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Ultrasonic Techniques for Detection of Thinning Defects in Metal Plates

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Abstract— **This paper describes the use of ultrasonic nondestructive evaluation in corrosion detection of aircrafts structures. Initiating on the inside or in the interface of an aircraft's skin, the corrosion must be tested from the outside surface. Corroded aluminum as well as corrosion simulation samples were inspected using pulse-echo technique of ultrasonic nondestructive evaluation and the values of the remaining thickness obtained was compared with the non-corroded plate of the same type of aluminum alloy. Surface roughness of those plates was also investigated to establish its relation with the determined remaining thicknesses. The estimated depth of the real corrosion by this method shows good agreement with that measured with a micrometer**.

Keywords: Ultrasonic, A-scan, Hidden corrosion, Nondestructive evaluation, Aluminum

I. Introduction

MOST metals used in aircraft structures are subjected to degradation due to exposure to adverse environments including humidity-induced stresses and wide temperature excursions [1]. These conditions may cause localized corrosion attacks in various forms. The severity of corrosion attacks varies with aircraft type, design techniques, operating environments, and operators' maintenance programs [2].

When an aircraft lands and the door is opened, the inside of the plane often fills with warm moist air. When the plane takes flight and reaches altitude, the skin of the aircraft becomes very cold due to the temperature of the outside air. This causes moisture in the air inside the cabin to condense on the inside of the aircraft skin. The water will collect at low areas and serve as the electrolyte needed for corrosion to occur. Furthermore, it has been found that some aircraft corrosion rather than fatigue cracking will be life-limiting such that corrosion can have a detrimental effect on the integrity of aircraft structures by promoting fatigue crack initiation and growth, and by decreasing the residual strength of components.

Generally, pitting, crevice, and exfoliation corrosion are the most common forms of corrosion in aircraft aluminum alloys and, although considerable research has been conducted on electrochemical and metallurgical aspects of these forms of corrosion, little is known about the kinetics of corrosion initiation and propagation.

Despite careful maintenance programs to assure a lower rate of progress of such corrosion damage (proper sealing or cleaning in galley area, proper draining, etc.), corrosion does occur and effective inspection techniques are needed to detect them as early as possible. Detection of each of the corrosion types that can be induced in an aircraft metallic structure may require a different inspection approach due to the unique characteristics that are involved [1].

Several nondestructive evaluation (NDE) methods are widely used for corrosion detection and evaluation. When the inspected area is physically accessible, visual tests are commonly used for periodic checks. Sometimes, tools such as magnifying glasses and borescopes are employed for further evaluation and for less accessible areas, respectively [2]. The inspection involves a visual search for cracks, change of color, change of texture, or bulges. Surface corrosion at its embryonic stage can be visually detected from localized indication such as discoloration, faint powder lines, pimples on the paint and paint damage. Concealed corrosion is very difficult to detect since in most cases the characteristics of the damage are not sufficient to trigger an indication in conventional NDE tests.

Generally, several NDE methods are available to detect and characterize hidden corrosion including X-ray and neutron radiography, ultrasonic, eddy current and acoustic emission. All existing NDE methods for detection of corrosion are limited in capability and sensitivity. Frequently, corrosion is detected only after several subsequent inspection schedules, in which case the damage is fairly extensive and may require the replacement of the structural component involved. Complicating the inspection for hidden corrosion is the presence of multiple structural features. Several technologies are capable of performing accurate measurements of material thickness when there is only a single sheet of the material. However, for example aircraft lap splices are composed of 2, 3 or 4 layers of

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material due to the presence of bonded doublers, tear straps and stringers. Sometimes these layers are of different alloys. [3]

Over 80 percent of the inspections done to an aircraft are visual inspections. At regular intervals, inspectors look at various components of the aircraft for signs of damage. During heavy maintenance work, much of the interior of the aircraft is stripped out so inspectors can look for damage to the inside surface of the fuselage. However, not all areas of the aircraft can be accessed for visual inspection and not all damage can be detected by visual means. This is where NDE plays a critical role in thoroughly inspecting aircrafts.

NDE methods allow inspectors to inspect areas of the plane that would otherwise be impossible to inspect without disassembling the structure to gain access to the internal areas. NDE methods also allow inspectors to detect damage that is too small to be detected by visual means. Eddy current and ultrasonic inspection methods are used extensively to locate tiny cracks that would otherwise be undetectable. These techniques are also used to measure the thickness of the aircraft skin from the outside and detect metal thinning from corrosion on the inside surface of the skin [4]. X-ray techniques are used to find defects buried deep within the structure and to locate areas where water has penetrated into certain structures [5]. Obviously, this task requires trained professionals who are capable of performing a variety of different NDE techniques to get a complete and accurate status of the airplane.

The main objective of this work is to demonstrate the use of ultrasonic nondestructive evaluation (NDE) in corrosion detection. In addition, surface roughness is commonly associated with corrosion thus it has also become the major interest of this experimental work along with the thickness degradation of the inspected plate.

II. Experimental Methodology and Specimens

A. Materials

The principal material specimen used in this work is Aluminum-7075 with thickness of 5±0.2mm. Other materials involved were the Nomex honeycomb structure as well as fiberglass epoxy composite laminate. Theoretical acoustic properties of the design material specimen in this project, found in the literature are tabulated in Table I.

Table I: Acoustic properties of the material specimen used [6]

Material	Longitudinal Velocity(c) m/s	Attenuation (β) nepers
Aluminum-7075	6350	0
Fiberglass epoxy composite laminate	2920	0.3
Nomex honeycomb	-	-

B. Test Specimens

Engineered specimens have been manufactured that include corrosion thinning regions and corrosion by-products. Three types of aluminum corrosion specimens have been used in the ultrasonic wave experimental work.

1) Stepped aluminum plate

Figure 1 shows the detailed dimension of the corrosion simulation specimen. Basically, a stepped aluminum plate would be fabricated in three steps of 2, 2 and 1mm using milling machine available in the laboratory. The stepped behavior exhibited by the plate in this part basically resembles the corrosion behavior where there is a variation of thickness along the plate. Since the machining process is expected to be a poor one, the margin of error is selected to be ±0.5mm.

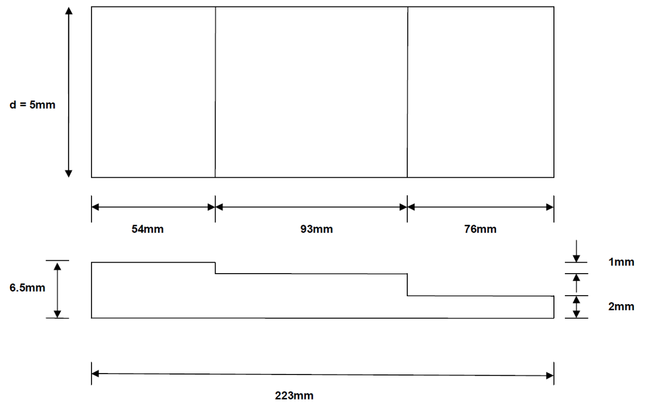


Figure 1 Stepped aluminum plate specimen

Before starting the machining of the aluminum plate using the milling machine, the designed specimen dimensions were precisely measured and marked to fulfill the margin of ±0.5mm. Some precautionary steps were taken and observed while completing the machining of the specimen.

2) Controlled corrosion on aluminum plates

Tube controlled corrosion on aluminum plates was conducted by filling PVC tubes mounted on the plates with a potassium hydroxide (KOH) solution of multi-molarities at a constant period of time. The weight loss of the aluminum plate due to the KOH solution in the tubes may be noted as a reduction in thickness of the plate. It is desirable for the theoretical thickness value of the plate to be measured using a micrometer and then compared to the thickness obtained from the ultrasonic testing. Figure 2 illustrates the mounted PVC tubes on an aluminum plate to provide the KOH solution contact areas.

It was noted from literature that KOH exhibits high corrosivity behavior in the presence of aluminum, brass, and zinc [7]. When it is wet, it attacks metals such as aluminum, tin, lead, and zinc, producing flammable hydrogen gas. In addition, its hygroscopic behavior when dissolved in water or alcohol or when the solution is treated with acid may lead to the generation of a great heat. All of these unique behaviors of KOH have led it to be implemented in this project.

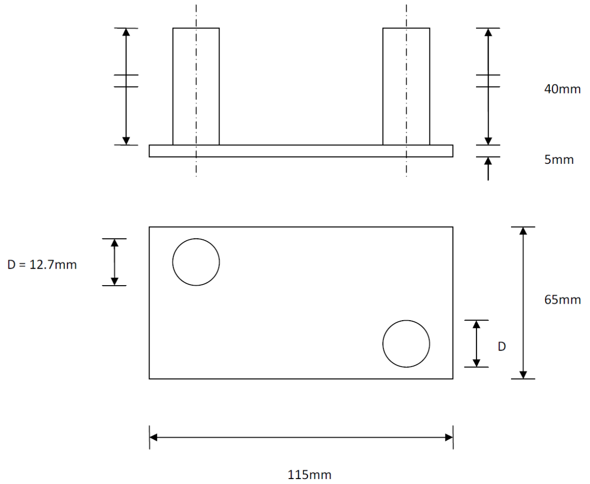


Figure 2 Controlled corrosion specimen

The KOH solution for concentrations of 1, 2, 3, 4, 5, and 6 Mol were provided for the tube controlled corrosion to occur on three aluminum plates that have been adhesively mounted with the PVC tubes. A constant period of 60 minutes was allowed for all specimens to react with the KOH solution in the tube. The initial and final weights of the specimens was recorded to verify a thickness reduction on the plates.

3) Corroded aluminum plate adhesively bonded to multi-wall construction

Figure 3 demonstrates a resemblance of corroded aluminum liner sitting in the multi-wall structure of the external fuel tank. In this work, it is desirable to fabricate this multi-wall structure as close as possible to the real one. The controlled corrosion aluminum plate, fabricated as shown in Figure 2, would be used to resemble the liner while the fiberglass epoxy laminate and Nomex honeycomb structure would also be used. An ultrasonic testing would be carried out on the fabricated multi-wall to observe how the waves travel inside the structure.

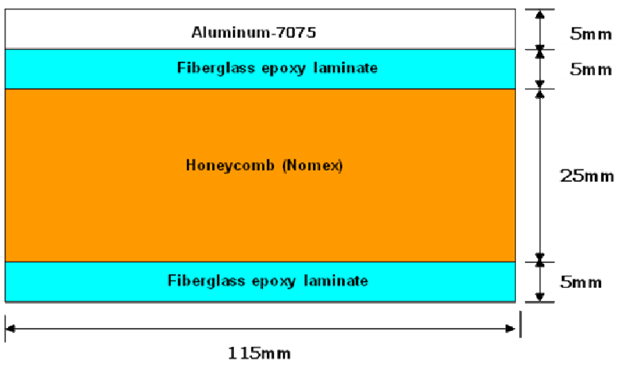
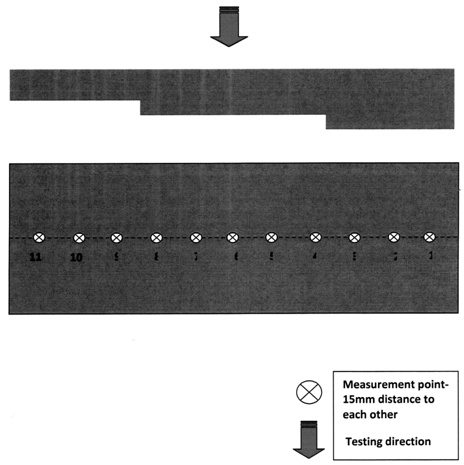


Figure 3 Corroded aluminum plate adhesively bonded to multi-wall construction specimen

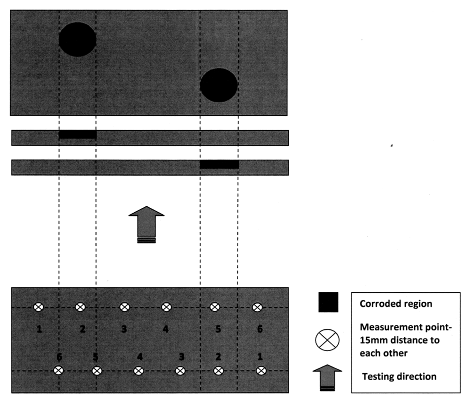
The corroded aluminum plate that was adhesively bonded with the multi-wall structure was fabricated using the method described in the above section B-2. However, the corrosion region on the aluminum plate was only exposed for 30 minutes to a concentration of 6M of KOH. For the fiberglass epoxy laminate plate, hand layup method was used to fabricate it. Ten layers of glass fiber were alternately layered with epoxy hardener and then exposed to a 500N force was exerted on the layer. The laminate was allowed to harden for approximately 24 hours. The honeycomb, fiberglass laminate composite, and the corroded aluminum plate were adhesively glued in the designed dimensions.

C. *Ultrasonic Testing*

The first step in the ultrasonic testing was a calibration procedure, performed by positioning the transducer at a distance from the specimen to discern noise signals from the wave signals travelling within the specimens. Point by point measurements of the thickness were taken on all specimens and the mechanical thickness was obtained at each marked point using a micrometer. The locations of the measurement points on each specimen are shown in Figure 4. For all specimens, the inspection was conducted from the back side of the corroded surface in order to detect if a hidden corrosion occurred on those specimens. This experiment requires a 5 MHz normal beam transducer for pulse-echo method to determine the thickness of the specimen from the A-Scan display. Oil was used as the couplant throughout the testing.



(a)



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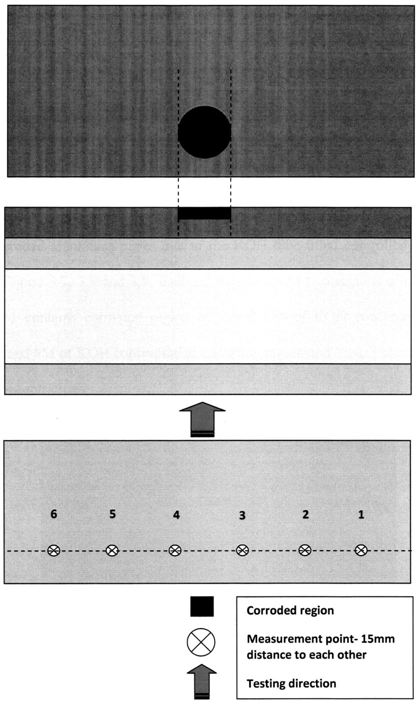

(c)

Figure 4 Measurement points for (a) stepped aluminum plate (b) corroded aluminum plate and (c) corroded aluminum plate on multi-wall structure

III. RESULTS AND DISCUSSIONS

A. Stepped aluminum plate results

Figure 5 shows the fabricated stepped aluminum liner used in each step, S1, S2 and S3 has an average mechanical thickness of 5.020, 4.060 and 2.395mm, respectively. As compared with the average ultrasonic thickness obtained, the deviation increases towards the downward step such that the plate's thickness is getting thinner. A wave that propagates through a small distance tends to attenuate more, causing disturbances to the signals. Table II contains all the thickness values for the specimen.

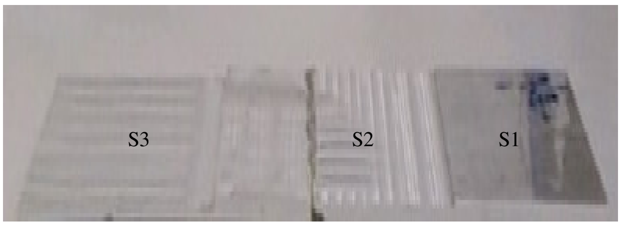

Figure 5 Fabricated stepped aluminum plate

During the fabrication of the specimen, a slight bending of the plate occurred. Due to the unique dimension of the plate which is rectangular in shape with its length and width ratio of 4 to 1, the milling blade tends to bend the plate while machining. The bending of the plate led to a variation in the surface roughness of the plate as illustrated in Table II. The surface roughness will act as a filter that will pass wavelengths below a certain frequency, partially attenuate wavelengths over a frequency range and completely block all wavelengths over a given frequency. Indeed, low frequency waves will reflect cleanly, following an "angle of incidence equals angle of reflection" rule. However, as the wavelength becomes small (increasing frequency) relative to the surface roughness the waves do not reflect cleanly and are scattered as a function of relative size [8]. It can be seen from Table II that as the roughness of the measurement point increases it will cause unclear echo signal edges thus resulting in less accurate readings of thickness measurement. This is due to the fact that signal information at higher frequencies is lost due to scattering.

Table II Thickness values for the fabricated stepped aluminum plate

Step No S	Average Mechanical thickness h_{ave} mm	Average Ultrasonic thickness $h_{UT\ ave}$ mm	% Error	Roughness Ra (μm)
1	5.02	4.92	1.99	1.22
2	4.06	3.96	2.46	1.30
3	2.33	2.15	7.72	1.56

The thickness measurement using the ultrasonic A-scan signal, h_{UT}, is illustrated in Figure 5. The thickness measured at point 1 on step 1 corresponds to the distance between two consecutive peaks which in this case is equal to 5.0 mm.

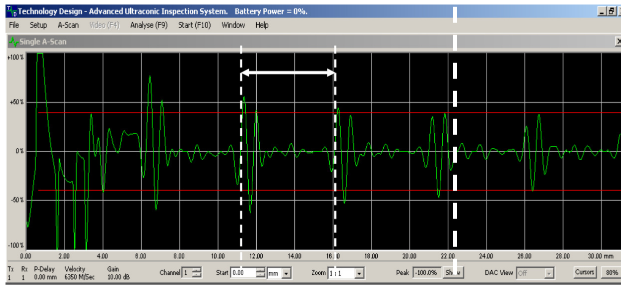

Figure 6 Ultrasonic A-scan display for the step 1 of aluminum plate at measurement point1

Similarly, the ultrasonic thickness, h_{UT}, at points 2 and 3 for step S1, shown in Figures 7 and 8, are estimated at 4.9 mm and 4.85 mm leading to an average thickness of 4.92 mm. Comparing the latter to the thickness measured mechanically using a micrometer, 5.02 mm, one obtains an error of thickness estimation of 1.99%.

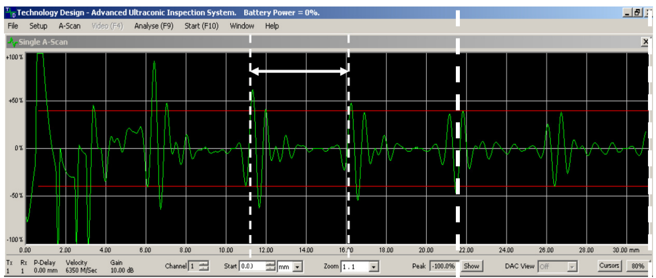

Figure 7 Ultrasonic A-scan display for the step 1 of aluminum plate at measurement point2

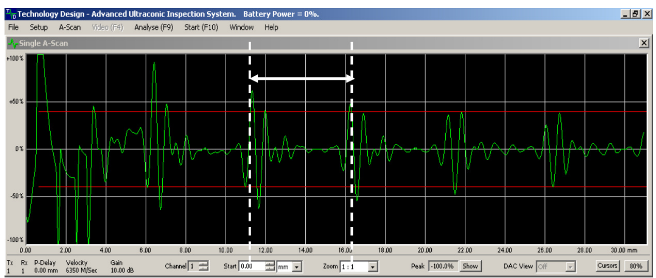

Figure 8 Ultrasonic A-scan display for the step 1 of aluminum plate at measurement point 3

B. Controlled corrosion on aluminum plate results

Corroded aluminum plates due to the KOH tube filled controlled corrosion are shown in Figure 8. Each of them contains two regions of corrosion such that Figure 8a contains corrosion region of 2 and 6M of KOH concentration, Figure 8b contains 3 and 4M of KOH concentration corrosion region and Figure 8c contains 1 and 5M of KOH concentration.

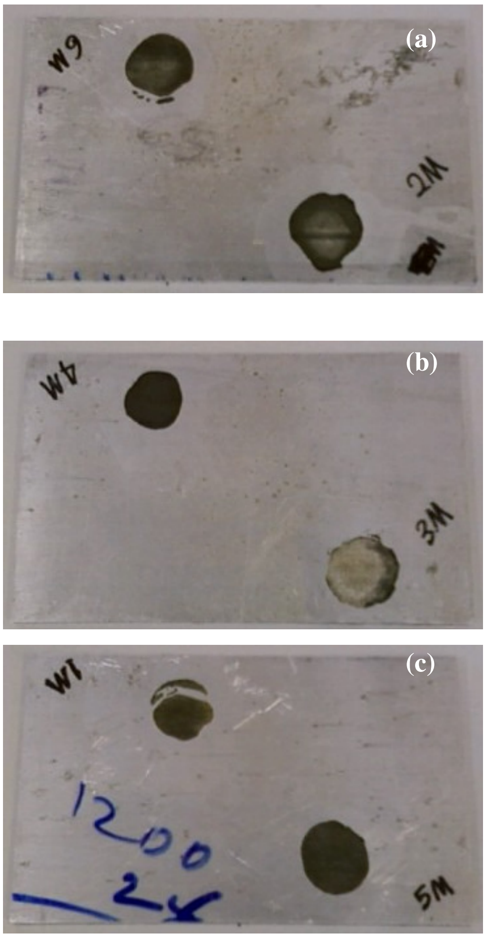

Figure 8 Corroded plates

Table III displays the thickness measurements obtained from both mechanical and NDE ultrasonic techniques of the corroded region for each technique and at each molarity. Generally, it was observed that the value estimated by ultrasonic measurements is in good agreement with the one measured by the micrometer with a maximum relative error of 2.3%. In the corroded region, the wave propagation is distorted due to the uneven surface incidence.

A similar behavior concerning the effect of surface roughness on the thickness measurement accuracy can also be depicted from Table III.

Table III Thickness measurement results on aluminum plates

Plate P	KOH solution concentration M (Mol)	Mechanical thickness h_{nom} (mm)	Ultrasonic thickness h_{UT} (mm)	Error (%)	Rough-ness Ra (μm)
1	6	4.785	4.8896	2.3	1.22
	2	4.840	4.889	1.0	0.43
2	4	4.846	4.889	0.9	0.36
	3	4.887	4.999	2.3	1.25
3	5	4.865	4.778	1.8	0.80
	1	4.891	4.889	0.1	0.11
4	6 (30mins)	4.933	4.999	1.3	0.51

The corrosion is said to be controlled here since the region of the corrosion is restricted by the tube diameter which is in about 0.5in and 60 minutes of time for the KOH solution to react with the aluminum plate. The plate that contains 6M of KOH solution with 30 minutes of reaction time would be the corroded plate that was bonded with the multi-wall structure.

Some precautions were needed when dealing with the mass calculation of the specimen. After 60 minutes of reaction period of the KOH solution, the plate with the mounted tube needs to be fully dried before conducting the weighing procedure since the excess water used to wash out the tube may add mass to the specimen, leading to deviation of the balance reading. Table III displays the changes in mass of the corroded specimens at different molarities which were used to estimate the rate of corrosion of the aluminum plates. It can be observed that as the concentration of the KOH solution decreases, the weight loss of the plate also decreases, indicating proportionality in the thickness reduction of the plate with the KOH solution concentration under assumption of uniform weight loss across the tube diameter.

Table IV Change in weight of the corroded specimens

KOH solution M Mol	Time t min	Initial weight W_o g	Final weight W_f g	Change in weight ΔW g
6	60	119.5051	119.4820	0.0231
5	60	112.4439	112.4226	0.0213
4	60	113.9697	113.9557	0.0140
3	60	121.5612	121.5453	0.0159
2	60	110.6868	110.6799	0.0069
1	60	121.5695	121.5639	0.0056
6	30	113.6963	113.6834	0.0129

Figure 9 shows the corrosion rate behavior with the varying concentration of KOH solution. As the concentration is increased, the corrosion rate computed also increases. Basically, the corrosion rates of the aluminum plates concerned in this experiment were computed by dividing the weight losses with the 60 minutes time of KOH tube-filled reaction on the plates.

The mechanical thickness measurement obtained using the micrometer should also be carried out in a precise manner so that the thickness obtained from the ultrasonic testing may be compared in confidence.

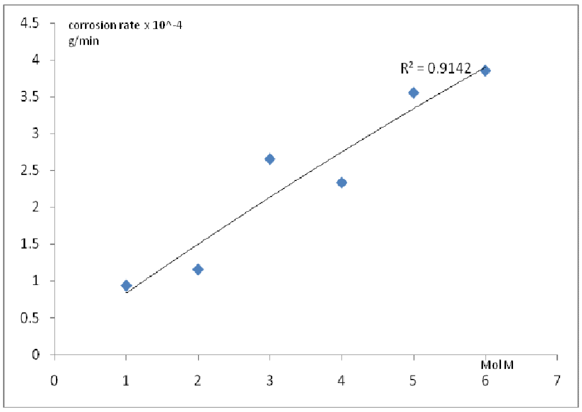

Figure 9 Corrosion rate behavior in function of KOH molarity

A sample calculation of the ultrasonic thickness, h_{UT} on plate 1 at region of concentration of KOH solution of 6M is shown in Figure 10 where the distance between two consecutive peaks is estimated to be 5.00 mm with a relative error of 2.3%.

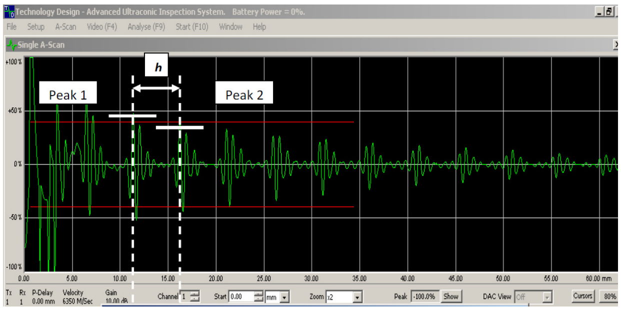

Figure 10 Ultrasonic single A-scan display at corroded region of plate 1 due to 6M of KOH solution

C. *Corroded aluminum plate adhesively bonded to multi-wall construction results*

Figure 11 shows the fabricated multi-wall structure of the fuel tank with a corroded aluminum plate as the liner.

Figure 11 Multi-wall construction of fuel tank.

Ultrasonic testing that has been done on the structure showed that the longitudinal waves travel through the structure is highly scattered and absorbed due to the anisotropic behavior of the layers. Also, with the presence of the honeycomb cellular structure, it is highly unlikely for waves to travel through the honeycomb and be reflected back to the transducer. This was validated by a pulse-echo experiment in which multi-wall structure was insonified by the 5 MHz transducer from the substrate side to detect the hidden corrosion on the liner. As shown in Figure 12, no signal was observed to be reflected to the transducer as the signals obtained from all points of measurement remain nearly the same as the calibration signal.

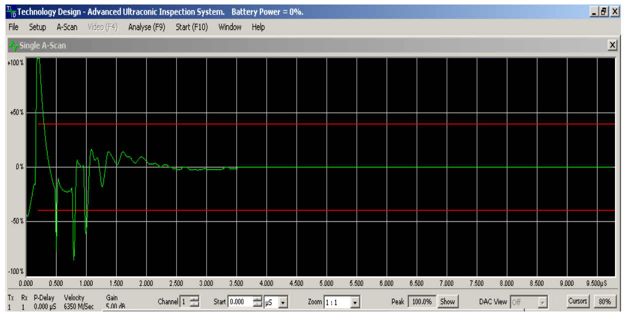

Figure 12 Ultrasonic testing signals for hidden corrosion of the multi-wall structure

Even though ultrasonic bulk waves are often used in thickness detection of plate structures by measuring the time-of-flight as demonstrated with the first two types of specimens, this technique showed its limitation when inspecting multi-layered specimens, especially with complex materials like honeycomb [9]. In the latter cases, conventional ultrasonic methods need to be enhanced with theoretical analyses such as standard Fast Fourier Transform (FFT) and inverse algorithms in order to reconstruct the thickness through a comparison of the theoretical and measured resonant frequencies of the liner, provided the acoustic properties of the liner are known a priori. Furthermore, measurements should be carried out in a wide frequency range to cover all materials making the multilayer structure.

IV. Conclusion

Material specimens simulating the corroded aluminum liner in the multi-wall construction of the fuel tank have been successfully designed and fabricated which included a stepped aluminum plate, a KOH tube-filled controlled corrosion as well as a corroded aluminum plate on the multi-wall structure.

The use of ultrasonic NDE in inspecting these fabricated specimens has been well demonstrated. For the first two types of specimens, the thickness obtained from both mechanical and ultrasonic techniques have shown a range of percentage deviation from 0.1 to 2.3 for the simulated corrosion specimen and 1.99 to 7.72 in the case of the stepped specimen. These errors are mainly attributed to the poor handling of the measurement apparatus, the micrometer as well as the ultrasonic testing apparatus. The fabrication of the stepped aluminum plate also seems to be poor with an overall error greater than 2%. Great attention must be put on the quality of the surface to be tested, since surface roughness can render the process ineffective and inaccurate.

For the multiwall specimen, even though the thickness reduction of the corroded plate was not able to be detected, the behavior of the wave propagating through the multi-wall structure may still be observed and analyzed with reference to other advanced works.

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