B. Nondestructive Inspection of Adhesive Metal/Metal Bonds (NDE 601[i])

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Objective

The goal of this project is to identify and develop a nondestructive inspection (NDI) method(s) for adhesive-bond evaluation to be used in an automotive manufacturing environment that would foster increased confidence and use in adhesive joining. The primary objective is to identify and validate an NDI method(s) which can 1) measure the adhesive area and thickness and 2) detect weak bonds having intimate contact but which have reduced strength ("kissing" bonds).

Approach

There are five major attributes which contribute to the strength of an adhesive bond on a metal flange: the width of the adhesive area, the thickness, the location of the bead relative to the edges of the flange, the state of cure, and the quality of the adhesion. The general approach is to develop a portfolio of methods that can be used on the plant floor which allow all these attributes to be measured nondestructively. These methods need to be single-side inspections that can follow a flange, deal with large changes in geometry and have resolution approaching 1 mm. To accomplish this, several sets of flat, adhesively-bonded specimens, representative of automobile flanges, have been generated by the OEMs and adhesive suppliers to test the feasibility of NDI techniques to assess bond area and bond-line thickness. The specimens vary in adhesive and adherent, type and thickness, stackup (2-3 layers), and cure state. A through-transmission ultrasound inspection was performed to characterize the specimens. The inspection images will be used as a gold standard to compare results from candidate inspection technologies such as pulse-echo ultrasound and pulsed thermography which can be deployed from one side of the flange. The specimens will be peeled destructively and photographs of the samples will also be compared with the inspection images. Similarly, weak-bond specimens will be manufactured for bond-strength quantification testing, which is the goal of the second and third years of the project. In addition, multiple automobile bodies-in-white (BIW) containing a number of adhesive joints were produced by the OEMs to determine whether complex geometry provides any inspection impediments and to provide a test-bed for the validation of promising inspection techniques.

Accomplishments

Pulsed-thermography and pulse-echo-ultrasound inspections of the adhesively-bonded specimens are currently in progress and preliminary results are encouraging. A pulse-echo ultrasonic linear-array scanning system is being developed and promises to reduce flange inspection time by deploying several small ultrasonic transducers placed in a single scanning probe. High-speed pulsing combined with rapid data capture permits the linear array to be quickly moved over the structure. Several promising techniques for assessing weak bonds have been identified. They include vibrothermography, angle-beam ultrasonic spectroscopy, nonlinear ultrasonics, and laser shock peening.

Future Direction

Pulsed-thermography and pulse-echo-ultrasound inspection results will be compared with the through-transmission ultrasound inspection images and photographs of the samples after a destructive peel test. The inspection technologies will then be adapted to accommodate the complex geometry of production components, eliminate any surface treatments currently needed to improve inspectibility, and reduce overall system cost. Weak adhesive-bond specimens will be fabricated and testing of promising inspection techniques identified in the first year for assessing weak bonds, will follow.

Introduction

Adhesive bonding is increasing every year as automotive manufacturers strive to make bodies stiffer and stronger. Recent applications see as much as 30 to 100 m of adhesive per vehicle being used. Adhesive joining is already widely used in automotive production today for improving body stiffness and durability where needed. Current quality control of these joints relies primarily on the robust control of the adhesive preparation and application. These controls include machine-vision inspection of the applied adhesive bead. However, there is no method available to test the overall quality of the final joints other than destructive testing. This lack of verification especially limits adhesives being used to meet crash-performance requirements. Adhesives are also seen as a critical enabler for the joining of dissimilar materials in order to avoid corrosion.

Adhesive joining is seen as a major weight-saving technology. When adhesives are used in combination with spot-welds or rivets, the resulting joints are much stiffer and stronger. Almost a doubling of shear strength has been produced in weld-bonded joints when compared with spot-welds alone. Moreover, by enabling dissimilar materials to be used in close proximity to each other, assemblies can be constructed with optimized, lightweight materials such as magnesium and aluminum joined to lower-cost steels.

A major strategy of this project is to leverage the many decades of development in the aerospace sector devoted to the nondestructive inspection (NDI) of adhesive joints. NDI is now commonly used in aerospace manufacturing involving adhesive joints, especially for composite panel joining. Entire structures are being inspected. Some of the NDI methods are also being used in routine, in-service aircraft inspections.

Within the automotive manufacturing arena, the inspections are especially needed in the body shop before the adhesive is cured. This is the most likely place within the manufacturing process where discrepant joints would be repaired. However, inspections are also needed at the end of line to ensure the quality of the entire assembled, cured, and painted product. NDI inspections are also seen as a major cost savings for accelerating engineering and environmental testing, ramp-up to production, and monitoring the long-term performance of the joints.

Coupon Preparation and Characterization

Several sets of flat, adhesively-bonded specimens, representative of automobile flanges, have been generated by the automotive OEMs and adhesive suppliers to test the feasibility of NDI techniques to assess bond area and bond-line thickness. The specimens vary in adhesive and adherent, type and thickness, stack-up (2-3 layers), and cure state. These were designed to include many of the variations that can occur in production. Multiples of the same conditions are made to allow parallel testing with different nondestructive and destructive methods early on. An example of the coupons prior to assembly is shown in Figure 1 showing the wire spacers used to control the adhesive thickness, intentional skips, and a section of Teflon tape to simulate a kissing bond. Most of these have also been spot-welded using typical production equipment and weld schedules.

Figure 1. Coupons prior to assembly.

All the coupons have been nondestructively characterized using a lab-only method of ultrasonic through-transmission in an immersion tank. The transmitted signal strength allows the areas where all interfaces in the stack are wetted to be imaged (Figure 2a). Using the experimentally-measured speed-of-sound for each adhesive in its state-of-cure, a map of the adhesive thickness is simultaneously measured (Figure 2b).

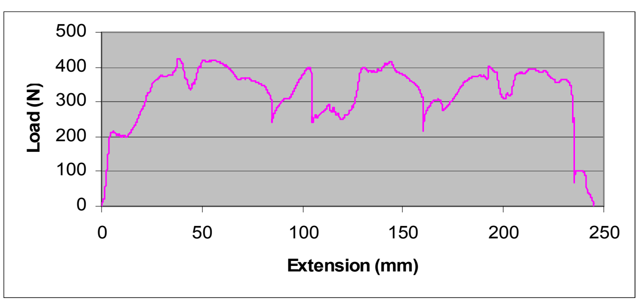
a) Ultrasonic transmission intensity.

b) Ultrasonic thickness measurement.

Figure 2. Ultrasonic characterization of a 600-mm-long weld-bonded coupon.

The results of a destructive peel test on a 2-layer coupon are shown in Figure 3. This shows the effect of varying bead width on the strength of the bond.

a) Peeled coupons.



b) Peel force along coupon.

Figure 3. The peel-force trace and resulting sample faces for a 2-layer coupon with skips.

Determining Adhesive Area and Bond-Line Thickness

Candidate NDI technologies such as pulse-echo ultrasound and pulsed thermography, which can be deployed from one side of the flange, are currently being used to inspect the coupons described above and automobile bodies-in-white (BIW) containing a number of uncured adhesive joints.

Pulsed Thermography

Basic Description:

This technology uses thermal gradients to analyze the physical characteristics of a structure such as internal defects. This is done by converting a thermal gradient into a visible image by using a thermally-sensitive detector such as an infrared (IR) camera. A heat source, such as flash lamps, is used to raise the surface temperature of the structure. As the heat diffuses through the structure, the surface temperature is monitored for a period of time by an infrared camera. Areas that appear hotter or cooler than normal may indicate the presence of a flaw beneath the surface that is preventing or assisting heat diffusion into deeper layers. By using a computer to analyze the infrared data captured over time, subtle variations can be enhanced in the image. By plotting the log of temperature versus time, quantitative adhesive bond-line thickness measurements can be obtained.

Figure 4 illustrates a pulsed thermography inspection performed on a BIW truck-floor assembly having uncured adhesive areas. Note that the flash lamps which are not visible in Figure 1 are located within the rectangular shroud just below the IR camera.

Figure 5 is an infrared image indicating the presence of adhesive (adhesive area) from one location of the truck-floor assembly.

Temperature-versus-time plots were generated and shown in Figure 6 for each of the square cursors areas depicted in Figure 5. The cursor located at the top of Figure 5 is positioned in an area where adhesive was omitted. The middle and bottom cursors are located in the bond area.

Figure 4. Pulsed-thermography inspection of a BIW truck-floor assembly.

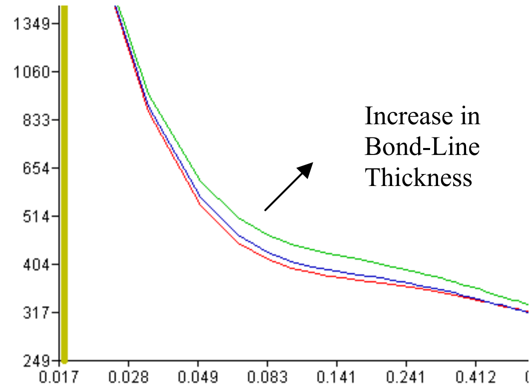


Figure 6. Log of temperature vs. log of time depicts thickness variations.

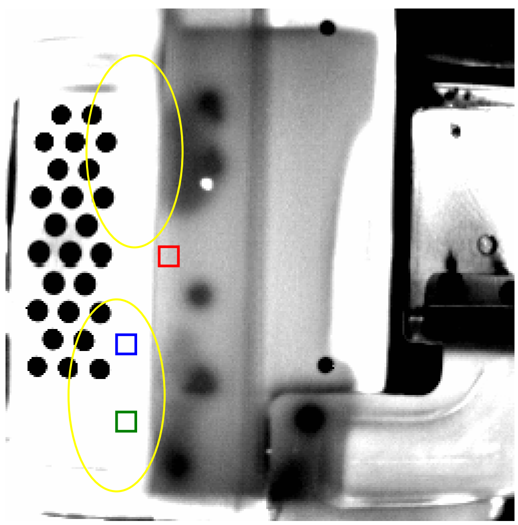


Figure 5. Pulsed-thermography-inspection image (0.868 sec after flash).

While Sandia National Laboratories is conducting pulsed-thermography inspections of BIW vehicles, similar inspections of the flat, adhesively-bonded specimens are being conducted concurrently at Thermal Wave Imaging Inc.

Unfortunately, the high optical reflectivity and low infrared emissivity of aluminum and steel typically prohibits a successful pulsed-thermography inspection. Only by the application of a surface treatment to the material (e.g., flat- black washable paint) will a pulsed thermography inspection become feasible. The painted material will improve the absorption of light (heat) from the flash lamps and the material will reradiate effectively as it cools. An investigation will be performed in the next few months to determine whether the technique can be modified to eliminate the surface-treatment step.

Pulse-Echo Ultrasonics

Basic Description

Short bursts of high-frequency sound waves are introduced into the material for the detection of surface and subsurface flaws in the material. The sound waves travel through the material with some attendant loss of energy (attenuations) and are reflected at interfaces. The reflected beam is displayed and then analyzed to define the presence and location of flaws. Complete reflection, partial reflection, scattering, or other detectable effects on the ultrasonic waves can be used as the basis of flaw detection. In addition to wave reflection, the time of transit through the test piece can be used to assess bond-line thickness.

Pulse-echo ultrasonic inspections of the flat adhesively bonded specimens are currently being performed at Lawrence Livermore National Laboratories, New Mexico State University, and Sandia National Laboratories.

Figure 7 illustrates a probe holder which houses a 17-MHz linear-array ultrasonic transducer. The probe holder has been designed specifically for the inspection of long and narrow flanges. The probe holder which is made of polycarbonate is approximately 1.5” wide by 3.5” long. Wheels facilitate the movement of the probe and probe holder over the flange and the holder can travel in both forward and backward directions. The angled inlet port is used to supply water below the probe to couple the sound generated by the ultrasonic probe to the part. The two vertical ports are used to vacuum excess water from the part. An encoder is attached to the rear wheel and it is used to track the displacement of the probe. The linear array system is currently being tested at Sandia National Laboratories.

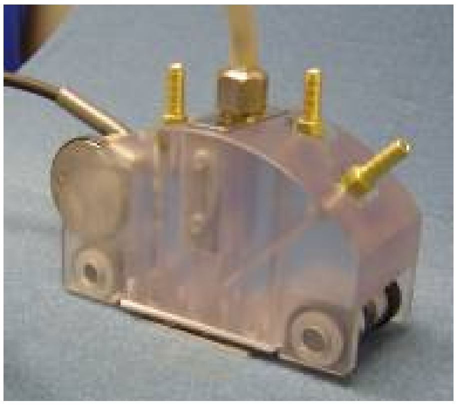


Figure 7. 17-MHz ultrasonic linear probe and custom probe holder.

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[i] Denotes Project 601 of the Nondestructive Evaluation (NDE) Working Group of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research set up by the "Big Three" traditionally U.S.-based automakers to conduct joint pre-competitive research and development.