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Pulse Echo Ultrasonic Testing of Adhesive Bonded Joints for Automotive Applications

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PULSE ECHO ULTRASONIC TESTING OF ADHESIVE BONDED JOINTS FOR AUTOMOTIVE APPLICATIONS

A Thesis
Presented to
the Graduate School of
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In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Mechanical Engineering

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by
Arun Ganapathi
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Accepted by:
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Dr. Mohammed Daqaq

ABSTRACT

The growing prominence of adhesive bonding technology in automotive manufacture has necessitated the development of reliable and robust quality assurance techniques. Of the different Nondestructive testing technologies available, Ultrasonic testing has shown itself to be the most promising technique to satisfy the requirements in automobile production. The current work attempts to apply two variations of the Ultrasonic Pulse Echo technique namely Contact and Immersion testing for inspecting typical hem bonded automotive joints. The joints have been tested for disbond at the various metal-adhesive interfaces by using an ultrasonic scan comparison method which compares the acquired signals against a reference scan from the unbonded metal sheet.

The results for the above tests have been documented. Detection of the absence of adhesive has been possible at the interfaces using the Contact testing variation. In the case of the Immersion testing, suitable distinction between the echoes from the different interfaces has not been achieved. Based on the results obtained, it has been proposed that the testing frequency be increased to obtain a clear distinction between the adherend and adhesive surface echoes.

DEDICATION

This thesis is dedicated to my parents and my brother for their unconditional love and support throughout my life. This work is also dedicated to the God almighty, by whose grace I continue to live this life of privilege.

ACKNOWLEDGMENTS

I would like to acknowledge the support and guidance provided by Dr.Mohammad Omar in completing this work. I would also like to thank the members of my advisory committee Dr. Yong Huang and Dr. Mohammed Daqaq for their valuable suggestions and inputs.

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CHAPTER ONE

ADHESIVE BONDING TECHNOLOGY

1.1 JOINING METHODS USED IN AUTOMOTIVE APPLICATIONS

Over the years, requirements for automobiles with respect to fuel economy and exhaust emissions have become progressively stringent while consumer expectations with respect to performance and luxury and reliability have also increased. These requirements make for conflicting technical requirements that have to be met by the automotive manufacturers. Material substitution and alternate body constructions have been the major strategies in the drive to reduce the weight of the vehicles. The traditional steel used in body construction has been substituted with aluminum and advanced high strength steels. Alternate body constructions like the Space frame have also been adopted with the aim of maintaining or enhancing the existing stiffness of the bodies. The change in materials has also necessitated a review of the joining methods used traditionally. The following section examines the details of the traditional methods like welding variants and mechanical joining techniques along with the non-traditional adhesive bonding used for joining different metals with each other, polymers and composite materials.

The various joining methods employed in automotive manufacture are

- Welding
    1. Arc welding

    2. Resistance spot welding
    3. Laser beam welding
    4. Friction stir welding
- Mechanical Fastening
    1. Self-piercing rivets
    2. Clinch fasteners
- Adhesive Bonding.

1.1.1 Welding

The process of welding relies on heating the substrate materials to a point where they melt and fuse together to form a permanent joint. Depending on the mode of heating the metals, the process is classified into Metal Inert Gas (MIG), Spot welding, Laser welding. and friction stir welding. In MIG welding, a metal electrode is brought in contact with the substrate metals. The passage of a very high value of current in the electrode ensures the melting of the electrode and the substrate metals, thus resulting in a permanently fused bond. A stream of inert gas is passed around the region of the fusion to prevent oxidation of the base metals. Numerous combinations of electrodes and gas are used to optimize the process for different base metals and process rates.

MIG welding is one of the widely used joining methods due mainly to its versatility. The method requires only a single sided access to the region of bonding and procedures for large scale production are standardized. While the method is well suited for joining steel, welding Aluminum is complicated by the formation of an oxide layer. The unreactive oxide layer has a far higher melting temperature compared to the base metal.

Higher heating of the surface is required to completely melt the layer and get to the underlying metal. This results in a higher process time, slower feed rate and disruptions in the process if optimal parameters are not set. Due to the above reasons, arc welding of aluminum is an energy intensive process. The production of aluminum oxide fumes and dust particles contribute to environmental and safety issues. The prevalent use of arc welding in spite of such drawbacks can be attributed to the high level of existing expertise in the welding process, which has partly alleviated some of the technical challenges.

Spot Welding is a modification of the standard welding process with electric current being passed through the adherend materials by means of an electrode. The resistance of the metal causes enough localized heating to melt the metal. The two adherends are held together under the application of force for a short ‘hold’ time during which the melted metal solidifies to render a bond. Typical automotive Bodies-in-White contain approximately 5000 spot welds. This method of bonding is highly popular due to the rapid process time and the consequent joint quality achieved. This method has similar drawbacks to arc welding for aluminum sheets. An added requirement is the need for access on two sides. It has been shown that the current and force required to weld Aluminum sheets are in multiples of that required for steel[1]. This in turn results in higher process costs accrued from larger transformers and frequent coating of electrodes. Again, due to its high process speed and current widespread use, methods have been devised to overcome technical difficulties in the implementation of the technique for modern construction. The increased costs have been passed on to the consumer.

Laser welding utilizing Carbon dioxide and ND:YAG lasers have been utilized for fabrication of tailor welded blanks The use of tailor welded blanks has contributed to significant weight savings. The very small heat affected zone as a result of the low beam scattering and the potential for process automation with robots have contributed to the widespread use of laser based welding techniques. Some of the limitations of the technology are the high process cost, small tolerance for gaps due to the small beam size and health hazards associated with high power lasers.

Friction Stir welding consists of a high speed rotating tool which when brought in contact with two butted edges of sheet metal melts the metal along the joint line, thus resulting in a welded joint.

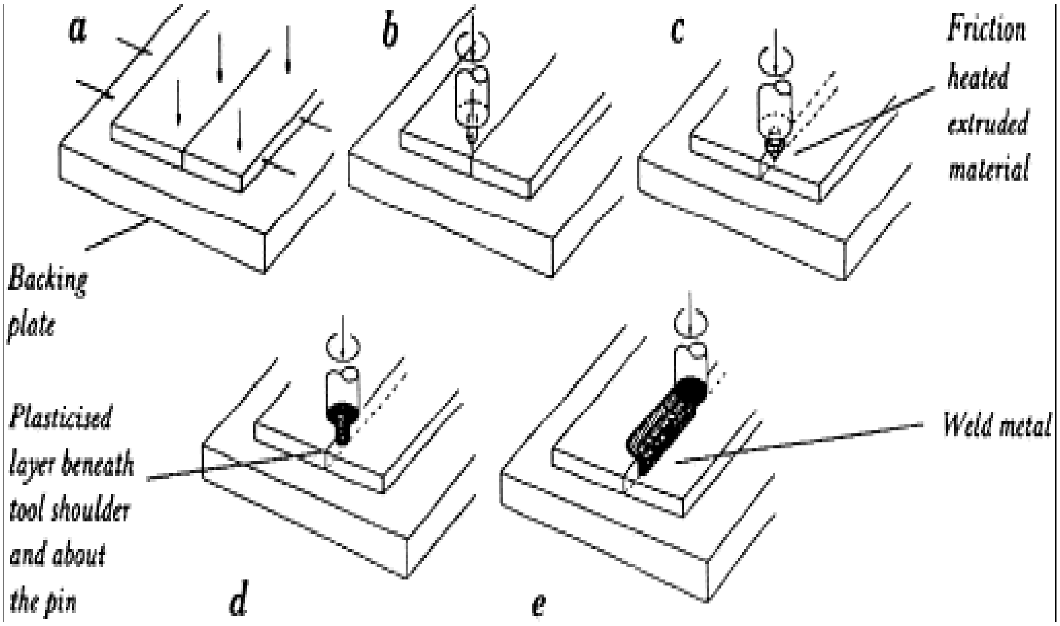


Figure 1-1 Friction Stir Welding schematic [1]

Being a solid phase welding process, the problems associates with the previous welding methods like the formation of oxide layer are overcome. The process is also inexpensive and does not consume high energy.

Disadvantages of the process include the slow process speeds and the need for rigid clamping of the sheets. This results in residual stresses which necessitate additional heat treatment for relief. The nature of the process also ensures that joining is effective only along straight lines.

1.1.2 Mechanical Fastening

The types of mechanical fastening techniques applicable in automotive bodies include self-piercing rivets and clinch joints.

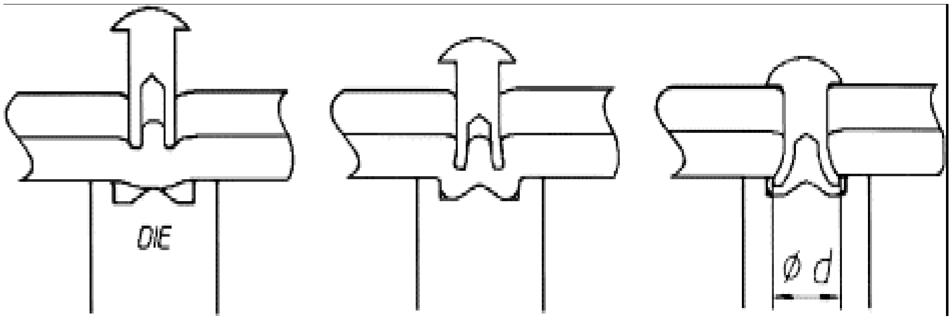
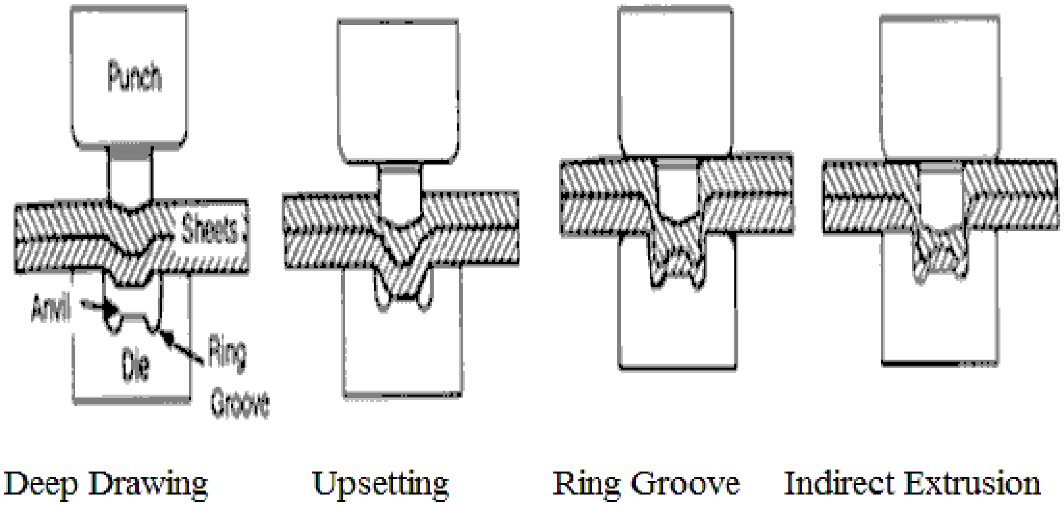


Figure 1-2 Self piercing joints [2]

As shown in the figure 1-2, the rivet pierces the first sheet and expands into the lower sheet of metal without completely piercing it. The expanded rivet holds the two sheets together securely in an interlock.

Figure 1-3 shows the schematic of a clinch joint. The clinch joint functions by cold forming the two metal sheets between a punch and a die without piercing the sheets. The interlocking achieved is thus sealed against moisture ingress.



Deep Drawing   Upsetting   Ring Groove   Indirect Extrusion

Figure 1-3 Clinch Joint [2]

The advantages of the above mechanical fastening methods include the ability to automate the process and process rates suitable for large scale production. It is also simple to non-destructively test the components using ultrasonic testing.

Disadvantages of the methods include added weight through the introduction of rivets, dents on the surface of the sheets (typically 0.7- 2 mm). Minor crevasses and gaps left at the joints serve as initiating points for corrosion on sustained usage.

1.1.3 Adhesive Bonding

Adhesive bonding, as defined by Messler[3] , is the process of joining materials with the aid of a substance, acting as a chemical agent capable of holding the materials together by means of surface attachment forces. Adhesive joints have found increasing use in non-load bearing and structural body applications due to some inherent advantages like uniform stress distribution in joints, lack of thermal damage and the ability to join multiple materials. While initial drawbacks with respect to automation of the adhesive application process have been overcome, numerous challenges relating to the joint failure and their quality control through non-destructive testing still exist. A detailed comparison of the various joining processes based on different functional requirements is provided in table 1.1.

Table 1.2 compares the different production related aspects of the conventional joining methods in use for engineering applications. It can be seen that the use of adhesive bonding technologies match up well on the production related aspects with the conventional methods like welding and mechanical fastening. A detailed description of the advantages afforded by adhesives in the design process has been provided in further sections.

PROPERTY	WELDING	MECHANICAL FASTENING	ADHESIVE BONDING
Permanence	Permanent Joints	Disassembly possible with threaded fasteners	Permanent Joints
Stress Distribution	Local Stress Points in structure	high stresses at point of fastening	Uniform stress distribution
Appearance	Acceptable. Some dressing required	Surface discontinuities.	No appearance issues
Materials Joined	Similar material groups	different combinations can be fastened	joins all combination of materials
Temperature Resistance	very high temperature resistance	high temperature resistance	Poor temperature resistance

Mechanical Resistance	Special provisions necessary to prevent fatigue failure	Special provisions to be made	Good fatigue properties, reduced corrosion due to insulating nature

Table 1.1 Joint type comparison [4]

	WELDING	**MECHANICAL FASTENING**	**ADHESIVE BONDING**
Joint Preparation	very little for thin sheets. Edge preparation for thick sheets	Hole preparation and threading required	Cleaning often necessary
Post Processing	Heat transfer sometimes required	No post processing	Not often required
Equipment Required	Expensive, bulky and heavy power supply	inexpensive and portable equipment	Large, complicated joint equipment expensive

Consumables	Inexpensive consumables: wires, rods etc.	Moderately expensive consumables	Structural and crash resistant adhesives expensive
Production Rate	High rates achievable	Low production due to manual nature	Depending on type of joint
Quality Assurance	NDT Methods well established	torque controlled tightening	**Limited NDT available**

Table 1.2 Production aspects of conventional joints [3]

1.2 ADHESIVE BONDING TECHNOLOGY- STATE OF THE ART

Tests for incorporating adhesive bonding technology in automobiles have been done as early as 1983. Adhesive technology has been examined for bonding fiber reinforced panels in automobile hoods. The study carried out by Lupton[5] involves the selection of an adhesive for bonding Sheet molded composites with each other and steel at both room temperature and oven curing temperature of 200^0C. A four step approach has been used to screen and test candidate materials for bonding hood panels. The conclusions show that a 2 component Epoxy and a 1 component Urethane are best suited for the hood panels. The potential and challenges for adhesive technology in automobiles during the early 1990s have been described by Lawley. Successful application in body closures, roof stiffeners, drives shafts, lamps, windscreens and interior trim have been reported. The application of adhesives has also enabled a change in material usage, a case in point being the change from steel to carbon fiber for the propeller shaft in the Renault Espace[6]. Detailed studies on the feasibility of adhesives for automotive application have also been carried out by the commission on adhesive bonding for automotive body (ABAS)[7]. After detailed testing involving bond properties like peel strength and tensile shear strength for assemblies of composites, steel and aluminum, the recommendations of the committee indicate a need for further research into the field. The concern highlighted by numerous researchers being over the durability of the bonds [7-10]. Adhesive bonding technology has been furthered by close co-ordination of suppliers with Automotive Original Equipment Manufacturers (OEMs). Such collaborations have resulted in bonding systems meeting the specific requirements of the automotive industry related to parameters like crash worthiness, fracture behavior, durability and ageing. The brittleness of typical adhesives used in aerospace applications in extremely high strain rate scenarios has been overcome with the development of crash resistant adhesives. One of the commercially available bonding systems uses toughened nanoscale particles which are uniformly distributed in the adhesive matrix. The toughened particles are in turn created along with a flexibilizer in a chemical process commercially known as synergistic rubber toughening [11]. Experimental studies conducted by Peroni et.al have shown that adhesively bonded front rail structure perform as well as those joined by spot welding, apart from providing increased stiffness, fatigue strength and vibration response[12].The above developments have resulted in the increasing use of adhesive technology. The technology has been adopted by the leading car makers, initially in their high end models. Examples being the 86 meter increase in the length of adhesives used against a decrease of 1045 spot welds on the 2005 Audi A6 [11].The BMW 7 series contains over 10 Kg of structural adhesives. Graph 1 shows the increasing use of adhesive joining techniques used in automobile models over the years.

It must be noted that the increasing usage of adhesive joining coincides with the diversification of material usage from the traditional steel to the High strength steels, Aluminum, plastics and composites for body panels. Adhesive bonding offers greater synergies when compared to the traditional joining process of welding and its variations.

1.3 ADVANTAGES OF ADHESIVE TECHNOLOGY

The advantages of using adhesives in place of traditional joining process in the automotive assembly can be classified under the following broad headings:

- Mechanical advantages
- Design Advantages

1.3.1 Mechanical Advantages

The mechanical advantages of using adhesives for joining center around the ability of adhesives to uniformly distribute stresses between the adherends, thus eliminating stress concentrations found in mechanical fastening. In the case of welding and mechanical fasteners, the adherend materials are designed to a higher gauge in order to withstand the higher localized stresses from the joint.

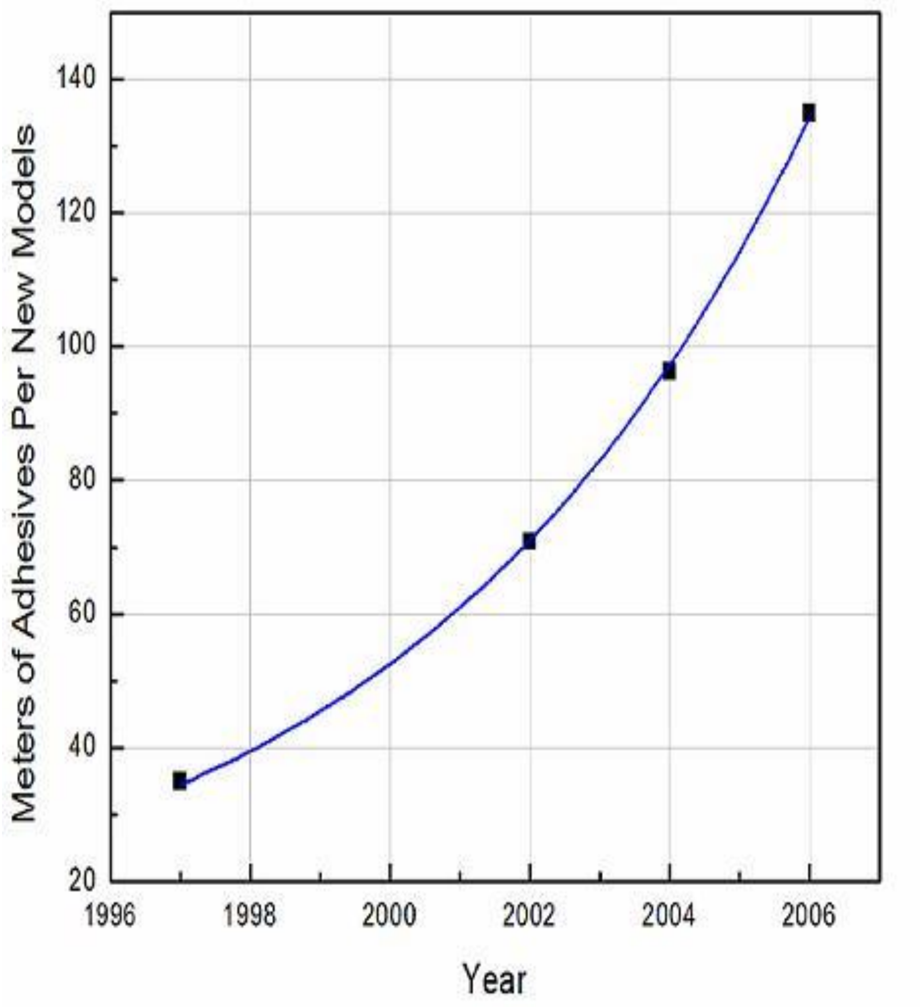


Figure 1-4 Adhesive usage in automobile models[13]

The use of adhesives (and the consequent uniform stress distribution) provides designers with the freedom to downgauge the adherend sheets, thus enabling weight savings. Weight savings of up to 20 Kg can be achieved on the current automotive designs[13].Table 1 shows the variation of certain design parameters for the BIW structures of different automotive models in production. Accounting for changes in materials during the redesign, it can be seen that the overall trend of increasing adhesive usage corresponds to an increase in the static and dynamic stiffnesses of the BIW structures and possible downgauging in spite of reduction in the number of spot welds.

	Vehicle 1		**Vehicle 2**		**Vehicle 3**	
Property	Benchmark (Opel Vectra)	Current (Opel Insignia 2008)	Benchmark (Volvo XC 90)	Current (Volvo XC 60)	Benchmark (Volvo V70)	Current (Volvo V70)
Structural Adhesive Length(m)	0.3	21.1	3.3	25.4	1.1	24.9
Spot Welds(nos.)	4613	6331	4799	4337	4595	4170
Static Stiffness(Torsion) %	100	141	100	115	100	113
Dynamic Stiffness(Torsion) %	100	114	100	109	100	103

Table 1.3 Structural adhesive application in automobiles[14]

1.3.2 Design Advantages

The design of joints for adhesive bonding provides certain advantages over other joining methods-

1. Joins any combination of similar or dissimilar materials
2. Provides a large stress bearing area
3. Process heating, if required, is too low to affect the component adherends thermally
4. Provides sealing at the joints

The above advantages of adhesively bonded joints can be leveraged in the design stage to facilitate the usage of alternate materials with a view of weight savings. Adhesive bonding thus plays the role of an enabling technology. Apart from satisfying the primary functional requirements, adhesives also satisfy secondary requirements like sealing, vibration damping and gap filling. The multi-functional applications of adhesives can be utilized during the design phase to develop multipurpose joints. Possible design modifications have been suggested by Daniels[15].The use of completely closed extruded parts, previously impossible due to spot welding requirements has been enabled with the use of adhesives. Other areas in the automotive Body- in- White (BIW) being the load bearing joints between the sill and the B-pillar, roof panel and the header rails etc. The use of adhesives here has been suggested in order to overcome practical issues with joint accessibility on both sides for spot welding. The accessibility requirement results in a less than desired stiffness in the resulting structure. The potential for modular design and flexible manufacturing with smaller production lines have been envisioned by Daniels.

The use of structural adhesives in the automotive industry had been driven by the following main factors:

- Cost Reduction: Reducing cost associated with the joining processes for alternative body materials like High Strength Steel, Aluminum and Composite materials.
- Corporate Average Fuel Economy (CAFE) requirements
- Increasingly stringent crashworthiness requirements

1.4 CLASSIFICATION OF COMMERCIAL AUTOMOTIVE ADHESIVES

For automotive applications, the type of adhesive used can be classified as either load bearing or non-load bearing adhesive based on the location of the joint. Load bearing applications include locations in the Body-in-White where the joint strength is around the failure stress of the adherends or the adhesive, thus taking advantage of the adherend’s strength and achieving high joint efficiency. Examples of ***structural adhesives*** include epoxies and cyanoacrylates. Semi-structural adhesives or anti flutter adhesives are used partly as sealants and also serve the purpose of increasing the stiffness of the body in white structure. By filling the gap between inner and outer panels, they aid in noise and vibration damping. ***Non- Structural*** adhesives are used for joining interior trims and glass panels. While they hold together two adherends, they fail on the application of substantial loads.

Based on the curing temperature and conditions required during assembly, adhesives can be classified into the following types[16]:

- Rapid set at room temperature adhesives
- Rapid set at high temperature
- Curing on evaporation of moisture
- Pressure Sensitive adhesives

Classification can also be done based on the physical state of the adhesive:

- Liquid adhesives: adhesives used in conjunction with water or ethanol to enhance the ease with which they can be spread on the adherend surface.
- One Component adhesives(1K): The adhesive contain an adhesive and a curing agent pre mixed in the desired proportion. However, they cure at high temperatures through cross linking of the polymers. Although they have low shelf lives, they do provide good joining properties, and hence find wide usage.
- Two Component adhesives(2K): consist of separate adhesive and curing agents which are active at low temperatures.

Further classification of adhesives can also be done based on their chemical composition:

- Thermoplastic Adhesives: These adhesives are made up of thermoplastic polymers. They can be softened on the application of heat above their glass transition temperature. This, to an extent enables their joint strength to be recovered after deterioration in the presence of moisture and environmental conditions.

- Thermosetting Adhesives: These adhesives operate by forming complex cross links between the molecules once the temperature is raised over their glass transition temperature. They usually result in high bond strength and hence find application as structural adhesives. However they can degrade on the application of excessive heat.
- Hybrid adhesives: These adhesives contain additives other than the primary components for different applications. Additives can be used to enhance specific properties like moisture rejection, shrinkage at high temperatures. More than one adhesive have been used for a single joint in order to enhance the performance of the joint over a wide temperature range. Using a stiff adhesive at the center of the bond and a low stiffness adhesive near the edges of a lap joint have resulted in an increased joint strength compared to bonds with a single adhesive[17].This effect has been achieved based on the understanding that for a given set of adherends, the stress concentration at the edges is lower with the application of a low modulus adhesive. The concept of the mixed adhesive has been investigated further by Da Silva et.al and applied to applications with multi material adherends over a wide range of temperatures [18].The study conducted on double lap joints with titanium and a composite conclude that the use of dual adhesives over a wide temperature range is only justified for adherends with largely varying coefficients of thermal expansions.

1.5 FACTORS INFLUENCING THE SELECTION OF ADHESIVES IN AUTOMOTIVE APPLICATIONS

The following factors need to be considered while selecting an adhesive for a particular joint application

- Type of application
- Joint type
- Nature of the adherends
- Curing methods employed
- Type of stresses expected to withstand in service
- Handling strength desired
- Surface preparation
- Washout resistance in downstream workstations
- Cost

Type of Application:

Depending on this factor, choice can be made on the use of structural, Non-Structural or Anti-Flutter adhesive. Due to the presence of paint bake ovens in the assembly line, structural adhesives usually need to be able to withstand approximately 150^{o}C.

Nature of the Adherends:

Although adhesives can be used to join a wide range of materials with each other, the material of the adherend and the loading expected in the joint during its life are key factors in determining the type of adhesive and the quantity. This is quantified by two factors namely joint hem width and the bondline thickness. Harris and Fay have established that thinner joints have higher strength in static and fatigue loading conditions.[19] It also has to be ensured that the joint strength developed is comparable to that of the individual adherend materials in order to have an effective joint.

Curing Time

Curing time is one of the most critical parameters affecting the strength of adhesively bonded joints. The process of curing results in the completely bonded joint. Adhesives with a wide range of curing temperatures are available depending on the application. An important factor to be considered during the curing of the adhesive bond is the Glass Transition Temperature of the adhesive. This refers to the range of temperature in which the adhesive transitions from a glassy hard state to a soft and rubbery material. Thermoset adhesives are effective only when the operating temperature is at least 50^{0}C below the Glass Transition Temperature. Although discrete values are provided for different adhesives, the amorphous component in the adhesive transitions over a range of temperature as opposed to a single value. The range is further dependent on the rate at which the change in temperature takes place. This factor often has a critical effect on the strength of the adhesive material. For structural adhesive applications, the residual stresses in the joint as a result of cooling also need to be taken into account while designing the joints for strength.

Types of Stresses expected in service

This factor is determined by the loading which the adhesive joint is subjected to in its service. It has been proven that joints with lesser value of bondline thickness perform better under static and fatigue loads [20]. Hence, the bondline thickness together with the adhesive seam width is a factor which determines the effectiveness of the joint at achieving a uniform load distribution. Automotive body applications have governmental regulations on crash performance. This has led to detailed study into the behavior of adhesive joints under high strain rate conditions at various temperatures. Studies conducted over the years[21],[22-24] highlight the changing nature of the requirements with respect to the nature of loads which adhesive bonded joints are required to withstand in service.

1.6 DISADVANTAGES OF ADHESIVES

Although adhesives open up numerous alternatives for the design and use of joints, their disadvantages have to be carefully considered and accounted for while designing the joints. Some of the prominent limitations on the use of adhesives being:

- Preparation of adherend surfaces
- Strict process control with respect to cleanliness
- Shelf life of certain adhesive components
- Long curing times, hence a possible bottleneck in process sequence
- Inability to rework completed joints
- Susceptibility to environmental factors like humidity and temperature

Specific limits for joint strength and environmental conditions (humidity, temperature, exposure to solvents and radiations) have to be set. The following sections deals with the two major environmental factors in detail

1.6.1 Humidity

The behavior of adhesive joints in the presence of high humidity has been an area of research for a considerable time. Numerous experiments have been performed in order to better understand the actual phenomenon. Through experiments conducted by Brewis, Comin *et al* it has been shown that on exposure to atmosphere with a relative humidity of 100% and a temperature of 50^0C the joint strength falls nearly by half before stabilizing at a value.[8, 25] However at relative humidity levels of 50% negligible weakening of the joint takes place. Further observations from the experiments have proven that most of the strength lost on exposure to very high relative humidity can be recovered on exposure to lower levels of humidity. Based on the above observations, predictions of a critical value of relative humidity and water content in the adhesive which promote the onset of weakening have been made. Experiments have been carried out to verify the hypotheses for different combinations of adhesives and adherends**.**

In conclusion, it can be said that the humidity levels present in the service environment have a determining effect on the selection of adhesive for an application. The condition could even dictate a move to another type of joining process.

1.6.2 Temperature

One of the greatest benefits of using adhesives is the ability to join two fundamentally different materials without altering their microstructure. However the two constituents expand or cool at different rates according to their individual coefficients of thermal expansion during service conditions. This possible mismatch can lead to stresses at the adherend-adhesive interface, thus causing the joint to fail at loads below the limit. Numerous efforts have been undertaken to understand the thermal behavior of adhesive assemblies [8, 23, 26, 27] . It has been established that while the properties of adherends do not vary over a range of possible service temperature (-40^{0}C to 90^{0}C) the properties of the bonding adhesive do vary drastically over the range [27]. Adhesives used for high temperature applications exhibit brittleness at low temperatures, thus reducing the bond strength, whereas those used for low temperature applications fail to carry sufficient load at temperatures above their glass transition temperature. This has led to the development of mixed modulus joints which use more than one type of adhesive in a joint with different adherend materials operating at extreme temperatures.

With the extensive use of adhesive bonding systems for wide ranging applications in the automotive industry, the need for quality assurance on the plant floor has arisen. Joint quality in aerospace applications is achieved by strict process control - which is helped by the low volume of production. The above approach is however cannot be applied in automotive applications due to constraints on process cost and time. In order to develop testing methods specific to the automotive industry, a ‘first principles’ approach is required. This entails a detailed understanding of the mechanism of adhesion and the principles related to non-destructive testing.

CHAPTER TWO

ULTRASONIC TESTING

2.1 INTRODUCTION

The development of applications for adhesive bonds has consequently given rise to the need for quality assurance of the joints. Acoustical methods for testing have been in development and usage for nearly three decades. In the aerospace industry, adhesive bonding has been successful primarily due to the high level of process control achieved. The role of non-destructive testing is supplementary. While Numerous Non-Destructive test methods exist for the testing of adhesive joints, acoustic methods have been proven to be the most effective given the constraints on cost, adherend geometry and testing requirements. Table 2.1 summarizes the drawbacks of the various non-destructive testing methods while testing adhesive bonds:

It can be seen that some of the drawbacks mentioned in the table are with the fundamental principles of the testing methods. In this respect, acoustic methods establish themselves as the method with the least number of contradictions.

2.2 TYPES OF ULTRASONIC TESTS

Examination of metallic objects (bells, coins, cups etc.) by listening to their ring has been in practice for a long time. The Second World War saw the development of the radar which in turn led to further research into acoustics [28]

TESTING TECHNIQUE	REASON FOR UNSUITABILITY
Thermography	Low sensitivity to rear bondline defects, inability to handle complex geometries, complex temperature variations
Radiography	Insensitive to disbonds, defects masked by high attenuation in metals
Magnetic Resonance Imaging	incompatibility with metallic structures, cost
Optical	Requirement of bonded region to be stressed
Low Frequency vibration	Low Sensitivity
Dielectric	Low sensitivity

Table 2.1 Non Destructive Testing Methods[29]

The consequent discovery of ‘piezoelectric’ crystals like quartz led to the development of ultrasonic through transmission methods to measure the thickness and internal defects in objects. Currently used ultrasonic testing methods can be broadly classified into the following types:

- Contact testing
    1. Longitudinal Wave Techniques
    2. Angled Wave Techniques
- Non –Contact testing
    1. Immersion testing techniques
    2. Air coupled testing techniques

2.2.1 Contact Testing

The contact method involves direct contact between the test probe and the test specimen with a layer of ultrasonic couplant between the two materials in order to match the acoustic impedances of the two materials. Based on the mode of wave propagation, contact testing is divided into different applications:

- Longitudinal Waves used for Interior flaw detection and thickness measurement
- Shear waves for testing irregular geometry like welded surfaces
- Rayleigh waves for sub surface defects in composite materials and laminates
- Lamb waves for inspection of long large plate like structures.

Based on the physical setup of the apparatus for testing, contact testing can further be classified into

1 Longitudinal Wave Techniques
  - Through Transmission
  - Pulse Echo technique

2 Angled Wave Techniques
  - Shear Wave Technique
  - Lamb Wave Technique

1. Longitudinal Wave Techniques

Through Transmission

The Through Transmission method monitors the energy of the transmitted pulse. Transducers located on the opposite sides of the workpiece are used for generating and receiving the ultrasonic pulse. The presence of a defect is indicated by a decrease in the amplitude of the received pulses. Acoustic coupling of the transducers to the test specimen(to reduce interfacial damping) is achieved by means of water or couplant agent gels.

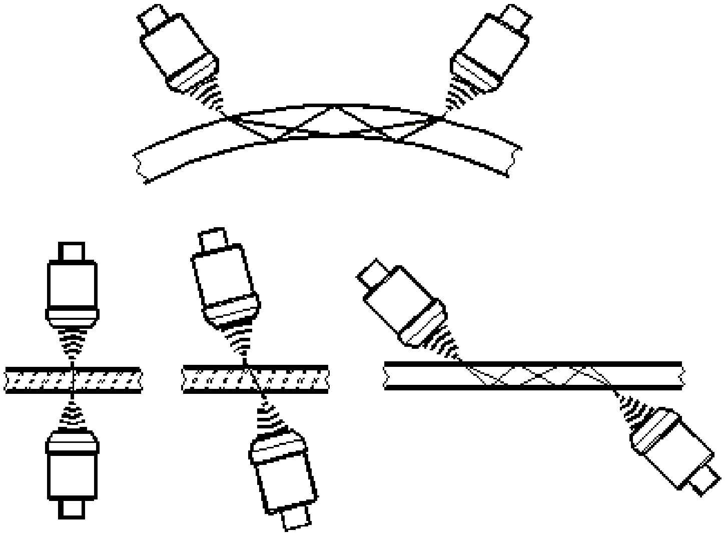


Figure 2-1 Ultrasonic Through Transmission[30]

Some of the disadvantages of the through transmission method, which have led to the development of other testing methods are:

Inability to detect defects parallel to the direction of wave propagation

- Lack of detailed information about the scan
- Inability to analyze complex structures
- Large space requirement In production environments

Pulse Echo Technique

Pulse Echo method to measure the thickness of metallic objects. Commercial equipment for the above purpose was available in the 1950s [28] The examination comprises of ultrasonic pulses generated by a transducer which are directed into the material to be examined.

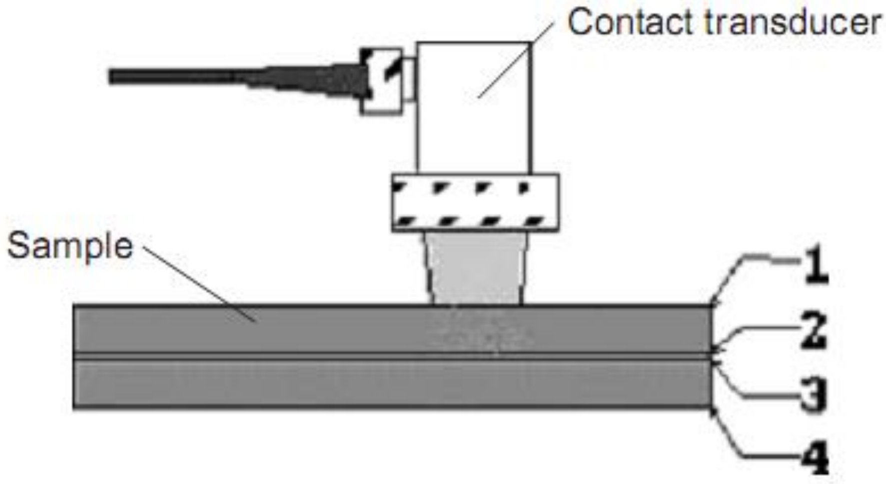


Figure 2-2 Pulse Echo Technique[31]

The reflected pulses or ‘echoes’, after internal reflection and absorption are collected in a receiver and analyzed on an oscilloscope screen. The amplitude and location of the echo determine the location and size of any defects in the test specimen. Generated wave frequency ranges from 1 -20 MHz with a resolutions of 0.5-2mm. The Pulse echo method is ideally suited to detect macroscopic defects in the test specimen. The final readout on the CRT displays the reflections of the wave from the different interfaces within the specimen. The ‘echoes’ superpositioned with information on the time of flight of the wave and distance can be used to detect defects in the specimen. The critical difference from the through transmission being that the single transducer acts as both pulsing and receiving unit. This requires for the position of the transducer to be manipulated perfectly perpendicular to the testing surface for obtaining acceptable reflected signals. The factors which affect the amplitude of the received echo are:

- Power of the input pulse
- Angle of incidence of the pulses to the test surface
- Size and position of the defect
- Losses at the receiver probe due to coupling between media
- Attenuation due to scattering and absorption in the material(material dependent)

2. Angle Beam Transmission Methods

Shear Wave Transmission Technique

Shear waves are generated using the longitudinal wave transducers in conjunction with angle blocks. Depending on the angle of the incident waves and the testing material, the reflected waves are either longitudinal or at an angle. The method finds extensive application in the testing of welded joints

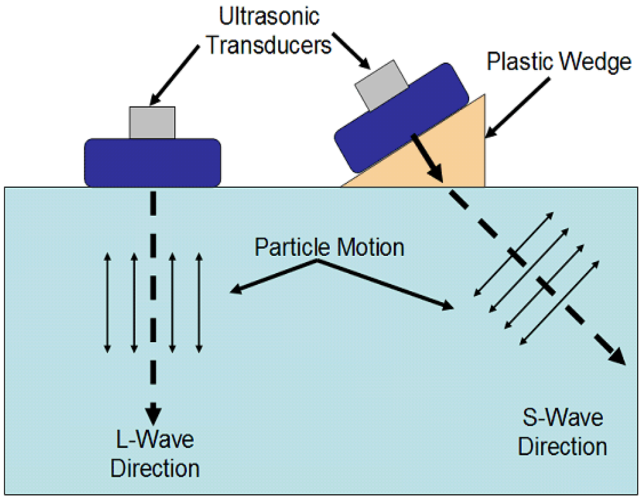


Figure 2-3 Oblique Wave Testing Scheme[32]

Lamb Wave Technique

At very high angles of incidence, where the incident angles exceed the second critical angle of refraction for the material combination, the waves travel near the surface of the specimen (up to three wavelengths) this propagation aids in the detection of defects very close to the surface, whose echoes could otherwise be masked by the back wall reflections.

2.2.2 Non-contact Testing

1. Immersion Testing

Immersion testing is done with the use of a waterproof transducer used to send sound waves through a column of water. Depending on the type of testing, the test specimen can be either completely immersed or only the region of testing being immersed. The entry angle of the ultrasonic wave can be adjusted using a controller to regulate the angle of entry of the wave into the test specimen.

	ELECTROMAGNETIC ACOUSTIC TRANSDUCER	LASER ULTRASONICS	AIR COUPLED TRANSDUCER
Distance of Operation	Short distance- order of millimeters for lamb waves	Large Distance, few meters	Many meters of separation between transducer and specimen
Frequency	0.5 to 10 MHz	Very large	Optimal at less

range		frequency at generation	than 1 MHz.
Types of waves	Longitudinal, shear and lamb waves	Longitudinal, shear vertical and surface waves	Longitudinal.
Orientation	Should follow surface	No restrictions	Identical to conventional transducers
Specimen Material	Conductive materials	All materials at low laser intensity	All materials
Safety	No safety limitations	Enclosed area with limited access	No limitations

Table 2.2 Acoustic testing techniques for adhesive joints[33]

2.3 PULSE ECHO TECHNIQUE

The Pulse-echo technique is one of the most widely used ultrasonic testing techniques. The application of the technique for adhesive bond testing has been studied and surveys have been published by numerous authors. It is used for testing adhesive bonds in the automotive industry since it is well suited to the following unique challenges:

- Large scale of manufacture and consequent testing
- Infeasibility of maintaining aerospace industry level of process control
- Constraints on the use of couplants due to incompatibility with the painting process
- Single side access to the bonded surface due to geometry

The current section deals with the pulse echo technique in detail by examining the fundamentals behind the working of the method. The testing apparatus broadly consists of the following three units- a Pulser, an amplifier and a receiver.

Pulser:

The pulser unit consists of a clock circuit and the transducer. The pulser emits a unidirectional pulse which is passed to the transducer through the coaxial cable. Depending on the voltage of the pulse, the sensitivity of the instrument can be adjusted. A lower voltage signal is used when a higher resolution is required to distinguish between two or more closely spaced reflectors. The repetition rate of the pulses is also varied to this end. A short, single cycle pulse is used for this case. In case of highly attenuative medium or high penetration depths, a high voltage is used to generate the ultrasonic signals. Pulser units with a voltage output varying between 100 - 1000 Volts are frequently used with the provision to electronically vary the pulse height and width. The transducer, using a piezoelectric crystal, converts the electrical signal into a mechanical wave, which then traverses the specimen materials. On reflection, the waves incident on the transducer are converted back to electronic signals and displayed on the CRT based display unit.

Amplifier:

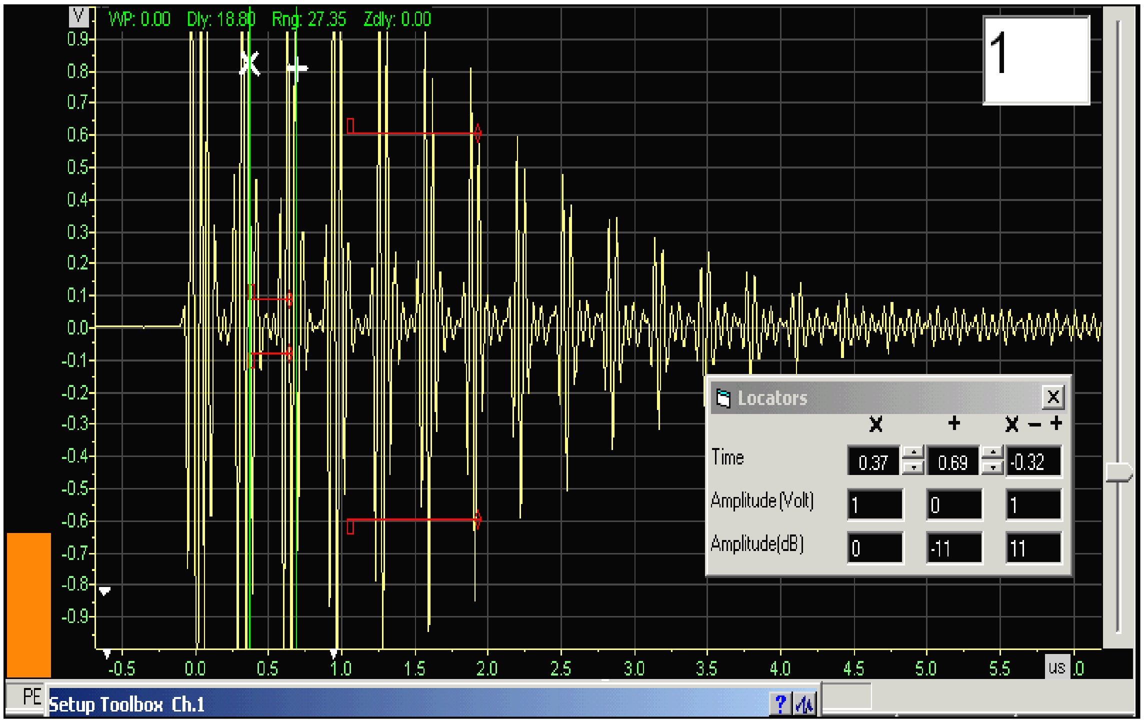
The amplifier serves to boost the strength of the received waves electronically in order to display it on the CRT screen. The level of electronic amplification required is controlled by the operator. The boost in signal strength can be expressed either in relative terms- a 2:1 gain or in its decibels (dB) equivalent of dB the amplifiers can also be adjusted to accept either a broad range of frequencies or filter in a certain preset frequency. On matching the resonant frequency of the transducer with the filtering frequency, noise free signals can be displayed on the unit.

Display Unit:

The acquired signals can be displayed in three different display formats namely A-scan, B-scan and C-scan.

A-Scan Display: The A-scan display figure 2-4 shows the strength of the signal on its vertical axis and time on the horizontal axis. The variations in the signal strength with time from a specified reference point are displayed on the screen. The reference point, at the left extreme of the screen is the time of the initial pulse to excite the transducer. The vertical axis represents the intensity of the pulse. The horizontal axis represents the time elapsed since the initial pulse on a linear scale. The subsequent pulses are displayed on the screen after the transducer receives the reflected mechanical waves from the specimen and converts them into electronic signals. The subsequent pulses are displayed at varying times when they are received by the transducer. The reducing intensity of the subsequent pulses is represented by the pulse amplitude along the vertical scale. Greater the attenuation in the material, lesser is the relative amplitude of the subsequent waves. Hence, when the material of the test specimen is known, the horizontal axis can be calibrated to display the distance in the sample. Thus the A-scan can be calibrated to show the distance/depth of the defect from its surface.

B-scan display: The B-scan is used to display scanning data when the transducer is moved across the testing specimen. In the case of an A-scan, the reflection of the sound waves as they travel along a single line is known, In order to conclusively decide if a specimen has no defects, numerous A-scans at different points on the surface are required. The sectional view of the specimen is displayed as the ultrasonic wave is passed through it.



WP: 0.00 Dly: 18.80 Rng: 27.35 Zdly: 0.00

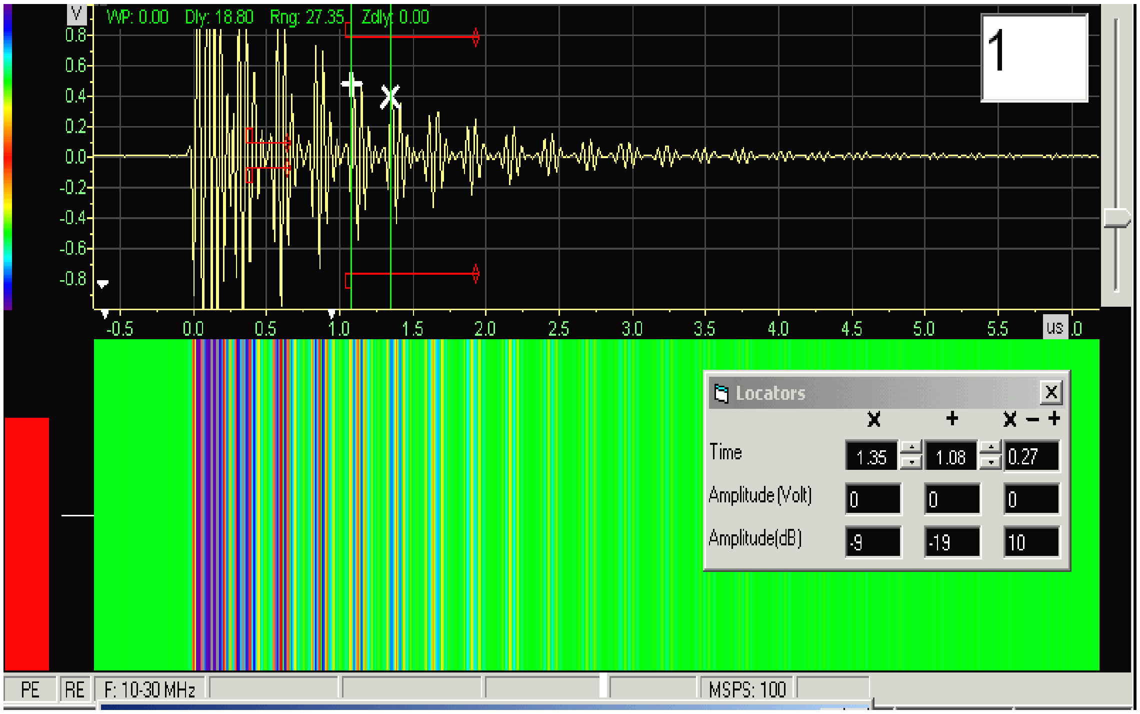
	X	+	X − +
Time	0.37	0.69	-0.32
Amplitude (Volt)	1	0	1
Amplitude(dB)	0	-11	11

Figure 2-4 A-scan display of an Aluminum sheet

The display consists of the X-positional display along with the time history from the A-scan. The display best reflects the discontinuities and reflecting surfaces which are perpendicular to the direction of ultrasound propagation. A shadow of the internal discontinuity is seen as a loss of reflected signals in the scan. The B-scan display is used to display a two dimensional view of the defect. However, it is possible to entirely miss sufficiently small defects which are parallel to the direction of the ultrasound propagation.

C-scan display: The C-scan is produced by compiling the A scan data of the specimen taken after scanning the specimen in a regular pattern. The acquired A scans are matched against their co-ordinates to display the top view of the specimen. The view is generated using signal criteria depending on the amplitude of the received pulse and time of arrival for every X-Y coordinate scanned. The settings of the instrument can be manipulated to display defects where the reflected signal power is below a specified threshold value. While A-scans can be done manually by technicians, the C-scans are highly automated and provide the user with a display which is similar to an X-ray image.

In order to distinguish between two similar sized defects at differing thicknesses that are close to each other, the resolution of the transducer needs to be sufficient and the step size of the scan. A tradeoff has to be achieved between scanning speed, and the ability to detect defects with the help of judicious selection of transducer diameter.



WP: 0.00 Dly: 18.80 Rng: 27.35 Zdly: 0.00

	X	+	X − +
Time	1.35	1.08	0.27
Amplitude (Volt)	0	0	0
Amplitude(dB)	-9	-19	10

PE | RE | F: 10-30 MHz | MSPS: 100

Figure2-5 B-scan Display

<u>Transducer</u>

The transducer is the fundamental component of an ultrasonic testing system. The success of an ultrasonic test hence depends on the appropriate selection of a transducer. Physically, the transducer is made up of a piezoelectric encased in a covering and activated using the timing circuit in the pulser through the coaxial cable. The frequency of a particular transducer is dependent on the thickness of the crystal. Thinner the crystal, the higher the frequency it vibrates at for a given exciting voltage. Hence, in Pulse echo transducers, the frequency achieved is limited by the thickness of the crystal. Above frequencies of 80-90 MHz, the decreasing thickness of the crystals limits mechanical rigidity.

The factors to be taken into account during the selection of a transducer are the material of the specimen, the desired sensitivity and resolution. A tradeoff between the sensitivity of the measurement and the resolution is often sought for a given material. A lower frequency transducer produces waves of higher wavelength that can counter the attenuation of the material due to its grain structure (in the case of metals). This results in greater depths of penetration into the test specimen while possibly not distinguishing small or very closely spaced defects. On increasing the frequency, thus reducing the wavelength, the closely spaced defects can be detected but the waves are scattered within the material, causing larger attenuation of the returning signal.

Based on the above tradeoff, transducers can be broadly classed as one of the following:

- High penetration- Low resolution transducers
- Medium penetration- High resolution transducers
- Broadband transducers

2.4 FACTORS DETERMINING SUCCESS OF A TEST

2.4.1 Surface Condition and Preparation

The surface condition of the surface influences the testing in two different ways. The surface condition influences the sensitivity of the utilized method, hence necessitating surface preparation. The surface condition also determines the wear and tear of the testing probe. The layers of dirt or oxide layers often leave minute air gaps between them, which prevent the passage of ultrasound through them. In cases where ultrasonic couplants are used, the particles of dirt serve to reduce the effectiveness of the coupling, thus introducing an element of uncertainty in the testing. In such situations, the surface is cleaned with steel brushes of grinding wheels, thus producing the required smooth surface conducive to testing.

2.4.2 Curved Surfaces

In the case of curved test surfaces like tubes, pipes and rails, guided waves are divided into three different modes- longitudinal, torsional and circumferential. It is observed that convex surfaces are better suited in terms of the area of contact with a flat faced transducer. The rectangular contact patch enlarges the angle of divergence of the acoustic beam in the plane normal to the cylinder axis. This reduces the sensitivity of the testing instrument. The use of plastic wedges which can adapt to the curved surface. (Thus providing increased contact area and maintaining the beam normality) The testing of curved surfaces has often been carried out using separate transmitters and receivers in the pitch-catch mode with lamb waves.

2.4.3 Ultrasonic Coupling

Ultrasonic waves undergo reflection and refraction at the interface of two different media. The degree to which the waves reflect is a function of the two media and the difference in their acoustic impedance. Greater the mismatch between the two impedances, greater is the reflection of the sound waves. Hence, in order for the waves to pass from the transducer to the testing material, an intermediate medium which facilitates transmission is required. Ultrasonic coupling agents or gels function to couple the two acoustically different media by displacing the air between them and facilitating smooth relative movement. Frequently used coupling agents include oil of low to medium viscosity, grade SAE 30. Where the testing of vertical walls or overhead surfaces is required, an agent of high viscosity like glycerine is used. Grease and petroleum jelly are the expensive alternatives available to testers. Water can be used as a coupling agent effectively if sufficient wetting of the test surface can be achieved. This has given rise to immersion testing- where the test specimen is completely submerged in a tank of water and the ultrasonic probe is moved across the surface to be tested without physical contact with the specimen. When suitable water proofing the transducer assembly is achieved, the immersion testing technique completely eliminates the problem associated with transducer wear.

The use of air as a coupling agent has grown over time. Initially proposed by Luukkala et.al [34] for generating plate waves for the contactless inspection of metal plates for on-line testing. Air coupling has been developed as viable alternative for low frequency (40 KHz – 2 MHz) ultrasonic testing. The extremely low acoustic impedance of air limits the upper bound of sonic frequency that can be used for testing. Additional care must be devoted to the design of the transducer with respect to sensitivity and bandwidth. The use of oblique waves for testing is common due to the low energy transmission coefficient for normal beam incidence. A system using the ‘focused slanted transmission mode’ has been developed by Solodov et.al[35].The system has been shown to produce enhanced C-scans with better contrast for flaw detection. In order to satisfy the requirement of efficient on line testing in an industrial setting, the air coupled transducers hold out great promise. Contact testing with liquid couplants poses problems with cleaning and reactivity with certain materials. Immersion testing is not always possible due to the large time requirement in addition to problems with high temperature specimens. Air coupled systems have been developed by researchers include [36-38]

2.4.4 Ultrasound Frequency and Probe Type

The ultrasonic testing of specimens is aimed at answering two questions- the presence of defects and the location and shape of the defects. In order to detect flaws, occurring at a random position and orientation in the specimen, the field from the transducer is required to cover the maximum possible sector area with a uniformly high sensitivity, however, increasing the scanned sector area with a large diameter of the probe results in lower sensitivity. The size of flaws that can be detected is hence a function of the transducer diameter- larger the diameter, larger the minimum size of flaws. Defects smaller than a threshold value are hence not detectable with a large probe diameter.

In order to detect minute defects, a narrow sound beam of high intensity is required. Using smaller sized probes, as a consequence increases the time required for scanning the entire specimen. The sensitivity of testing can only be increased at the expense of testing time. This still does not guarantee detection of all flaws in the specimen. This inherent contradiction has also prompted researchers to combine ultrasonic testing with other non-destructive testing methods. The frequency of the waves and the diameter of the transducer probe determine the sound beam pattern. The near field of the probe is determined by its diameter(near field length being proportional to the square of the diameter)A longer near field is indicative of high sensitivity to small flaws at large values of depth, neglecting the effect of attenuation in the material.

2.4.5 Attenuation in the Material

When acoustic waves pass through a material, a decrease in their intensity is observed with increasing distance from the transducer. The phenomenon is common in all materials and is caused due to two causes- scattering of the waves and absorption in the material. Attenuation is the term used to collectively define the above two phenomena.

The scattering inside a material is caused due to the inhomogeneties in the test materials. The inhomogeneity could be a change in the crystal structure, thus a change in density which causes sound waves to be reflected off the interface. While the inhomogeneity could be due to the presence of inclusions and pores, as in the case of metal castings and forgings, they could also be completely natural changes in density caused due to the presence of acoustically different phases. (eg. Ferrite and graphite in cast Iron, fiber and matrix materials in a composite material) Even in the case of a homogeneous material, the random orientation of crystals with respect to each other causes elastic anisotropy resulting in the scattering of acoustic waves. The scattering can be visualized in the case of materials with a coarse grain structure as the reflection and refraction at the grain boundary. The refracted wave undergoes the same effect at other boundaries along its path. The magnitude of the scattering is dependent on the relative difference between the sound wavelength and the grain sizes. In instances where the grain size is between 1/ 1000th and 1/100th of the wavelength, scattering is minimal. However when the grain size approaches values of 1/10th of the wavelength, geometric division of the waves is observed.

CHAPTER THREE

ADHESION MECHANISMS

3.1 INTRODUCTION

The current chapter examines the fundamental mechanism of adhesion the existing theories which explain the process. With an understanding of the basic theory, the possible defects present in adhesively bonded joints have been summarized. A fundamental knowledge of the different adhesion mechanisms and the defect types will be helpful in formulating and evaluating techniques for testing adhesive bonds between different adherends.

The theories propounded to explain the phenomenon of adhesion can be broadly classified into the four following types

1. Mechanical interlocking
2. Diffusion theory
3. Electronic theory
4. Adsorption theory

3.2 MECHANICAL INTERLOCKING

The mechanical interlocking theory, one of the earliest proposed theories to explain adhesion proposes that mechanical interlocking between the surface irregularities of the adherend and the cured adhesive results in adhesion. From this theory, it stands to reason that the effectiveness of adhesion is a function of surface roughness, porosity and the number of irregularities. Another critical factor is the wettability of the adhesive in its liquid state. In case of the situation described in the figure, where the adhesive not sufficiently enter the pores and irregularities on the adherend surface, proper adhesion is not possible.

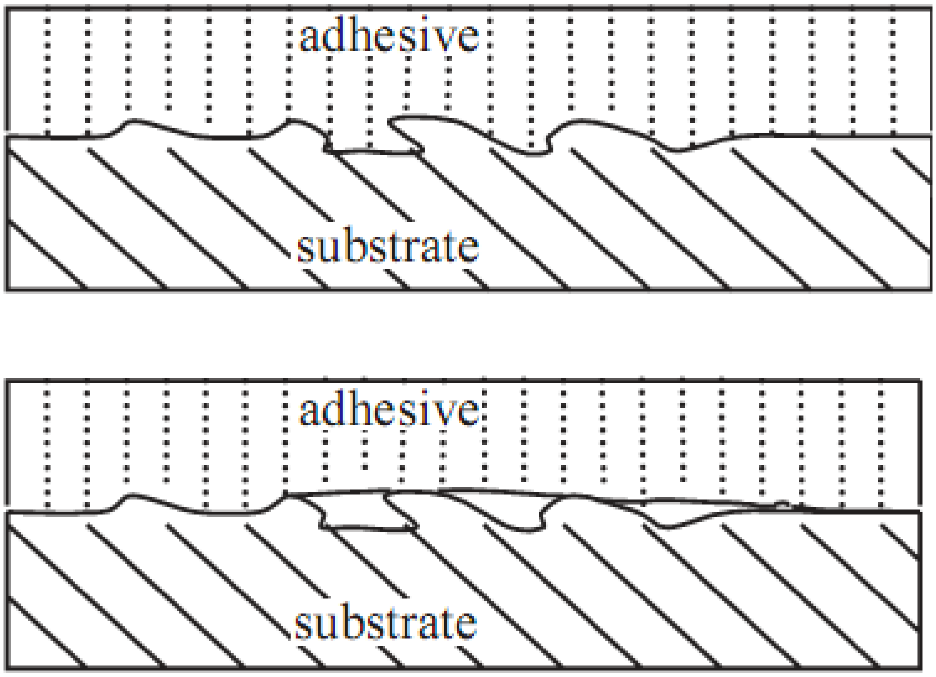


Figure 3-1 Wetting of Adherend Surface[31]

The interlocking theory effectively explains the adhesion mechanisms encountered in porous materials like fiber, wood, and textiles. It also explains the bonding between rubber and steel. The applications of the theory have led to further research into pretreating adherend surfaces (mechanically and chemically). The theory however does not explain the adhesion phenomenon in all instances. Observed bonding between very smooth adherends is not explained. The theory also fails to account for the molecular level interaction between the adhesive and adherend.

3.3 DIFFUSION THEORY

The diffusion theory proposed by Voyutski explains the bonding formed between polymers. The adhesion of polymers to themselves (termed as autoadhesion) and to other polymers has been put down to two way diffusion of the molecules across the physical interface between them. This inter diffusion of molecules occurs only between two polymers which have nearly equal solubility parameters. The solubility parameter of a polymer $\boldsymbol{\delta_{sol}}$ is given by the relation:

$$\delta_{\mathrm{sol}} = \left(\Delta H_V - \frac{R \times T}{V}\right)^{\frac{1}{2}} \qquad \text{Equation 3.1}$$

Where ΔH_V – Molar heat of vaporization

R – Universal gas constant

T- Temperature in Kelvin

V- Molar volume

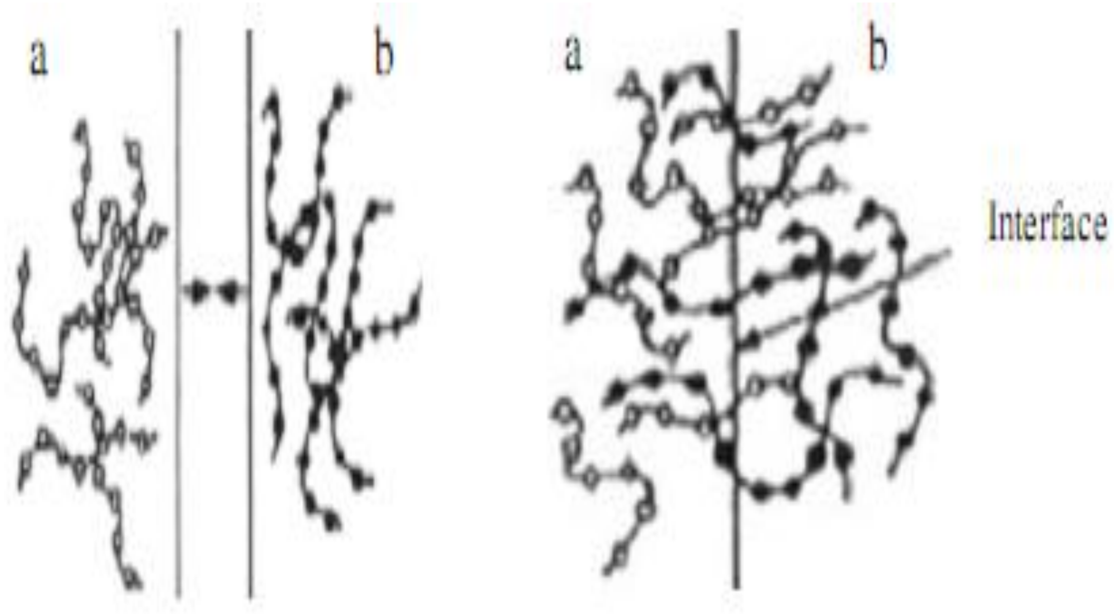


Figure 3-2 Diffusion Phenomenon at Molecular Level[31]

The solubility parameter thus can be viewed as a measure of the compatibility of two polymers.

When in contact, the factors that affect the adhesion of the polymers are contact time, temperature, type of polymers, molecular weight and the viscosity. This dependence of the adhesive strength has been likened to the process of diffusion. Hence, Fick's law of diffusion has been used to theoretically model the process to acceptable level of correlation with experiments.

The model explains the bonding process for amorphous processes but fails to account for the bonding between crystalline and highly cross linked polymers. The bonding occurring at temperatures below the glass transition temperatures of the polymers is also not explained by the theory.

One of the applications of the theory has been the bonding of metals and polymers. Diffusion has been recorded and the formation of an *interphase* has been reported when certain metals have been sputtered on to polymeric surfaces. Polymer metal hybrids recently find applications in load bearing components like the rear longitudinal beam [39]The major commercially used technologies in the automotive industry can be classified as Injection overmolding technologies, metal overmolding technologies followed by secondary joining operations and adhesively bonded polymer-metal hybrids[39].

3.4 ELECTRONIC THEORY

The electronic theory proposed by Deryaguin et al is founded on the difference in electronegativities of the constituent materials of an adhesive bond. The assembly of the adherends with the adhesive in between has been considered as an electronic double layer similar to that of a capacitor. The double layer implies the formation of positively and negatively charged regions. This gives rise to the attraction between the two materials which results in adhesion.

The theory has been debated since the electrostatic forces have been attributed as the reason for the strong adhesion rather than being a result of the high joint strength. Another limitation of the theory is that it explains only the bonding between dissimilar adherends. While subsequent works carried out to experimentally verify the theory have demonstrated the formation of the double layer in certain adherend/adhesive combinations, the theory does not hold applicable for adhesion as a whole.

3.5 ADSORBTION THEORY

The adsorption theory proposed by Sharpe and Schonhorn explains the phenomenon of adhesion between two materials as the result of intermolecular or even interatomic forces of attraction when sufficiently intimate contact is achieved between them.

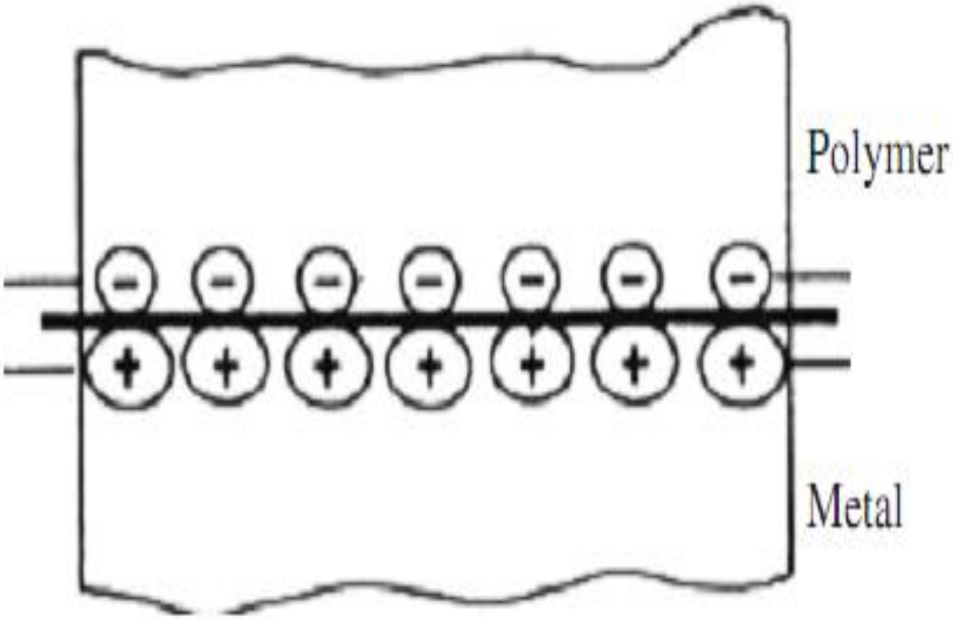


Figure 3-3 Electronic Double Layer [31]

The forces between the constituent materials can be either of the following types- Primary forces like metallic, ionic or covalent or secondary forces like Van der Waals and hydrogen bonds. It has also been shown by the authors that the adhesive joint strength is determined by the ability of the adhesive to spread over the adherend surface spontaneously. The theory is generic enough to account for numerous different combinations of adherends and adhesives. The bonding by different mechanisms have been studied independently have enabled the characterization of bonding between different adherends and adhesives.

Sections 3.1- 3.4 briefly describe the various theories of adhesion. The individual theories offer insight into certain specific situations while failing to account for numerous other cases. The most widely accepted theory is the adsorption theory proposed by Sharpe and co-workers. While it is now widely agreed that the phenomenon of adhesion takes place at the molecular and atomic levels when the constituents are brought in intimate contact, the learnings from the other theories like the mechanical interlocking theory and the diffusion theory have resulted in methods for adherend pretreatment(both mechanical and chemical) and research into polymer- metal hybrids.

3.6 DEFECTS IN ADHESIVE JOINTS

The above understanding of the phenomenon of adhesion sets the tone for the possible defects encountered in adhesives joints.

According to Adams and Drinkwater, defects found in adhesive joints can be classified into four broad categories, namely:

1. Gross defects

2. Poor adhesion
3. Poor cohesive strength
4. Kissing Bonds

Gross Defects

As shown in the figure 2.4, gross defects include defects like porosities, voids, cracks and disbonds. The porosities are caused due to air trapped in the adhesive during the curing process. The occurrence of voids can be explained by insufficient adhesive at a particular point. This can be caused due to variation in the adhesive dispenser speed.

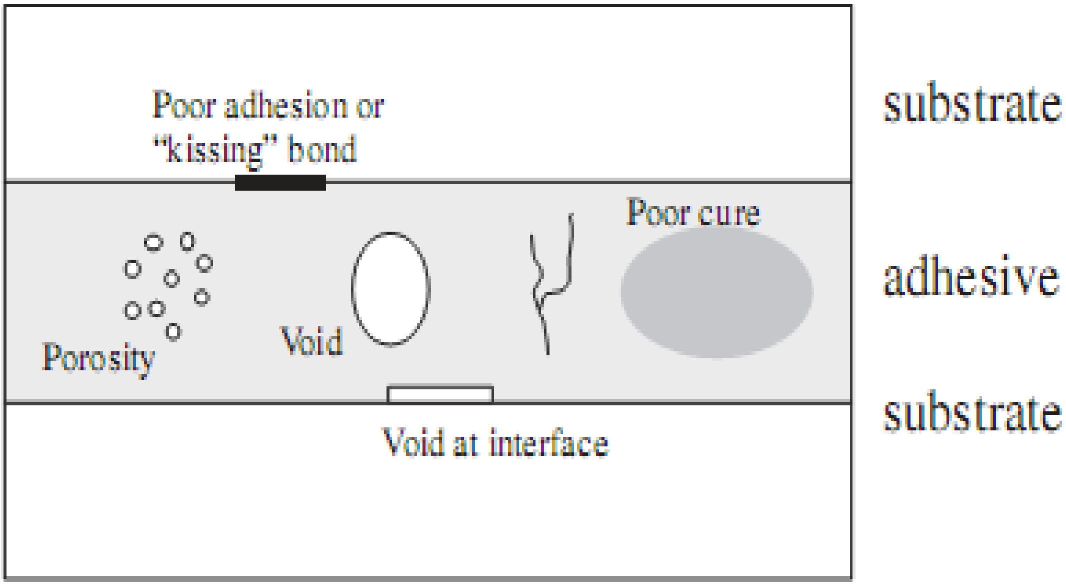


Figure 3-4 Typical Defects in adhesive joints[31]

Cracks occur in the adhesive layer due to non-uniform curing under thermal shrinkage. The presence of surface disbonds can be explained by rapid curing of the adhesive before completely contacting the adherend surface.

Poor Adhesion

Poor adhesion between the adhesive and the adherends can be the result of insufficient surface preparation of the adherends or impurities in the adhesive which cause a reduction in the adhesive strength of the bond.

Poor Cohesion

Poor cohesive strength of the adhesive could be due to insufficient mixing of the adhesive components or incomplete polymerization during the curing stage.

Kissing Bonds

Kissing bonds, also known as zero volume disbands are areas on the adhesive-adherend interface which are partly disbonded due to the presence of films of oil or water during the bonding process. Such defects could greatly affect the integrity of the bonded structure and are hard to detect using traditional testing methods.

It must be noted that detecting the above flaws is different from spotting potentially flawed components. Some of the above flaws in the joint could very well point to problems in the joint fabrication process, pretreatment of the adherend surfaces, improper mixing of the adhesive etc. Not all the flaws necessarily point to a potential failure of the joint within its specified load limit. The design of a robust Ultrasonic testing mechanism must also account for the above challenge.

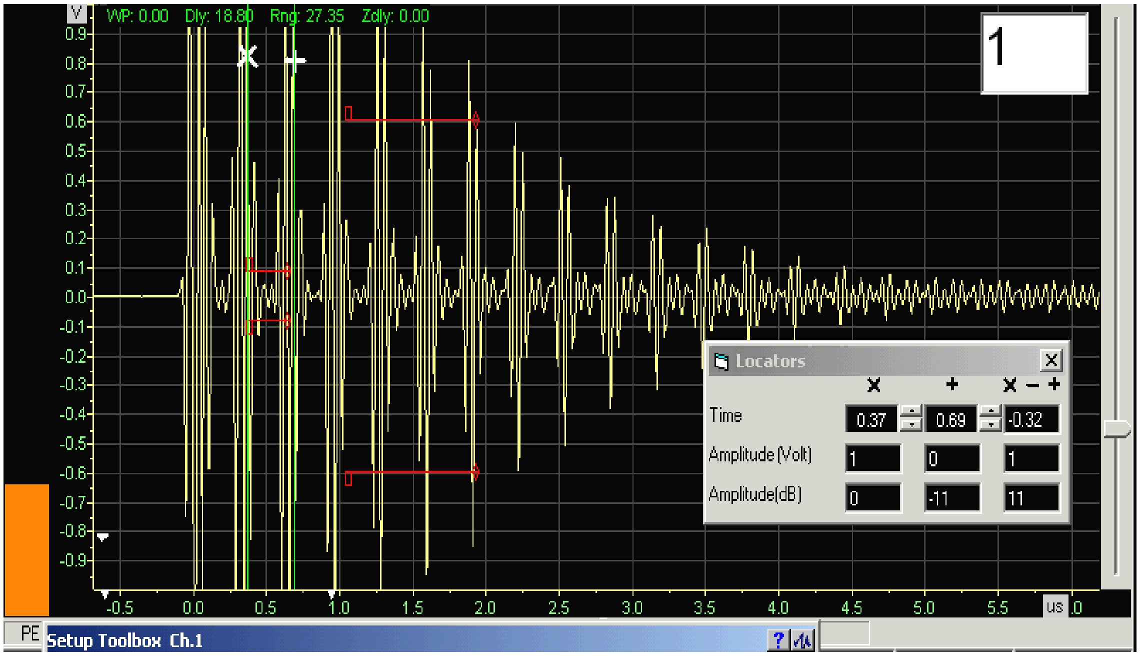
The previous sections examined the mechanism of adhesion as explained by the different theories and the possible defects that can occur in adhesively bonded joints. A suitable testing procedure must account for the above defect types and provide reliable results based on which conclusions can be drawn.

3.6 INSPECTION OF SPECIMENS

Inspecting the adhesive bonds is done by scanning the samples with the respective transducers. The corresponding A and B scans can be viewed on the display screen. However, unlike typical applications involving resistance spot welds in metal sheets, the current application has the added challenge of acoustic impedance mismatch between the adherend plate and the adhesive. This makes it hard to get a good reading of the sample. Particularly challenging is the second interface involving the adhesive and metal. Echoes from this interface are highly damped due to the attenuation levels in the adhesive and are thus often masked by the subsequent echoes from the first metal sheet and the first interface.

Figure 3-5 shows A-scans obtained for three different cases using the contact testing mode. 3-5 (a) is from a single Aluminum sheet. The Horizontal axis represents the time elapsed in microseconds. The vertical axis represents the amplitude of the wave in volts. The periodic echoes on the scan are the reflections off the back wall of the sheet from the metal-air interface. The scan obtained from a sample with intermittent adhesive application is shown in figure 3-5(b). It can be seen that this is similar to the scan from a single sheet. Figure 3-5 (c) shows the A-Scan for a region with adhesive. The presence of adhesive is evident due to the rapid decay of the signals compared to the previous scans and the time elapsed between two major pulses, which is larger for the waves to travel the entire length of the stack- up, as opposed to just the first plate.

(a)



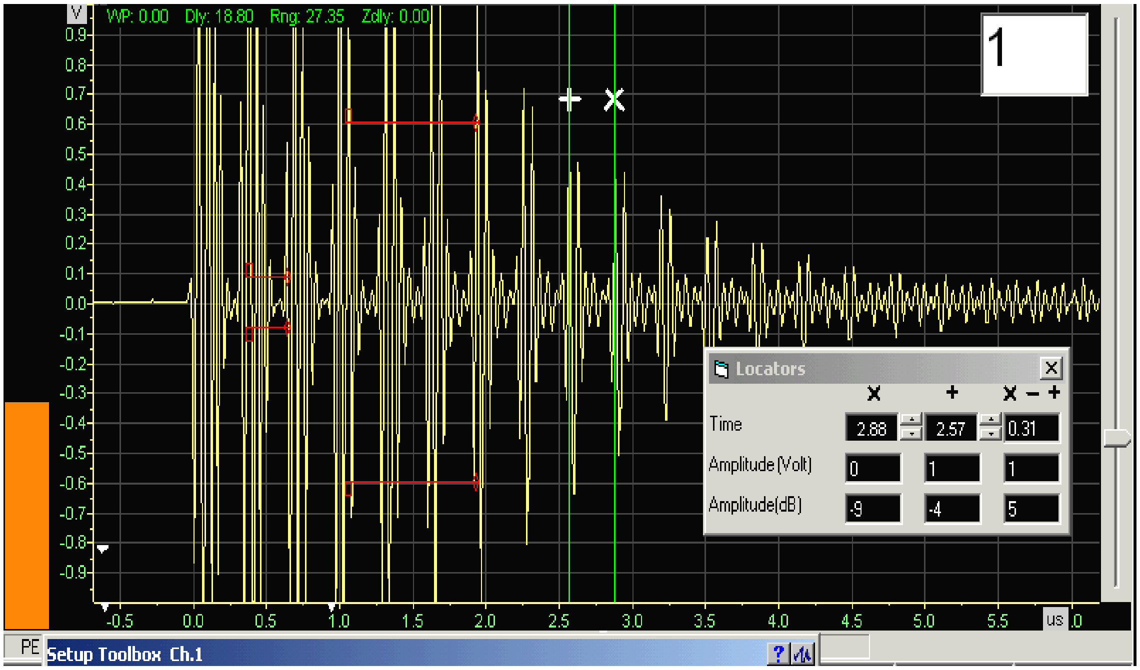
WP: 0.00 Dly: 18.80 Rng: 27.35 Zdly: 0.00

Locators

	×	+	× − +
Time	0.37	0.69	-0.32
Amplitude (Volt)	1	0	1
Amplitude(dB)	0	-11	11

Figure 3-5 (a) A-scan for single sheet (b) A-scan for area with no bond (c) A-scan of bonded region.

(b)

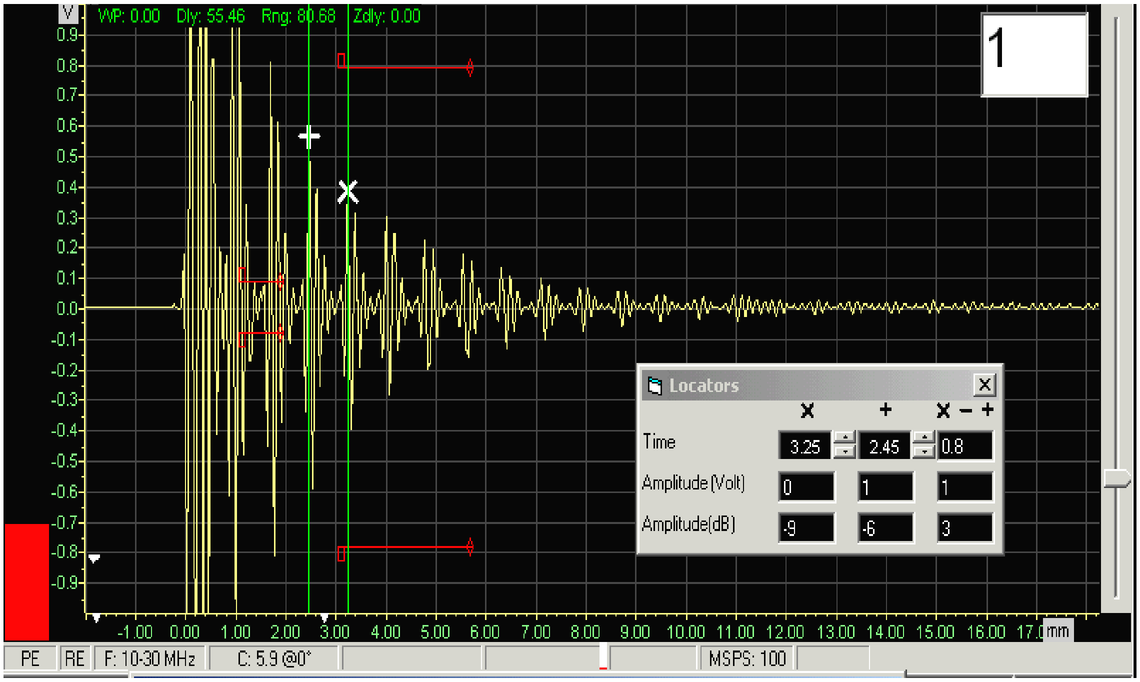


WP: 0.00 Dly: 18.80 Rng: 27.35 Zdly: 0.00

	X	+	X − +
Time	2.88	2.57	0.31
Amplitude (Volt)	0	1	1
Amplitude(dB)	-9	-4	5

PE Setup Toolbox Ch.1

(c)



WP: 0.00 Dly: 55.46 Rng: 80.68 Zdly: 0.00

	X	+	X − +
Time	3.25	2.45	0.8
Amplitude (Volt)	0	1	1
Amplitude(dB)	-9	-6	3

PE RE F: 10-30 MHz C: 5.9 @0° MSPS: 100

The A scans shown above were for individual points on the adhesive joint. Performing the above procedure for every point on the joint is a long process which cannot be replicated on the scale of an assembly.

Due to this challenge, the approach used to detect a disbond makes use of the reflection coefficient of the different interfaces. Every acoustic boundary has a reflection coefficient which depends on the acoustic impedances of the bordering materials and the order of the materials. Based on this, the current sample can be divided into interfaces as shown in the figure

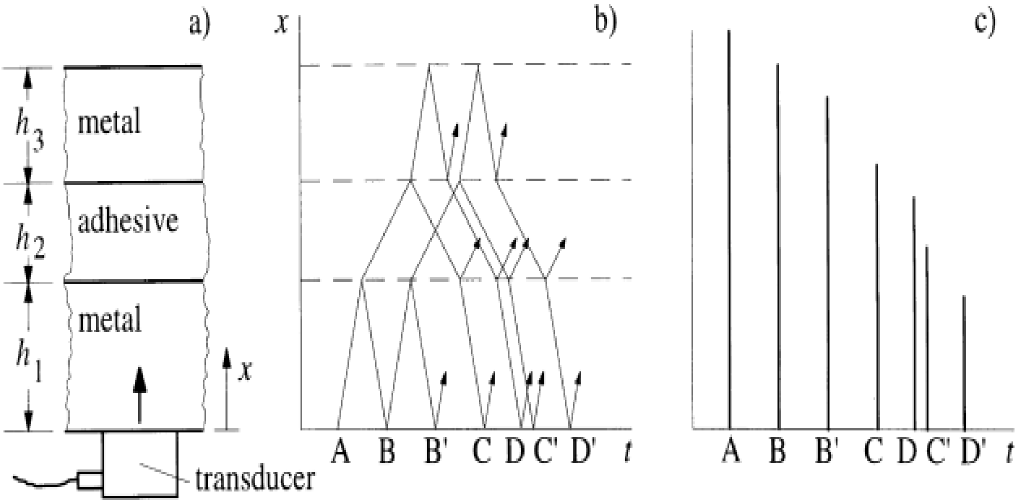


Figure 3-6 Interfaces and passage of acoustic waves [40]

The reflectivity coefficient of the materials at the interface has proved to be a reliable means to detect the state of the bond (Bond/ No-bond). Previous experiments conducted by researchers have shown reliable results[40];[41, 42]. Based on this, a threshold value is set. Areas of the bond where the signal amplitude is lesser than the threshold are classified as disbonded. In order to check for disbond at a point in the joint, the signals from both adhesive- metal interfaces have to be analyzed.

The reflectivity coefficients for the different interfaces are given by the equations

$$R_{M/A} = \frac{(Z_A - Z_M)}{(Z_A + Z_M)} \qquad \text{Equation 3.2}$$

$$R_{A/M} = \frac{(Z_M - Z_A)}{(Z_A + Z_M)} \qquad \text{Equation 3.3}$$

$$R_{A/a} = \frac{(Z_a - Z_A)}{(Z_a + Z_A)} \qquad \text{Equation 3.4}$$

A simplified approach involves the analysis of the most prominent set of pulses. The first set of pulses is one that is produced on reverberation of the wave in the first metal sheet. Another set of pulses is produced as the wave passes through the adhesive layer and is reflected off the second interface between the adhesive and metal. The reverberations in the first metal sheet are represented by the following equation:

$$a_n = -A_0 \cdot \left(\frac{T_0}{R_0}\right)^2 (R_0 \cdot |R_1| \cdot \eta_1)^n \qquad \text{Equation 3.5}$$

Where, A_0 is the magnitude of the main pulse from the transducer.

- T_0 and R_0 are the transmission and reflection coefficient at the transducer/first metal sheet interface.
- η_1 is the attenuation coefficient- a factor used to account for attenuation in the metal sheet.

For a pulse travelling once through the adhesive layer and ‘n-1’ times through the metal layer, the amplitude is given by:

$$h_n = -a_n \cdot \left(\frac{T_1}{R_1}\right)^2 (R_1 \cdot R_2 \cdot \eta_2) \qquad \text{Equation 3.6}$$

Where, R_2 is the reflectivity coefficient at the interface of the adhesive and the second metal sheet. Table 4-C shows the material and acoustic properties for the constituents of the joint.

Figure 3-7 shows the amplitudes of the waveforms reflected from the different interfaces in the assembly. This theoretical estimation assumes that the wave does not undergo any attenuation in the metal while undergoing damping in the adhesive. In case of the presence of adhesive, the reflected waves are highly damped when compared with the waves from the single sheet. As seen in the figure 4-6, the resultant wave and the reference wave are in phase with each other.

Material	Sound Velocity(ms^{-1})	Density(Kg/m^3)	Acoustic Impedance (10^6 $kgm^{-2}s^{-1}$)
Polystyrene(Transducer)	1056	2340	2.47
Steel	5900	5890	45.41
Aluminum	6230	6320	17.06
Adhesive(epoxy-based)	2300	2300	2.65

Table 3.1 Material Properties of joint constituents

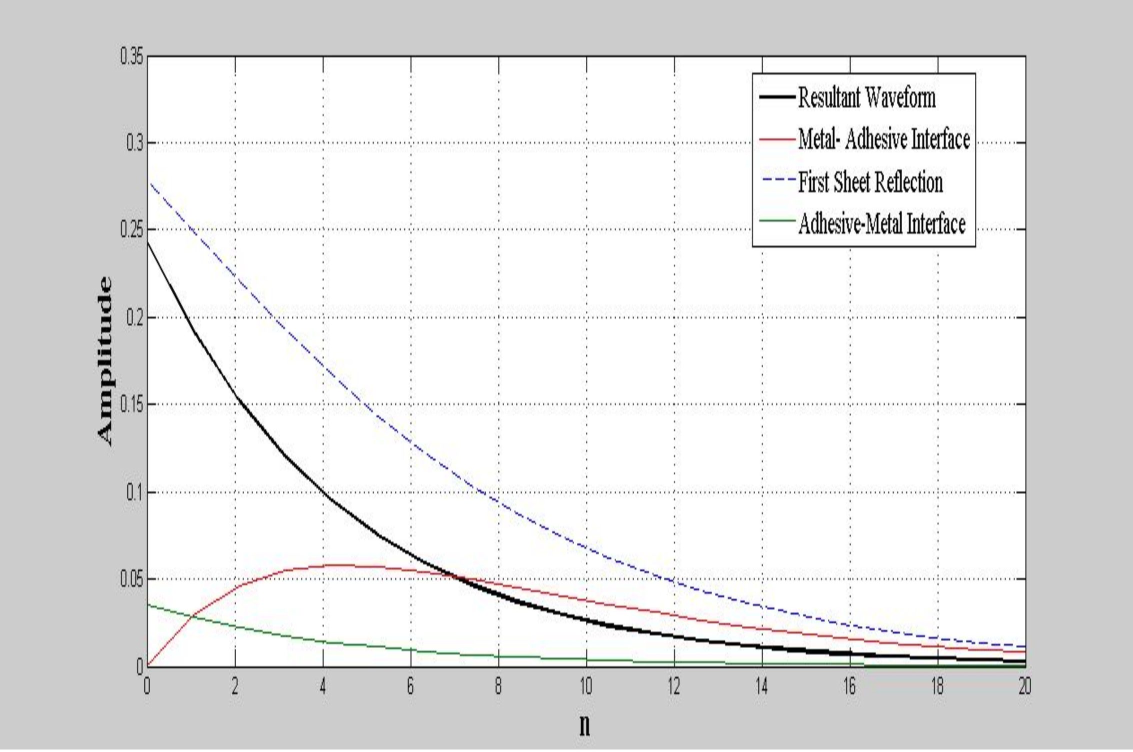


Figure 3-7 Theoretical wave decay in a sample joint with steel adherends

Signal Comparison Routine

In order to execute the procedure detailed above, the sample A-scan data is compared with a reference signal. The Instantaneous scan data from the Inspecting device is exported into MATLAB for comparison. The files containing text data corresponding to the signal amplitude and time elapsed in a matrix form is imported into the data analysis software. Signal manipulations like addition and subtraction are performed on MATLAB and the resultant waveform is plotted alongside the original waveform. Digital Image processing is an alternative which has been done for similar studies [41]; [42]has not been performed here due to restrictions on the output signal formats available from the current inspecting device.

The results of the above signal comparison routine on scans from the different samples have been presented as part of chapter 4.

CHAPTER 4

LABORATORY TESTING

4.1 INTRODUCTION

This chapter elaborates on the two modes of ultrasonic testing, namely contact and Immersion modes that have been carried out on the hem bonded samples. The preparation of the samples, the test apparatus, the scan validating scheme and the resulting ultrasonic scans has been discussed in detail.

4.2 SAMPLE PREPARATION

The samples consist of Aluminum and steel sheets bonded together similar to hem joints found in automotive applications. Another factor considered in the application of the adhesive in the joint. Two different configurations have been replicated- namely continuous and intermittent adhesive placement. The above samples suitably replicate the applications found in automotive bodies. The adhesive used for the applications is a commercially available epoxy adhesive. Figure 4-1 shows the prepared samples that have been used for tests. Dimensional details of the samples have are provided in table 4.1

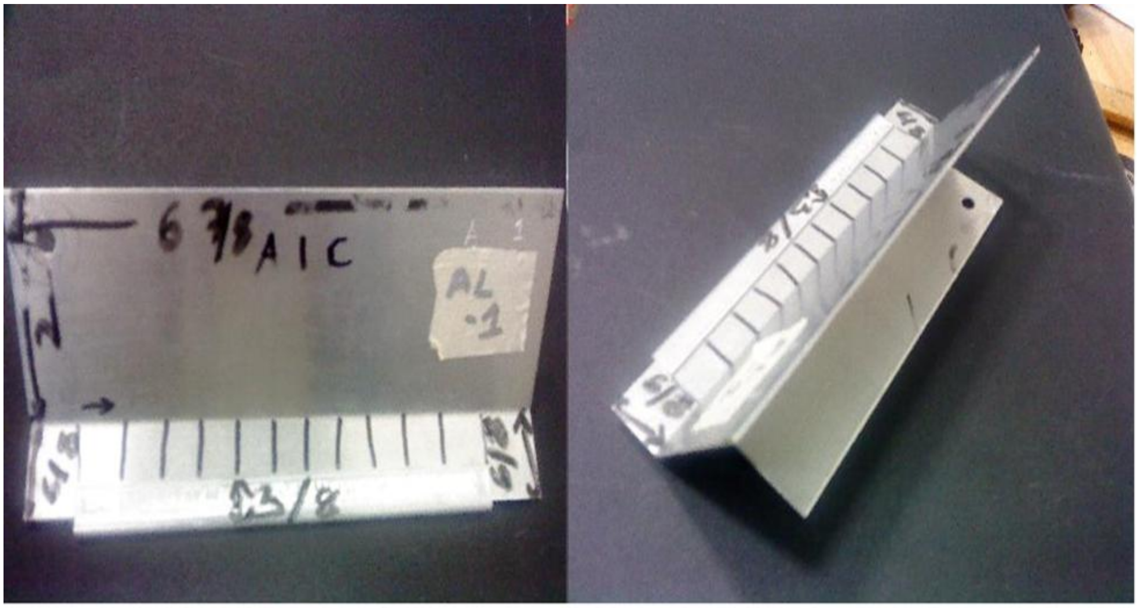


Figure 4-1 Testing Samples

4.3 TESTING APPARATUS

The adhesively bonded samples have been tested with the intention of detecting the following types of defects- absence of adhesive and presence of adhesive, but lack of adhesion. The system should be able to differentiate the above two instances from a situation where proper bonding exists between the adherends. The testing has been carried out with the help of a commercially available testing system. With suitable modifications in its configuration, the system has been adapted for the testing of adhesive bonds. The testing of the samples has been first carried out using two variations of the pulse-echo ultrasonic testing method- Immersion testing and Contact Testing.

Sample Material	Bond Type	Sheet 1 Thickness(mm)	Sheet 2 Thickness(mm)	Adhesive Thickness(Calculated)
ALUMINUM	Continuous seam	1	1	0.7
	Intermittent adhesive	1	1	0.6
STEEL	Continuous seam	1	1	0.7
	Intermittent adhesive	1	1	0.6

Table 4.1 Test Sample Dimensions

Figure 4-2 SWi ScanMaster Spotweld Inspector

4.3.1 IMMERSION TESTING

The samples have been subjected to immersion testing using a delay line transducer of frequency 10 MHz and diameter of 9.52 mm. The test is carried out on the immersion testing apparatus shown in figure below. The apparatus consists of the transducer attached to the XYZ motion mechanism, which can be moved electronically along different directions. The output from the transducer is fed to the SWI 100 x ScanMaster device to show real time A and B scans of the bonded area as the transducer is moved.

4.3.2 CONTACT TESTING

The Contact testing of the joint specimens has been carried out with the help of a contact transducer of 20 MHz central frequency and an element size of 4.5 mm. A commercially available industrial couplant has been used to enable acoustic coupling between the polystyrene membrane and the adherend metal. Table 4.2 shows the specifications of the transducers used for the testing. Figure 4-3 shows the contact transducers used for the current application. It consists of the piezoelectric element on one end. Provision is made for a water column which serves the purpose of channeling the waves from the element. The polystyrene membrane is provided to achieve proper contact with curved testing surfaces.

Figure 4-3 Contact Transducers

Sl no.	Transducer Make	Transducer Type	Frequency(MHz)	Diameter(mm)
1.	ScanMaster	Contact	20	4.5
2.	Olympus Panametrics	Immersion	10	9.52

Table 4.2 Transducer Specifications

4.4 RESULTS AND DISCUSSION

4.4.1 IMMERSION TESTING

The figure 4-4 shows the A-scan obtained for an area on the steel test specimen. The time difference between the initial pulse and first metal surface and the subsequent interfaces are calculated using the relation:

$$\tau = \frac{2 \times d}{v} \qquad \text{Equation 4.1}$$

where τ is the time delay, d represents the thickness of the acoustic medium and v is the velocity of sound in the medium. The distance is multiplied by a factor of 2 to account for the onward and the return travel of the acoustic waves.

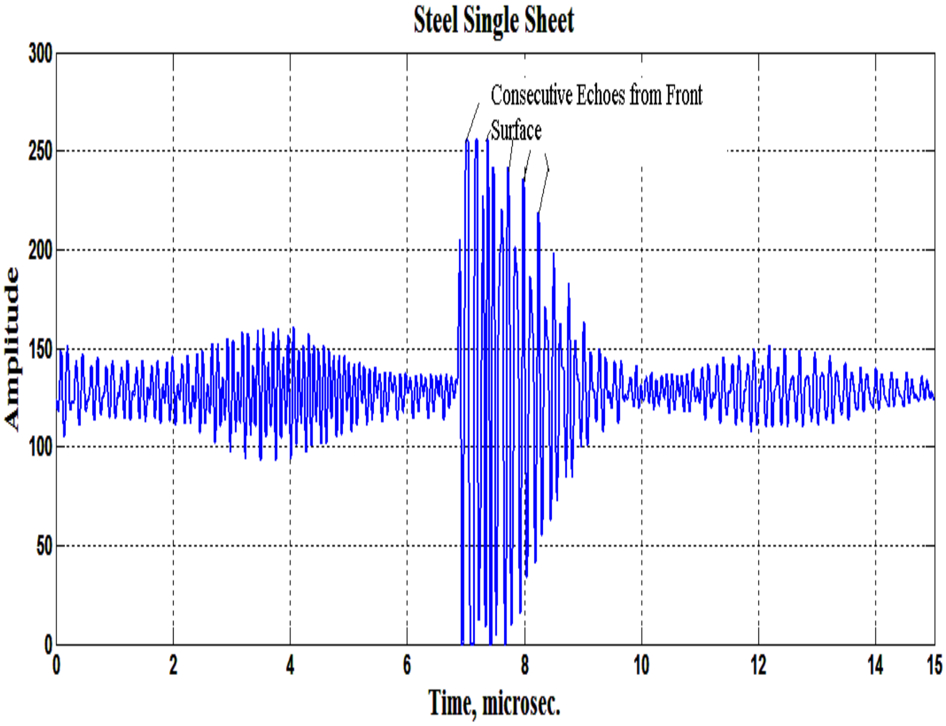


Figure 4-4 A-scan for a single Steel Sheet

Based on Equation 4.1, with a 0.5 cm thick water column between the transducer and the metal surface in the experimental setup, the calculated time delay for the first metal sheet echoes is found to be **6.75 µS**. This is in agreement with the scan shown for the metal sheet.

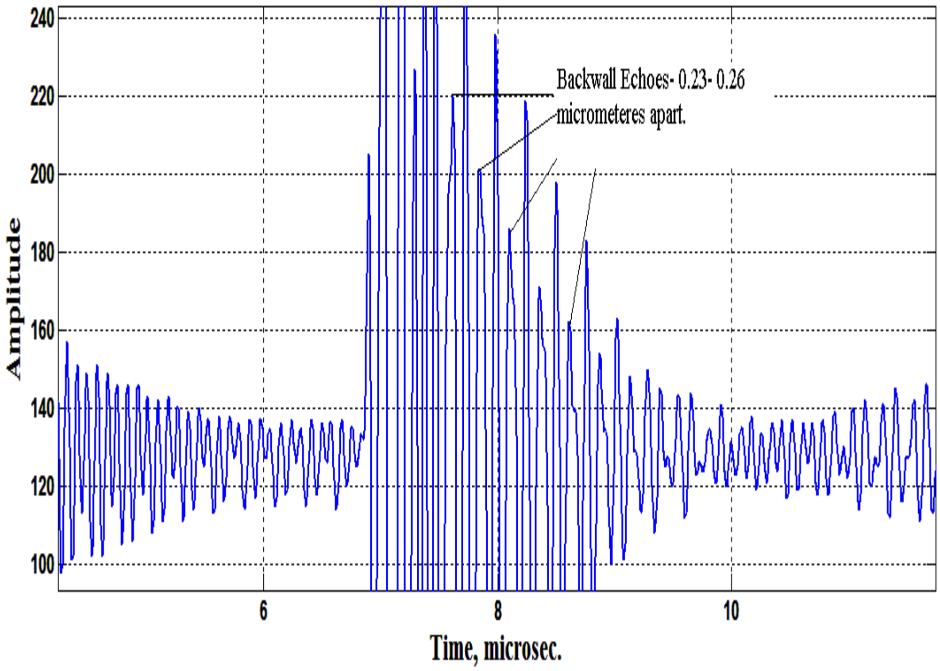


Figure 4-5 A-scan of a Single Steel Sheet

From Equation 4.1, on substituting 0.23 µS for the delay, the thickness of the steel sheet is calculated to be **1.2 mm**. which is close to the measured value of the sheet after accounting for variations in its thickness.

The above procedure serves to validate the accuracy of the testing procedure. Figure 4-6 shows a replication of the similar procedure for a single Aluminum sheet.

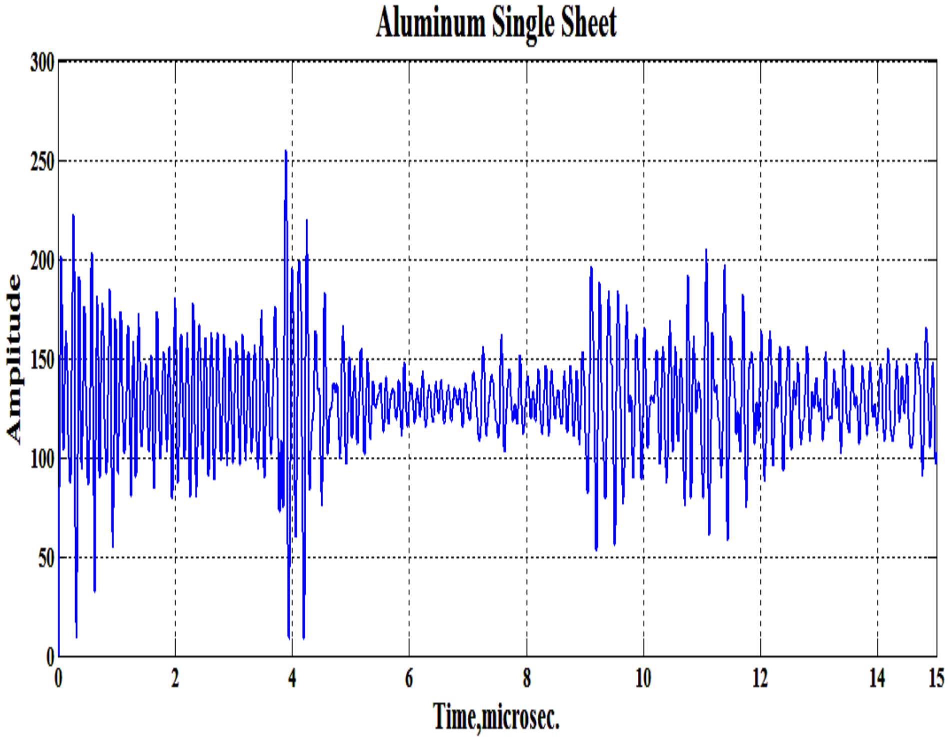


Figure 4-6 A-scan for Single Aluminum Sheet

Based on the above scan, it has also been possible to detect a defect in the aluminum sheet. From the closely spaced echoes between the two major echoes representing the front and back wall of the sheet, it can be deducted that an internal defect is present in the sheet.

Figures 4-7 and 4-8 present the A-scans of random regions on the steel and aluminum samples which have adhesive between the two sheets. While the presence of adhesives is verified visually, the state of the joint i.e bonded/disbonded needs to be deducted from the scans.

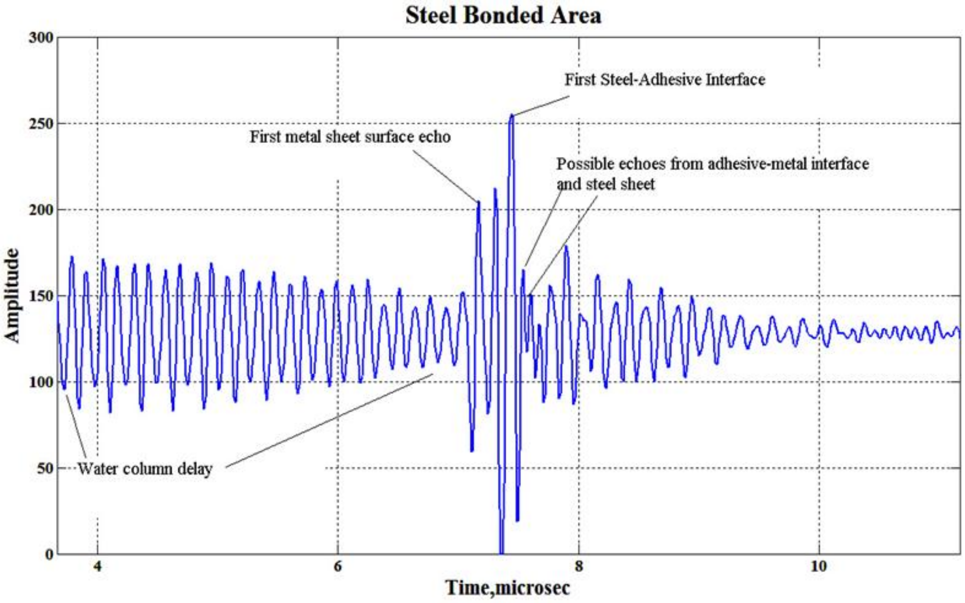


Figure 4-7 Steel Bonded Area

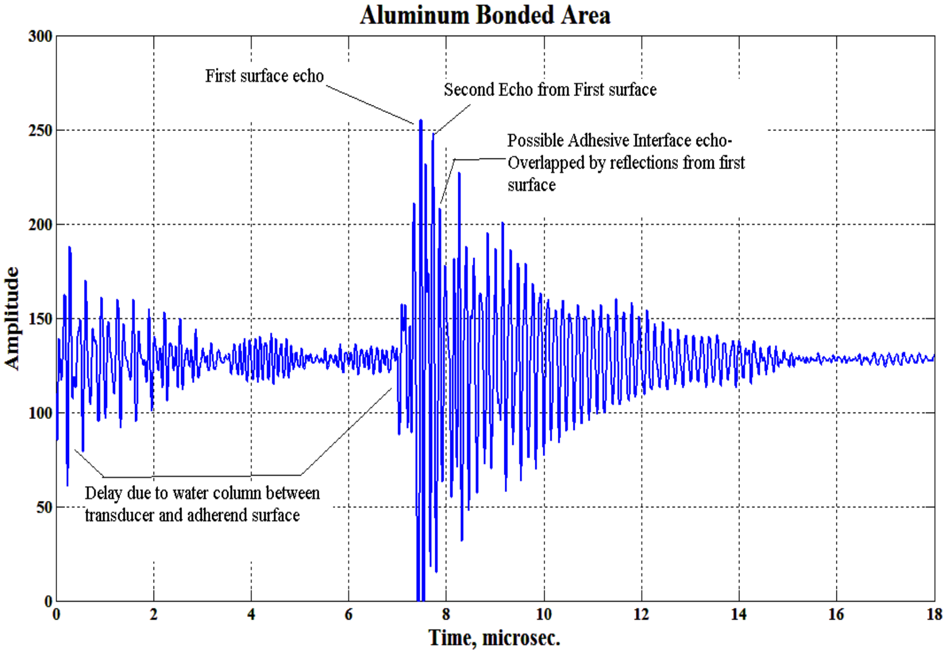


Figure 4-8 Aluminum Sample Bonded Area

Figures 4-7 and 4-8 are examples of numerous scans of areas on the adherend assemblies with the presence of adhesive. As can be seen, it is not possible using the pulse echo immersion technique with the current test parameters to distinguish between second adhesive –metal interface and subsequent metal face echoes.

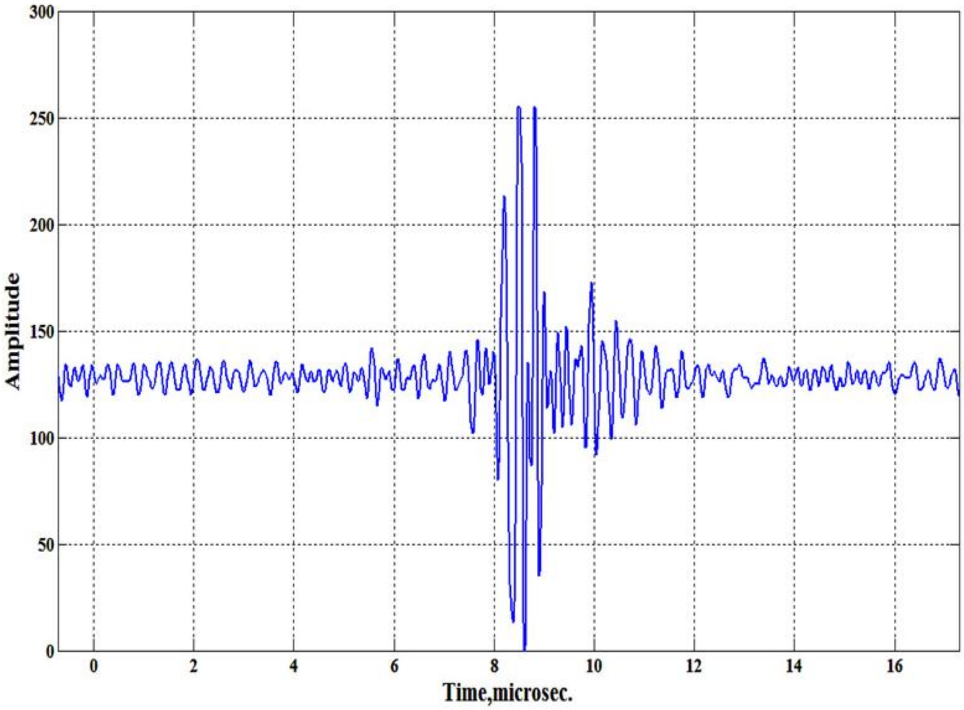


Figure 4-9 Steel Adherends- Random Point

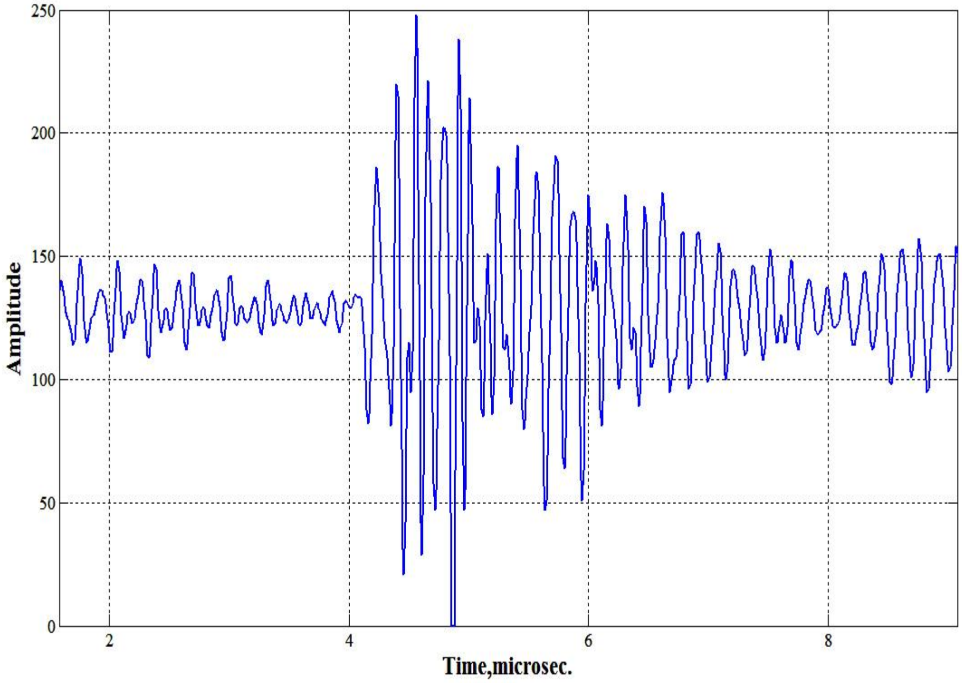


Figure 4-10 Aluminum Adherends- Random Point

4.4.2 CONTACT TESTING MODE

The objective behind testing the specimens using the contact mode is to achieve a higher resolution of the echoes from the interfaces. The higher resolution enables proper differentiation between the interface echoes. The effect of using an ultrasonic coupling agent between the transducer and the metal sheets is evident in the smooth waveform seen to the left end of the scan. The consecutive echoes decay in a near exponential manner as seen for a single reference sheet in figure 4-11.

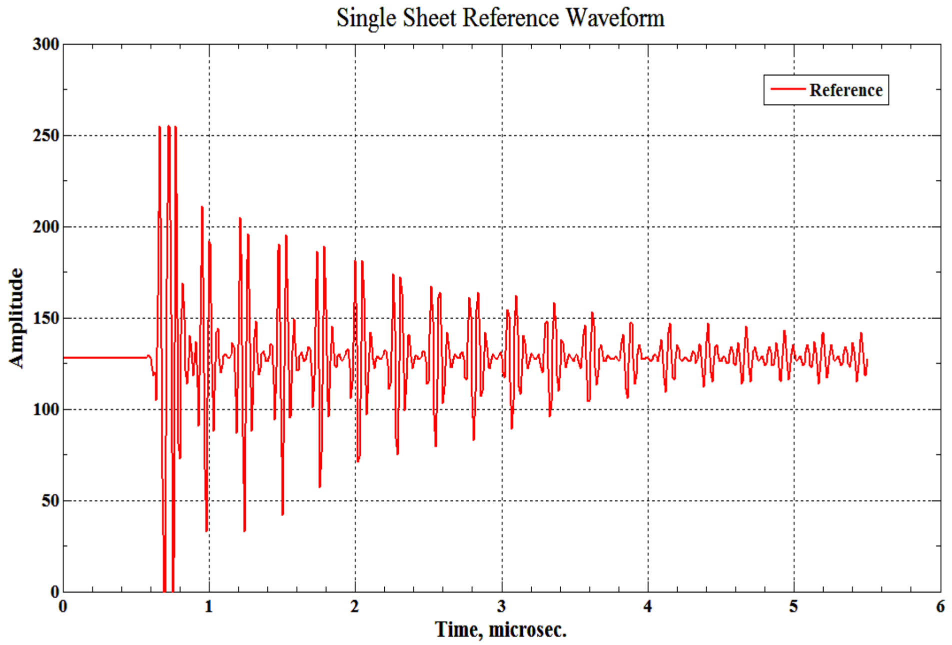


Figure 4-11 Contact Test- Single Aluminum Sheet.

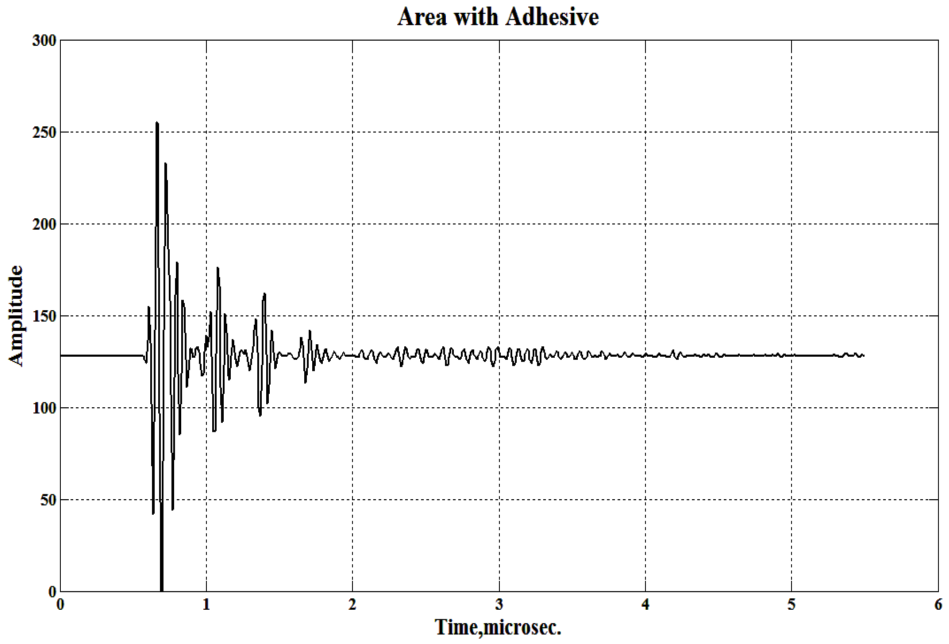


Figure 4-12 Contact Test-Adhesive Spot

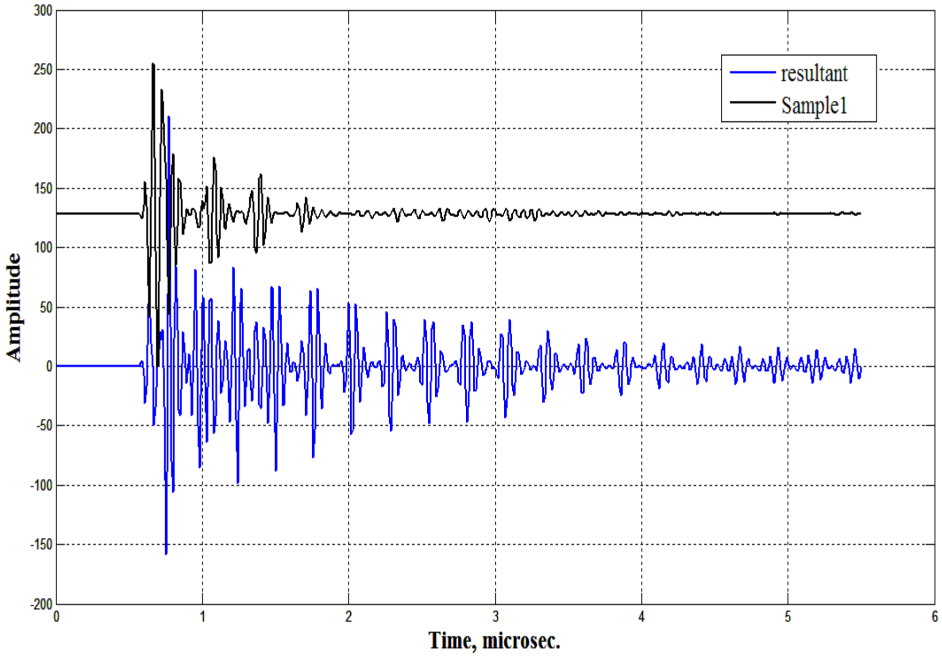


Figure 4-13 Contact Test- Signal Comparison

Figure 4-13 shows the results of the testing scheme adopted. In order to definitively state the condition of the joint at a particular point, two different possibilities have to be accounted for- bond/disbond at the first metal-adhesive interface and a bond/disbond at the second adhesive-metal interface. Due to the large attenuation at the interface caused by the adhesive at the interface, the resultant waveform has large amplitude relative to the reference wave. Figure 4-13 shows the resultant waveform after subtracting the reference A-scan from the sample signal. The large relative amplitude leads to the conclusion of proper adhesion at the first interface. The bonding at the second interface is checked by using the reference signal from a single sheet after accounting for a semi-infinite adhesive layer. This is done by introducing additional damping to the initial reference waveform equivalent to the adhesive. The sample signal is compared with the modified reference signal to determine the condition of the bond at the second interface. In the figure 4-14 the comparison yields a resultant signal, *out of phase* with the sample signal. For a disbond at the second adhesive-metal interface, the reflectivity coefficient is negative and the resultant signal is out of phase with the original signal.

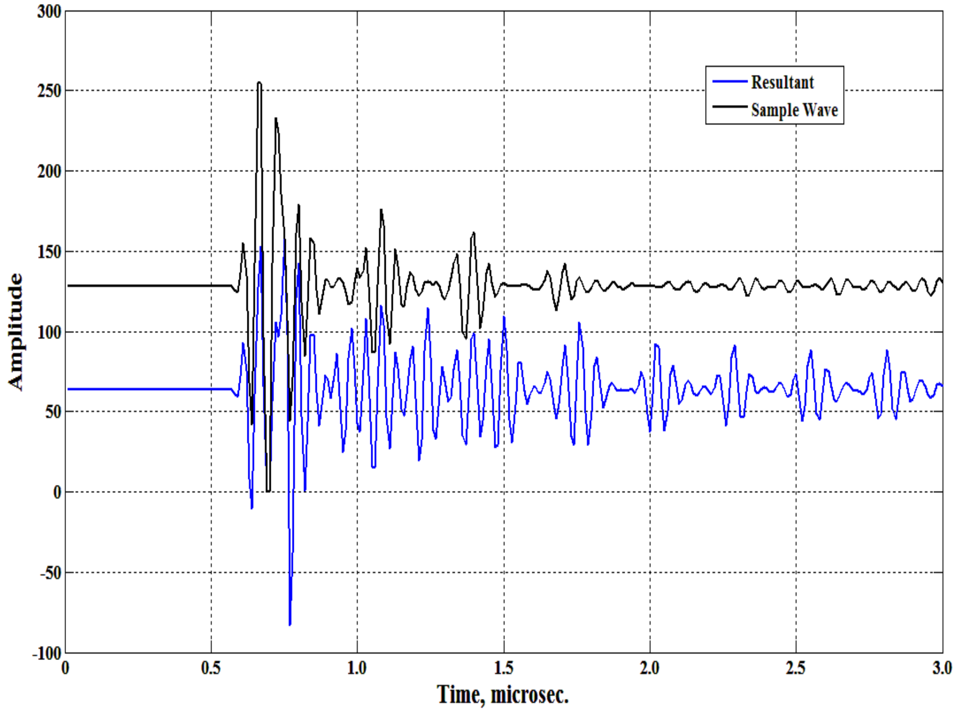


Figure 4-14 Second Interface Disbond

Figure 4-15 shows the plot for a proper bond at the second adhesive-steel interface. It can be seen that the two waves are in phase with each other- the required condition for a bonded joint.

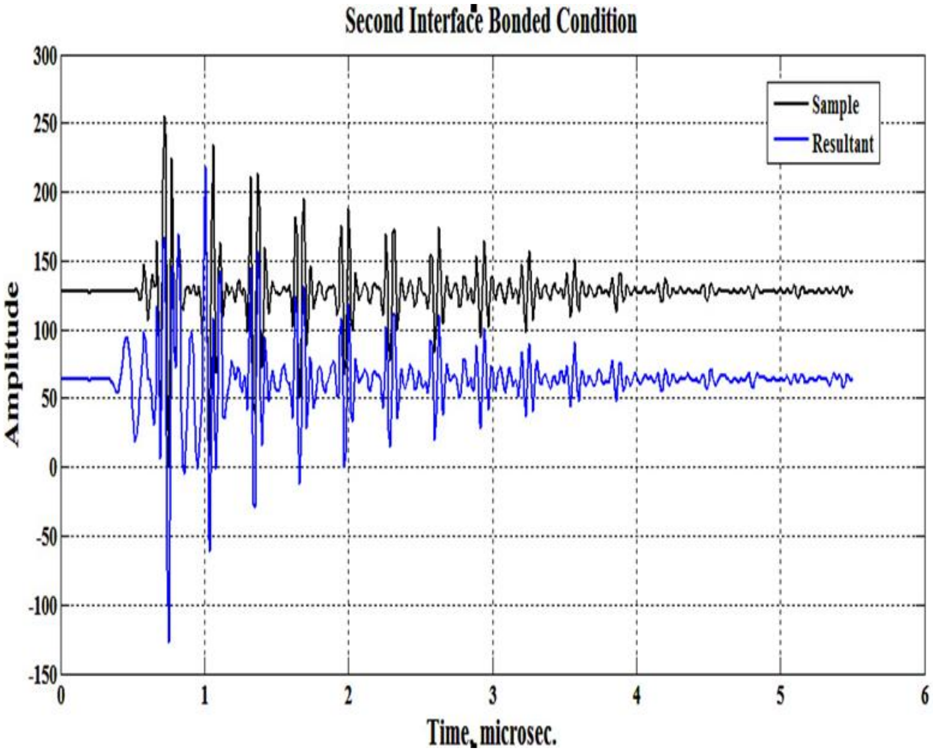


Figure 4-15 Contact Testing- Second Interface Bonded Condition

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

As part of the current work, typical straight line hem bonded adhesive joints found in automobiles have been tested for defects using the Pulse Echo Ultrasonic technique. The acquired signal from an area on the joint is compared with a reference scan to qualify if the area has proper bonding. This method has been applied to two variations of the method, namely Immersion and Contact Testing. Obtaining clear echoes from the second adhesive-metal interface has not been possible using the 10 MHz central frequency with the automated Immersion mode. Since the possibility of automation of the procedure is major advantage for the immersion mode, tests can be conducted with a transducer of higher central frequency. The manual contact testing scheme has provided better results using the 20 MHz transducer. A logical future step would be to perfect automation alternatives which would involve developing signal processing techniques for the entire length of the adhesive seam- as opposed to a single point in the current work.

The testing scheme also needs to be verified for complex joint geometries and varying thickness of adhesive layer.

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