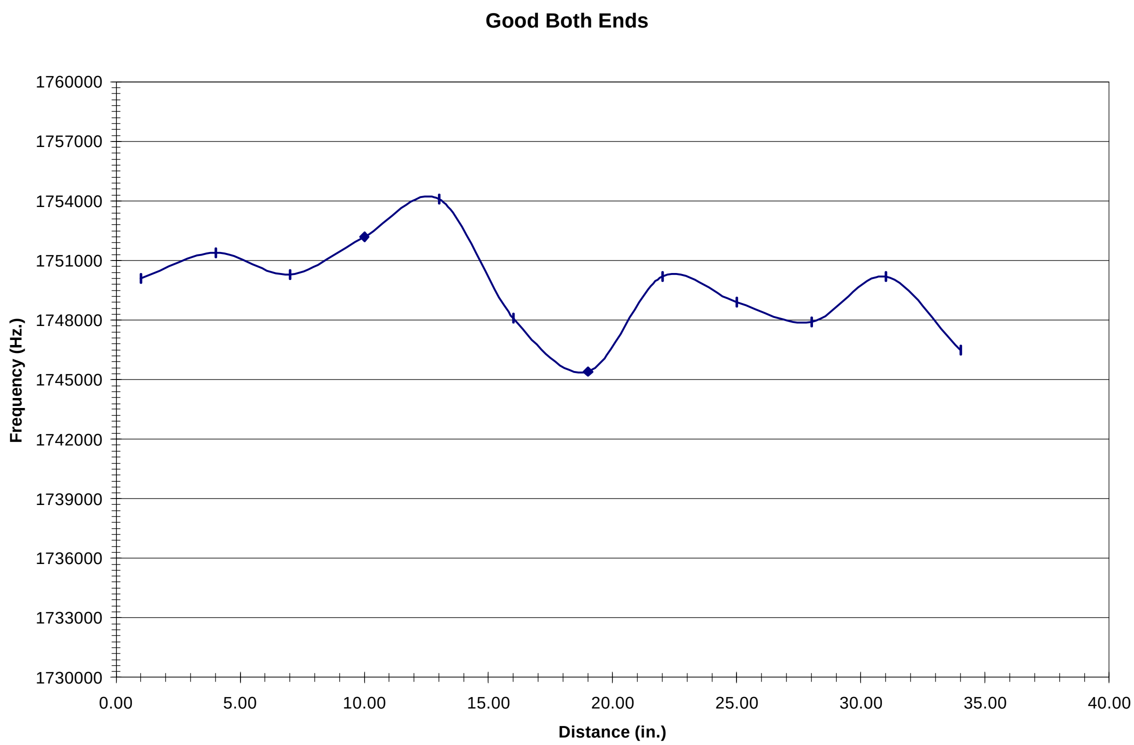
The frequency difference at this modality is .35% between sample groups A & D versus B & C. The diameter differences are negligible relative to the frequency differences in fact these diameter differences mask what would be a greater frequency delta provided all other material variables are constant.

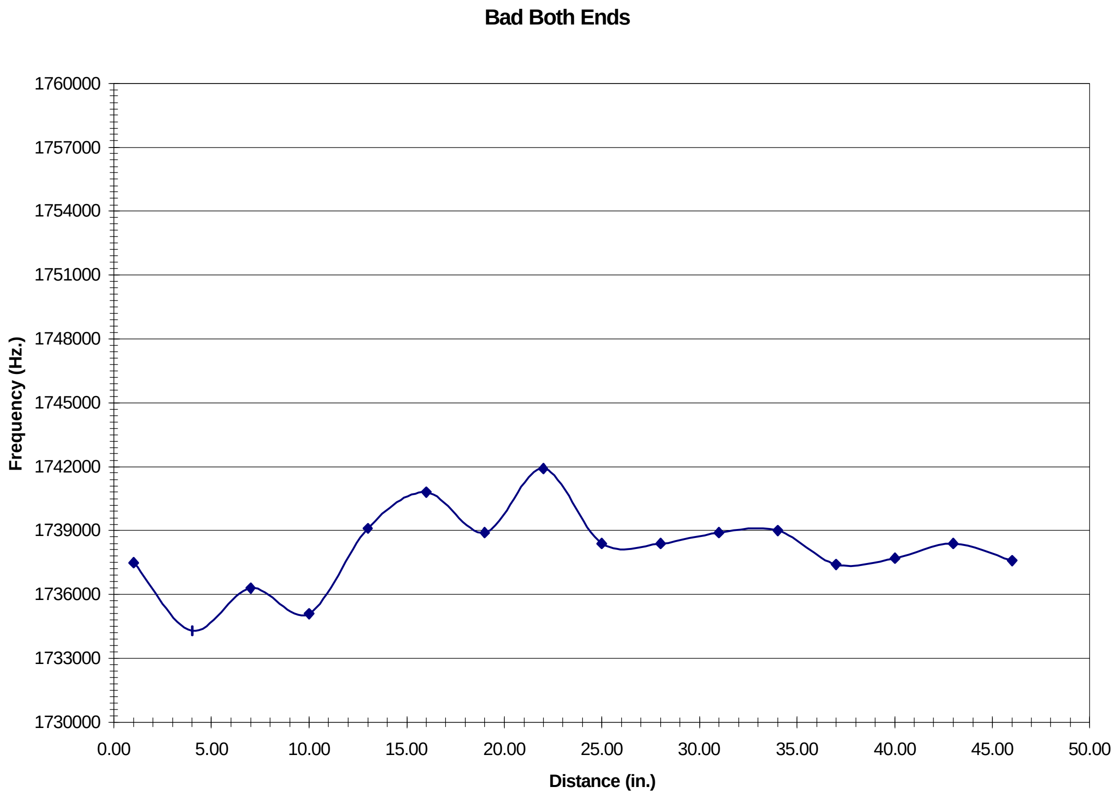
Two of the four in the .060" nominal diameter tubes were thoroughly tested with both plate and toroidal transducers. Presented are plots of these two samples, data was recorded at three inch intervals and these plots were generated with an N:3 toriodal transducer. First order resonance was determined and generated. The plots indicate significant gross frequency differences with variation along the sample length however, the variation does not exceed the gross trends between the two samples. The mean difference is 12,500Hz between these samples approximately .8%, coincidentally the frequency's are of the same magnitude as the original 6 samples.

The resonant frequency's of the samples as tested with the generated similar results with a frequency difference of 5.7kHz. The poor quality sample generating the lower resonant frequency.

- 36" "good both ends" 2nd order resonance 2.3071 MHz +/- 1.5 kHz
- 49" "bad both ends" 2nd order resonance 2.30 MHz +/- 1 kHz

Plots of the axial shear resonant modes generated by the toriodal transducer follow:

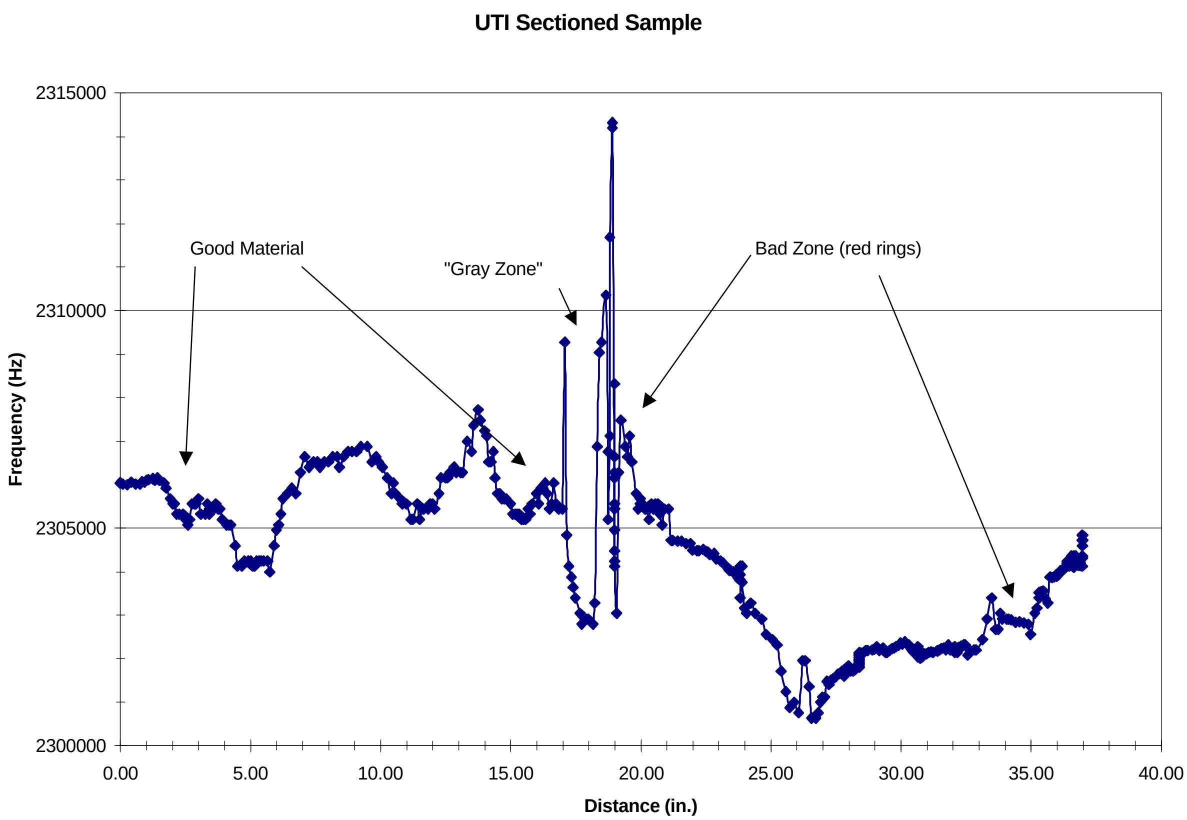




The three wavelength (N: 3) transducer was calculated to produce a resonance at 1.95 MHz for an axial shear mode in an all stainless tube the influence of the tantalum core and the nature of the intermetallic bond reduces the velocity of sound and thus the frequency accordingly. Recent work by Ogi and Hirao at the University of Osaka provide a method using electromagnetically generated acoustic resonances and have developed the calculations for determining the elastic constants of each layer in thin film multilayer flat materials. This work can also be applied to these measurements.

The sample presented for sectioning was a .060"dia. x approx. 37" length tube. This tube was tested extensively with both transducer configurations. The data presented was recorded with a rotary encoder connected to an ARIS unit and the data was plotted as a continuous distance versus frequency graph. The 2nd order resonance was calculated at 2.24 MHz using a modified through thickness resonance model. The sample was hand marked in the locations where the frequencies were changing and the sample was sectioned accordingly. The frequency output of the sample exhibits three distinct patterns. The first 14 inches is consistently above 2.306MHz past this point there is an abrupt change followed by a downtrend to a mean frequency of 2.302MHz, ignoring both ends due to physical damage. This corresponds to a .2% difference in frequency, a significant change in the ultrasonic domain. The abrupt frequency change at the transition point frequency is typical of the effects generated when the resonant field becomes "trapped" due to significant differences in elastic properties in the surrounding regions. The normal strain energy dispersion patterns along the axis of the material become altered and this elastic energy becomes highly localized or trapped.

"1. At 400X (optical), the good sample showed no evidence of delamination.
2. The gray sample showed an area along the ID interface (over a sector of about 30 deg.) with a high population of voids, some interconnected, that can be regarded as "incipient" delamination.
3. The bad sample showed delamination along the ID interface over about 300 deg. of the circumference. The non-delaminated areas (two 30 deg. sectors) were in approx. 180 deg. opposition to each other. No OD interfacial delamination was observed in the sample"



Summary

The bulk of the test conclusions accompany the data directly. As an overview the data indicates a span of .2% to 1.25% difference in resonant frequencies between “good” and “bad” samples or sections of samples without any overlap of the data between the two. Of note are the frequency spreads, sample to sample frequency were within .2%. These can be attributed to process variables including annealing properties, residual stresses introduced by excessive handling and internal dimensional variances. These factors cause localized frequency variance, the extent their contribution cannot be ascertained without sectioning and measurement of these parameters. Additional error sources in determining **absolute** materials properties during test also include external temperature and clamping force (as experienced during test). Specifically, these are not major contributors to measurement errors as long as they are kept relatively constant during test. The frequency repeatability was within .05% of the mean values.

As stated at the outset of this study increasing the resonant frequency through a higher periodicity toroidal or flat transducer will generate a larger difference between normal and delaminated material. Several designs were fabricated but the signal to noise ratios were not satisfactory. These transducers require coils made on special machinery and jigs and were beyond the scope of this evaluation. The advantage of higher frequency resonance is not in that the resonant fingerprint will change but the stress fields are more localized and the transducer spacing can be reduced both factors increasing the spatial resolution. But by the marking/sectioning tests the spatial resolution may be adequate as is.

While the study extended significantly beyond the estimated completion time the amount of time spent on lab work and research far exceeded our estimates based upon the evaluation of the original samples. However the field of electromagnetic acoustic resonance has been advanced into these small geometry structures