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Nondestructive Structure Characterization by Laser-Ultrasonics

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ABSTRACT

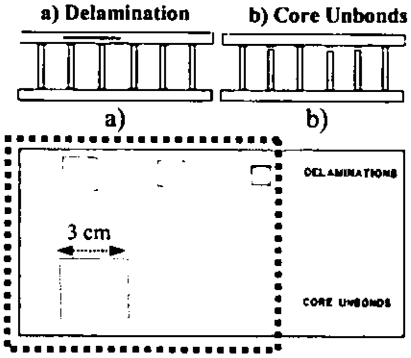
The evaluation of bonding quality is critical for many applications. This paper presents results of bonding assessment of foam-based sandwich structures and porous coatings using the laser-ultrasonic technique and the newly developed laser tapping technique. Laser-ultrasonics and laser tapping are nondestructive, non-contact techniques using lasers to generate and detect ultrasonic pulses and acoustic modes in a very large ultrasonic bandwidth. In laser-ultrasonics, the intensity of the echo is used to monitor the bonding quality at the foam/sheet interface. In laser tapping, disbonded layers are set into vibrations like a membrane by the thermal stresses induced by laser heating at the material surface. Laser-ultrasonic and laser tapping results obtained on honeycomb structures, and foam-based sandwich structures and coatings show the capability of both techniques for the bonding assessment on such structures.

INTRODUCTION

Metallic foams and porous metals have been used in composite structures for different applications to obtain, for example, structures with high stiffness, good thermal and environmental stability. Porous metallic coatings have also been used in different applications such as orthopedic implants, heat exchangers and electrodes to name a few. For those applications, the quality of the bonding between the metallic foam or porous metal and the solid substrate is very important. This bonding determines the mechanical, thermal and electrical properties of the construct and consequently the performance and reliability of the device. Therefore, probing those structures can be critical to assess the quality of newly produced parts and to track detachments that could develop during service.

Two techniques have been tested in this work: the laser-ultrasonics and the laser tapping techniques. Laser-ultrasonics is based on the reflection of ultrasonic pulses at the substrate-porous material interface, and the laser tapping technique is based on the monitoring of the low frequency vibration modes of the detached area.

As an example, both techniques were successfully applied to the inspection of aluminum honeycomb structure sandwiched between two carbon epoxy skins, shown in Figure 1 [1]. Delaminations within the carbon epoxy skins as well as honeycomb-skin unbonded areas were artificially introduced in the part.



c)

Figure 1. Schematic representation of a) a delamination within the composite skin and b) honeycomb-skin core unbonds. c) Picture of the part including the scanned area (dotted line) and the locations and sizes of the defects.

Results obtained with the laser-ultrasonic and laser tapping techniques are shown in Figure 2. The horizontal dimension of each scan was about 14 cm. With the laser-ultrasonic technique, the delaminations within the skin are clearly seen but the core unbonds between the skin and the honeycomb are not. With the laser tapping technique, both types of defects are clearly detected, which shows that the technique is well suited for unbond detection. Indeed, defects not intentionally produced in the part were also detected. Not surprisingly, the laser tapping image also reveals the honeycomb cell structure, which can be seen as a set of detached membranes.

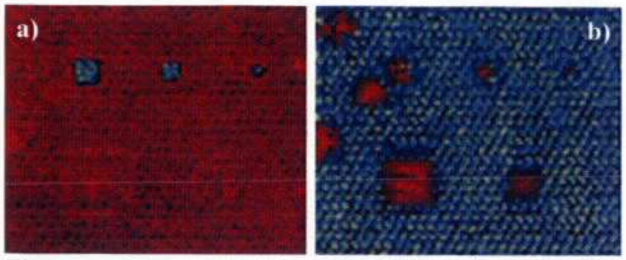


Figure 2: a) Laser-ultrasonic and b) laser-tapping images of the honeycomb part shown in Figure 1.

EXPERIMENTAL PROCEDURE

Material

Aluminum foam sandwiches with artificial defects were fabricated. Two sandwich structures were produced by adhesively bonding a 1 cm thick aluminum foam between two aluminum plates of 0.5 and 1.5 mm thicknesses. The aluminum foam (Alporas) has a density around 0.3 g/cm^3 and pore sizes varying between 1 mm and 10 mm. The aluminum sheets were bonded with the foam using a single-part heat cured toughened epoxy resin adhesive (Bondmaster ESP310). A bonding defect was produced by leaving a 25 mm diameter circular spot without adhesive. Figure 3a presents pictures of the side and front views of the aluminum foam sandwich. The unbonded area is indicated by a circular mark.

Tests were also done on the sample shown in Figure 3b and composed of a nickel foam (0.32 g/cm^3, 1.9 mm thick, INCO) diffusion bonded (1300°C for 2h in Ar-50%H_2) on a thin nickel sheet (0.15 mm, INCO). The laser-ultrasonic and laser tapping inspections were made from the porous and dense sides.

The two inspection techniques have also been used to monitor the quality of porous titanium coatings on acetabular cups. The foam was produced using the process described in [2]. Two cups coated with 1.5 mm thick titanium foam of different porosity were produced to evaluate the effect of the microstructure on the detected signal. One cup had fine pores uniformly distributed on the surface of the cup (Figure 3c) while the other had larger pores not uniformly distributed on the surface (Figure 3d). The titanium foam coating is about 1.5 mm thick. A boron nitride (BN) layer of about 2 cm diameter was also deposited on the surface of one titanium cup (Figure 3d) prior to the deposition of the foam to reduce the quality of the bonding at one location, thus creating an artificial defect. Both the laser excitation and detection beams were impinging on the porous surface of the cups.

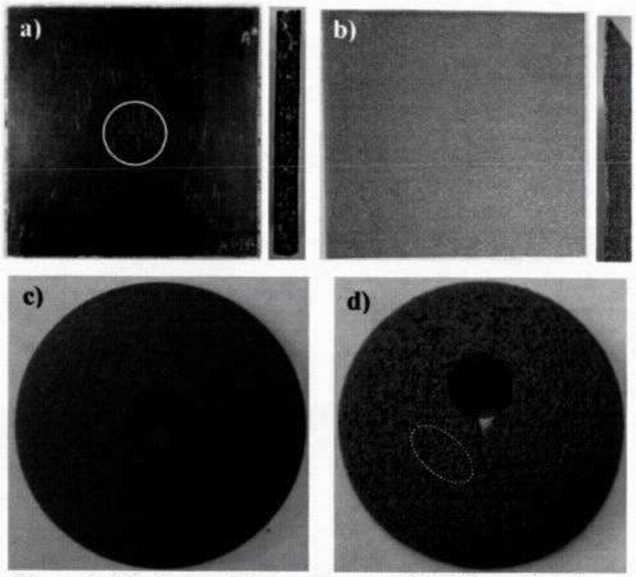


Figure 3: Pictures of the parts probed in this work: Front and side views of an aluminum foam sandwich (a) and of a thin nickel foam on a thin nickel strip (b), Titanium acetabular cups coated with a 1.5 mm thick titanium foam of uniformly distributed fine pores (c), and non uniformly distributed larger pores (d). The circle on (a) and (d) indicates the location of unbond areas.

Laser-ultrasonic setup

The excitation laser is a CO_2 TEA laser, which delivers 100 pulses of 120 ns duration per second at 10.6 μm wavelength. The laser light absorbed on the part surface simultaneously generates ultrasonic pulses that propagate in the materials, and makes detached areas to lift up and vibrate nearly like a membrane clamped at its edges. The excitation mechanism is purely thermoelastic and non-damaging. The detection of small surface movements created by the ultrasound or the membrane vibrations is performed by a single frequency Nd:YAG laser which delivers pulses of 65 μs duration at full width half maximum at a 1.064 μm wavelength. The detection laser light scattered off the material surface is sent to a Confocal Fabry-Perot interferometer for the laser-ultrasonic measurements, and to a two-wave mixing-based photorefractive adaptive interferometer [3] for the laser tapping measurements. The generation and detection laser beams were scanned on the part surface with a 1 mm step size along both X and Y axes. The scanning system is of stop-and-go type, and stops for each interrogation point. The two laser spot diameters on the part surface are about 2.5 mm. The beams were collinear and overlap so that generation and detection are performed at the same location. The laser-ultrasonic pulses are in the 1 to 10 MHz frequency range. Vibration frequencies detected by laser tapping are more likely to be in the 20 kHz to 1 MHz range depending on the material properties and detachment dimensions. The low frequency cutoff of the photorefractive interferometer was then adjusted to 15 kHz, which means a grating build up time of about 10 μs, by properly setting the optical pump power of the interferometer.

RESULTS

Aluminum foam sandwich

Figure 4 shows laser-ultrasonic images obtained on the 0.5 mm thick plates aluminum foam sandwich. The unbonded region is clearly visible on the scan made from the side with an unbonded area (Figure 4a), while no contrast is observed on the opposite well bonded side (Figure 4b). The dimension of the central spot in Figure 4a is about 2.5 cm, as expected.

In the laser tapping images, the unbonded area can be seen but appears smaller and less defined, as shown in Figure 5. The system was not optimized to detect the low frequency of such a large defect. A system equipped with a detection laser delivering longer pulses and a lower cut-off frequency for the interferometer would make the detection of such defects easier.

Scans made with both techniques on the 1.5 mm thick plates aluminum foam sandwich are shown in Figure 6. Both techniques clearly reveal the unbonded region. The laser tapping image is much clearer in this case since the thicker plate results in a higher fundamental vibration frequency, which lies in the detection bandwidth of the system. It should be added that the fundamental vibration frequency is proportional to the thickness of the membrane and to the inverse of the square of the diameter of the unbonded region. This vibration frequency can then be used to estimate the size of the defect without any scanning of the part.

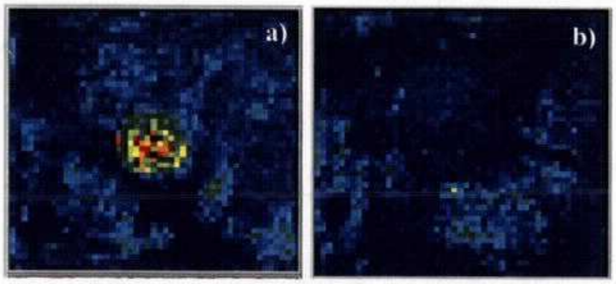


Figure 4: Laser- ultrasonic images taken from the sides a) with and b) without an unbonded area of the 0.5 mm thick plates aluminum foam sandwich.

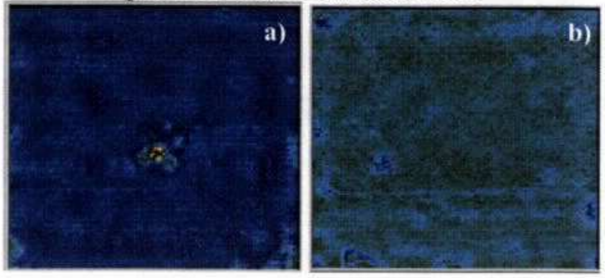


Figure 5 : Laser tapping images taken from the sides a) with and b) without an unbonded area of the 0.5 mm thick plates aluminum foam sandwich.

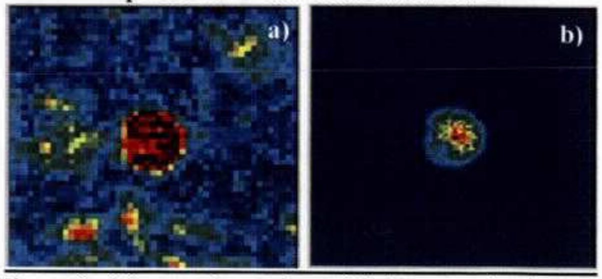


Figure 6: a) Laser-ultrasonic and b) laser tapping images obtained on the 1.5 mm thick plates aluminum foam sandwich.

Diffusion bonded nickel foam

Figure 7 shows laser-ultrasonic images obtained with the laser scanned on the porous (7a) and dense (7b) sides of the sample made of a diffusion bonded nickel foam on a thin nickel sheet. Note that the image from the dense side was flipped to ease image comparison. Only little similarities are observed on the images taken on the different surfaces.

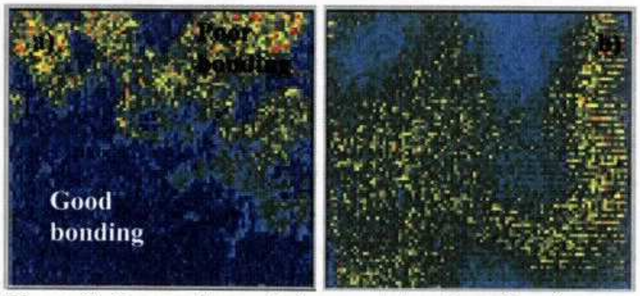


Figure 7: Laser-ultrasonic images taken from the a) porous side and b) dense side of the sample with a diffusion bonded nickel foam.

Figure 8 presents the images obtained using the laser tapping technique, with laser impinging on the porous (8a) and dense (8b) sides respectively. Both images show similar features. This suggests that laser tapping can be used to evaluate the bonding from either the porous or the dense side. Similar features appear in Figures 8 and Figure 7a. The laser-ultrasonic image of Figure 7b, taken from the dense side, does not reveal the region of poor bonding because the highly porous nickel strip has little effects on the reflection of the ultrasonic pulse at the foam/strip interface. The contrast in Figures 7 and 8 was successfully confirmed to be due to bonded and unbonded areas by intentionally producing a detachment between the foam and the sheet and by rescanning the part.

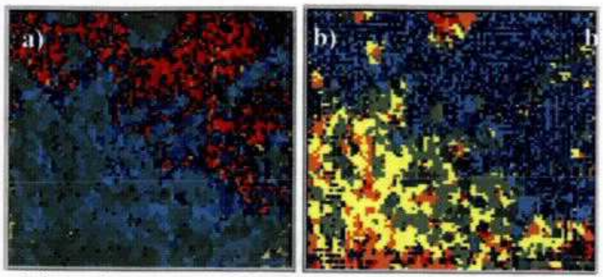


Figure 8 : Laser tapping image taken on a) porous side and b) dense side of the sample with a diffusion bonded nickel foam.

Titanium acetabular cups coated with porous titanium foam

Figure 9 presents images obtained on the acetabular cups by both laser-ultrasonic pulse echo and laser tapping techniques. Laser excitation and detection beams were impinging on the porous surface of the cups. As expected, the signals were highly affected by the foam microstructure, dominated by the pore size. The large pore foam strongly attenuated the ultrasound in the MHz range and, not surprisingly, no significant signals were obtained with the laser-ultrasonic pulse echo technique. Figure 9a shows the laser tapping image obtained on the large pore foam coated cup with the artificially unbond area. Indeed, the upper portion of the scan shows many bright spots coming from the large pores in the structure, while the lower portion is much more uniform and corresponds to a uniform structure with a smaller pore size. The area encircled in Figure 9a represents the portion where the BN coating was applied. A contrast is observed, but is not very good. This low contrast may however be due to the reaction between BN and titanium during sintering that could have restored a sufficiently good bonding.

Figure 9b and 9c shows the laser tapping and laser-ultrasonic pulse-echo images obtained on the cup with uniformly distributed fine pores. A small defect seen with both techniques is indicated by an arrow on the images. The contrast is however better in the laser tapping image. This defect is not visible on the surface of the cup. It can be attributed to an area of larger pores in the coating, to a badly bonded area or to metallurgical artifacts. Additional measurements should however be done with other techniques or by destructive metallography to properly identify the nature of the defect.

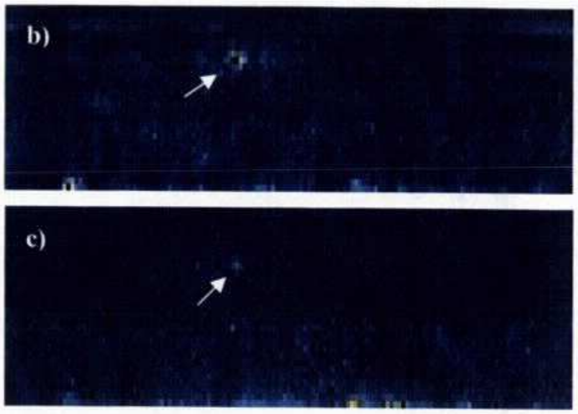


Figure 9: a) Laser tapping image on the large pore non-uniform coating. The dotted circle indicates the artificially produced unbonded area. b) Laser tapping and c) laser-ultrasonic images on the fine pore uniform coating.

CONCLUSION

Laser-ultrasonic pulse-echo and laser tapping techniques have been used to detect detachments between the sheet and the foam coating in metallic foam sandwiches and foam porous coatings. Experimental results on such coatings and sandwich structures with and without bonding defects show that the methods can be used on highly porous materials. Inspection can be done on both the porous and dense sides. The two techniques use the same hardware but are based on different acoustic mechanisms and operate in different frequency ranges. Both techniques provide a non-contact, nondestructive means to assess the bonding integrity of foam based sandwiches and coatings. The techniques require no surface preparation and can be used to optically scan flat or curved shape parts.

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