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Bond Interface Evaluation of Solid Woven Carbon Fiber Composite onto Aluminum Alloys

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ABSTRACT

Solid woven carbon fiber reinforced plastic (CFRP) consists of two or more components. The constituents retain their individual material properties in the composite matrix at the macroscopic level. Generally, one of the materials acts as a reinforcing agent and the other constituent serves as a polymeric binder for the carbon weave. The binder also creates covalent bonds between the composite and metal surface. All composites and metal-to-composite interfaces contain voids and micro-cracks. These manufacturing anomalies result in higher ultrasonic noise signals in the A scans. The B and C-scans produce a textured appearance. The interaction of sound dispersion and absorption within the composite makes the bondline interface between reinforced plastic and metal more difficult to evaluate. This paper explores nondestructive inspection techniques to evaluate the bondline and documents the elastic wave scattering through the metal-to-composite interface. A summary of the detection and analysis techniques developed to identify: lack of bonding and porosity levels within a solid laminate and bondline are presented.

INTRODUCTION

Composites are multilayered, anisotropic materials both on the microscopic and macroscopic scale. They are commonly made by curing weaves stacked in predefined layers. The sequence of the stacking layup is a function of design parameters. The plys can be produced manually or with mechanized winding machines. Discontinuities have a degrading effect on the performance of the given layup. The size, location and geometry coupled with external loads and bending moments all need to be considered in design and manufacturing steps. Adhesives contained in the composite's matrix help maintain the structural integrity and allows loads to be transferred between each ply layer. The condition of a bond can only be ensured with an inspection method that detects and characterizes the properties of the composite and the composite-to-metal interface. Ultrasonic inspections of composites and bonds are well established but, the reliability is hampered by the travel distance in the orthotropic, nonhomogeneous ply layers that lie between the interfaces.

The most common discontinuities that are introduced during processing are: inclusions in fibers, misalignment and lower than expected resin-to-fiber volume ratio. The geometry of a solid composite material allows designers to minimize the amount of material used and still maintain weight/strength to cost ratios. The structured laminate varies widely within aerospace structures but all contain common features. Solid laminate materials are generally used in sheet or molded form. The thickness of the finished product is made by bonding together two or more plys of material with a polymeric binder. The fibers are oriented in various directions and can vary in size and shape. The solid laminate may contain carbon weavings, strands or unidirectional tapes coated with binder materials. To increase the efficiency of the curing process, pre-impregnated ("pre-preg") composite plys were developed, which allow for the composite plys being stacked in a predefined sequence. Once the thickness and ply layup is completed, the sample is bagged with a vacuum seal and ready for the curing cycle. As temperature increases, the resin viscosity decreases but void pressure remains high. To eliminate void formations, the autoclave pressure is applied at the minimum resin viscosity. If pressure is applied prior to minimum viscosity, voids will be trapped inside the resin. Ultrasonic techniques play an important role in developing new composite designs.

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It has the ability to characterize discontinuities and measure sound velocities which can be used to calculate material constants. Care must be taken to insure that the reinforcement material is thoroughly laid flat (wrinkle free) so air cannot be trapped in the plys. The composite must be exposed to an elevated temperature and pressure. A vacuum must be maintained in the curing cycle to eliminate air bubbles being trapped in the resin [1]. Typically resin is cured in three stages: free fluid migration stage, 1) resin is heated until it reaches the glass transition temperature and starts to flow; polymerization stage, 2) autoclave pressure is introduced which causes the resin to react and form long linked polymer chains; and hardening stage, 3) the polymer chains form and cross link into the ply layers which produce three dimensional filler between plys. Covalent bonds will be created at the aluminum interface.

There are two major fabrication techniques to cure composite structures. Pre-cure is when plys are designed with a specific layup configuration and cured. The cured parts are then bonded to the next assembly. Co-cured is when the final assembly is layered with resin over the whole entire surface and cured as a final assembly. Both processes can induce discontinuities such as disbonds, porosity in the polymeric binder or voids at the bondline. The exact condition of the curing resin cycle will determine the duration of each processing step. Post curing of the composite allows the resin to be permanently set. The thermal coefficient of expansion difference between the layers, fibers, and polymeric binder during either pre or post curing may introduce unwanted discontinuities. Typical discontinuities that can be created are found in Table 1.

Table 1. Typical Defects Found During Pre or Post Curing.

Type of Defect	Detection
Delaminations	Post
Broken fibers	Pre and Post
Matrix cracking	Post
Misaligned fibers	Pre and post
Inclusions and contaminations	Pre and post
Incorrect fiber/resin mix ratios (curing cycle)	Post
Excessive voids	Post
Missing strands	Pre and post

WAVE SCATTERING THEORY

A wealth of information can be collected on composite materials when one studies the incident wave at preselected incident angles [2, 3]. Previous research has determined that bondline strength is a function of both cohesive strength of the polymer and the adhesive strength of the metal/polymer bond [4-7]. The inspection techniques deployed to detect bondline characteristics are optimized using ultrasonic spectroscopy. The elastic wave interacts with the materials and its fiber/polymer structure. Scattering is a function of the type of mode conversion as well as the carrier frequency. Factors that affect the ability to detect bondline variance are: composite surface texture (random or periodic surface roughness), fiber orientation and binder concentration. When an ultrasonic wave interacts with a composite-to-metal bondline, there is additional information contained in the frequency. Angular variance of the acoustic scatter takes on its characteristics from: longitudinal, shear and surface waves. It is assumed that the ply stacks are assembled with perfect bonded interfaces. In multi-ply variants, the interfacial zones are rich with matrix material. Traditional wave scattering relies on the behavior of elastic isotropic materials. In most metals this is the case and the material is assumed to be homogeneous. Aluminum lattice structure will scatter sound waves as a function of grain size and orientation. Metal absorption is a function of thermal conductivity of the material (motion energy losses). Composite materials scatter the sound wave due to fiber orientation (ply layup). Composite absorption is a function of polymer viscosity and relation to the adhesive bonds. Both scattering and attenuation are a function of the operating frequency of the probe. The mismatch in acoustic impedance can be seen as frequency increases. The attenuation slope is directly proportional to the porosity volume fraction between 0.2 and 0.4 percent [8]. Research has revealed that when a compressional wave passes through a composite material a slight increase in temperature is produced at points where the material is in compression. This heat flows from this region to the surroundings as a function of the composite's emissivity. The sound absorption of a polymer is proportional to the square of the probe frequency. This thermal effect becomes moot when the thickness of the composite increases.

SAMPLE DESIGN

Aluminum stock (6.35 mm) was machined with two steps (5.41 and 4.57 mm). These dimensions will accommodate composite plys of: 4, 8 and 12 respectively while maintaining a constant inspection surface. The first sample has plys bonded onto an aluminum plate with the dimensions of 10.16 cm by 30.48 cm. The ply layers are composed of eight harness satin weave. The second sample has the release film on the tool side. This allows the three-step composite to cure without bonding to the aluminum. Figure 1 displays a side and end view of a typical sample as well as the weave pattern within the composite.

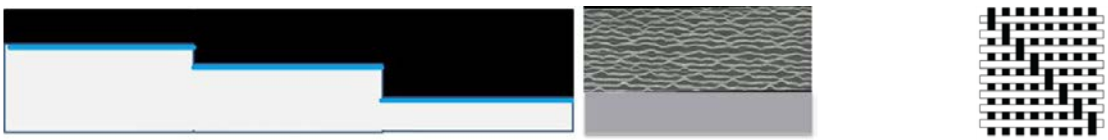
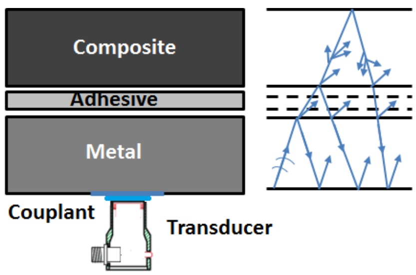


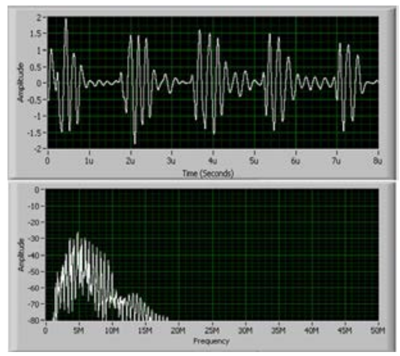
Figure 1: Specimens are constructed of carbon fiber reinforced plastic (CFRP) [4 ply [0/90]$_2$]$_s$ 8 ply [0/90]$_4$]$_s$ and 12 ply [0/90]$_6$]$_s$ preimpregnated 8 harness-satin weave with UF3352 TCR™ Resin

BONDLINE DETECTION WITH ULTRASONICS

Ultrasonic transducers transmit low or high frequency acoustic waves into materials and measure the response returned from the backwall echo. Obstructions from defects, porosity or cracks will change the amplitude and phase of the returned signal. Waves propagate through a material by creating stress and strain on the particles within the material. This atomic movement is constrained by the elastic properties of the composite. The movement of the atoms is passed along through the densely packed molecular structure in the form of mechanical energy. This transfer of energy carries the acoustic wave through the material as a plane body wave. Under most contact testing, the incident angle is normal to the surface. This allows the effect of material anisotropy to be neglected. There are two common ways to inspect composites: 1) through transmission, which measures signal attenuation by measuring signal loss after the sound has traveled the distance of the thickness, and 2) pulse echo, which measures backwall signals changes, small amplitude changes and variation in the time of flight measurement from the front to the back surface. Scattering by the fibers and isothermal absorption in the resin makes frequency selection very important. A short ultrasonic pulse (longitudinal wave) is launched from the probe and into the inspection surface. The wave travels until it reflects from another acoustic interface (cracks, edges or bondline). These signal reflections are then transmitted back to the probe where they are detected, amplified and displayed on the instrument's screen. Typically, the ultrasonic transducer is raster-scanned over the inspection area and variations within the material (amplitude and time) determine if defects are present. Refraction and mode conversion at non-perpendicular boundaries are always a challenge when inspecting a bondline. As the sound pressure wave travels through the first material it encounters a boundary (adhesive-to-second material). When this occurs, a portion of the wave energy is reflected forward at an angle equal to the angle of incidence. Some of the acoustic energy is reflected away from the probe. At the same time, a portion of the wave energy is transmitted into the second material. The general law that describes wave behavior at an interface is known as Snell's Law. Figures 2 through 7 display acoustic wave scatter, A-scans and power spectral density of the received signal.

Immersion ultrasonics requires the part and transducer to be placed in a tank filled with water. This arrangement allows better movement of the transducer while maintaining consistent coupling. Its disadvantage is that the part must be submerged for long periods of time and the composite will likely absorb water. The pulse echo inspection records the intensity of the scattered waves as the probe is moved around the inspection surface. The high incidence angle allows the reflection for the interface to become diffuse and attenuated. As the wave propagates through the aluminum-to-composite or composite-to-aluminum interface the amplitude of the wave decreases. These energy losses can be attributed to geometric effects (beam spread) and intrinsic effects (wave and material interactions). Figure 8 displays inspection data in the form of C-scan and A-scan images of the aluminum-to-composite interface.





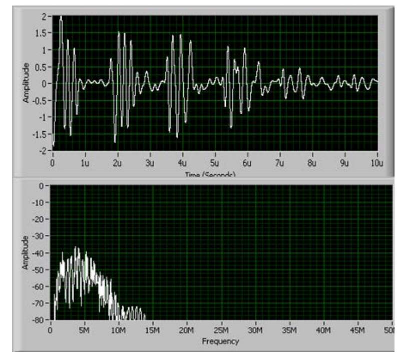
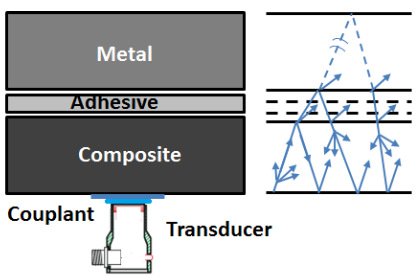
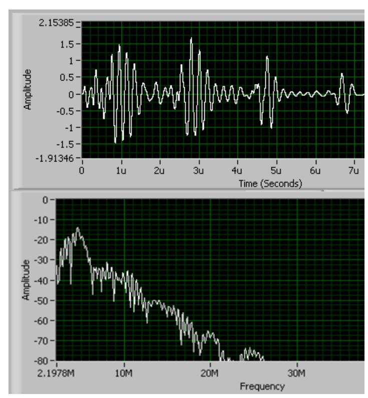


Figure 2: Typical acoustic wave scatter through metal and composite material.

Figure 3: Response of a 5 Mhz probe (metal composite contact only).

Figure 4: Response of a 5 Mhz probe (metal couplant composite only).





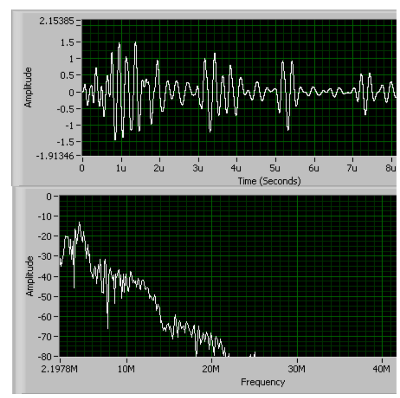


Figure 5: Typical acoustic wave scatter through composite and metal material.

Figure 6: Response of a 5 Mhz probe on bonded composite.

Figure 7: Response of a 5 Mhz probe on an unbonded composite).

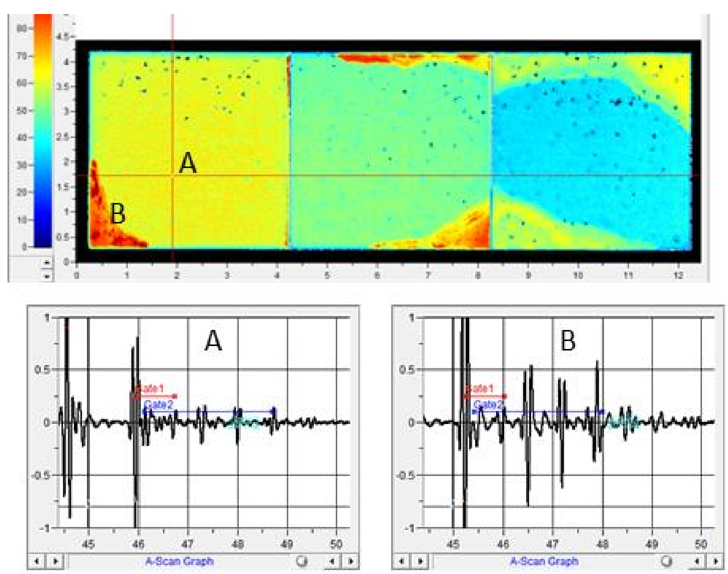


Figure 8: C-scan and A-scan display of the aluminum to composite interface (A- bonded and B- unbonded).

DATA ANALYSIS TO CHARACTERIZE BONDLINE

Lowering the test frequency will reduce high attenuations within the material. Through transmission is usually used to detect delamination, voids and areas where resin has not cured in a uniform way. All of these defects will cause a significant loss in ultrasonic attenuation. The major variable that alters attenuation is the entry surface roughness and the composite weave pattern. The bondline in this sample set can be detected with high confidence. The time of flight data has the most useful information. The accuracy of assessing the bondline interface depends on the consistency of the ultrasonic signal and how the velocity has changed from a purely bonded material. For best results, a reference signal is chosen and all other signals are compared to its amplitude at a given distance from the front surface. The biggest internal variable in elastic properties is variations between the material plys. The most common ultrasonic signal variations are caused from non-uniform resin and mixture ratios.

Conclusions

This paper investigates contact and immersion array methodologies to characterize the bondline scattering. If the composite layer is thin enough (less than eight plys) acoustic wave techniques can analyze the bondline. Both conventional and advanced ultrasonic methods can detect adhesive bonds between the metal and composite. This comparison of the pulse-echo signal measured is based at the point of interest (the interface). It is difficult to correlate ultrasonic signal to the strength of a bond. Bond strength is not a physical property but a structural parameter. The inspection methods described in the paper are not designed to find the weakest of the weakest area (i.e. highest stress in the weakest specific area of failure). Understanding the behavior of adhesively bonded interfaces with the use of ultrasonic inspection will ensure safety and reliability of designs. Ultrasonic techniques described above can detect most discontinuity types that are required. However, a high variance in the material properties and, surface roughness may not allow for a reliable assessment. The most important variable to understand for all composites is the role of attenuation.

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