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Laser Ultrasonics as an Alternative Inspection Method to Detect Microstructural Flaws in Aerospace Structures and Engines Manufactured by Advanced Metallic Material Processes

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Abstract
Advanced metallic material processes are used or developed for the production and the reparation of heavily loaded flying components. The inspection of these parts mainly made out of Titanium requires the determination of the percentage of bonded grain or the search for isolated defects which take the form of voids of different sizes around 10 to 30 µm or more, or gaps ranging from the intimate contact to disbond up to 20 µm. Ultrasonic techniques have the greatest potential for defect detection and sizing, unfortunately the smallest defect size can be much less than the wavelength of conventional ultrasound. Therefore, it has led us to use higher frequency equipments from 50 up to 150 MHz, point focusing transducers, signal processing techniques and high resolution mechanical scanning rigs. For a few years, a large amount of work has been carried out on ultrasound generated by pulsed laser, particularly in metallic materials such as aluminium and then in non metallic materials such as composites. Results using a picosecond pulsed laser have enabled to offer an alternative for the inspection of complex geometry parts. High ultrasonic frequencies can be generated and detected, supported by Fourier domain Synthetic Aperture Focusing Technique processing. Developments and comparative tests have been carried out to evaluate the potential of this method.
Keywords: Laser ultrasound, SAFT, welding, aerospace.

1. Introduction

A particular evolution of nondestructive testing in the last thirty years is that aircraft manufacturers have to fulfil the inspection of the materials they transform to make parts that can fly. The inspection of next generation aircrafts is a great challenge due to the fast increasing number of parts made of various materials with complex geometries. These new components are the result of new manufacturing technologies and metallic materials, such as super plastic forming and diffusion bonding of titanium and aluminium metal sheets (SPFDB), which are challenging the composite material processes such as resin transfer moulding (RTM). The particular problem which arises in SPFDB processing of titanium alloys is the development of defects at the bond-line which take the form of voids of different sizes, with a gap ranging from intimate contact up to 20 µm. The inspection requires the determination of the percentage of bonded grains, rather than the search for isolated defect [1].

Ultrasonic techniques have the greatest potential for defects detection and sizing in diffusion bonds. However, the smallest defect size can be much less than the wavelength of conventional ultrasound, therefore it has led us to look for higher frequency equipments from 50 up to 150 MHz, point focusing transducers, signal processing techniques and high resolution mechanical scanning rigs. For a few years, a large amount of work has also been carried out on ultrasound generated by a pulsed laser, particularly in metallic materials such as aluminium and titanium, and in non metallic materials such as carbon-epoxy composites [2]. Laser ultrasonics provides the benefits of being much more flexible with respect to the part geometry and of high frequency ultrasound generation and detection. These former developments are now being applied to the inspection of parts manufactured by advanced metallic material processes such as Direct Laser Manufacturing (DLM), Laser Beam Welding (LBW), Friction Stir Welding (FSW) and Electron Beam Welding (EBW) and parts repaired by Electron Beam Welding (EBW) and Laser Beam Welding (LBW). The inspection of these components requires the detection of tiny and various defects in the range of 10 µm, therefore very sensitive nondestructive methods are investigated such as acoustic microscopy, X-ray computed tomography and high frequencies laser-ultrasonics to tackle complex geometry parts. Development and comparative tests have been carried out to evaluate the potential of these methods as well as up to date sensitive eddy current techniques.

2. Reference Samples

In order to calibrate the different methods and to set up their performances, reference defects have to be manufactured. Obtaining representative and reproducible defects has always been a major issue; it is particularly the case for the targeted parts, as the limits of the manufacturing methods have been reached. Two approaches have been considered: the manufacturing of real defects and of flat bottom holes (FBH). The first approach has not been successful and does not seem feasible. A defect has been obtained directly by diffusion bonding of two titanium plates in which one plate had FBH filled with stop-off. However, only a 0.5 mm diameter defect was remaining, and smaller size defects could not be achieved. Pollution of the surface as well as high surface roughness has led to a poor bond line. The FBH approach calls for defect manufacturing by electroerosion. Defect diameter as small as 30 µm has been obtained, however their depth is limited to 25 µm and the bottom is not quite flat; also a 10 µm diameter FBH could not be made. Laser drilling will be investigated for smaller and deeper defects.

3. Results with different techniques

3.1 Acoustic Microscopy

Acoustic microscopy starts where conventional ultrasound end, around 25 MHz. Some applications can reach frequencies in the GHz domain. However, the smallest defect size expected and the attenuation of ultrasound in air and in the material have led us to use frequencies ranging from 50 up to 150 MHz, highly focussed transducers, signal processing techniques (SAFT) and high resolution mechanical scanning rigs. Specific transducers with the piezoelectric sensitive element made either of quartz or PVDF polymer have been used. Quartz piezoelectric elements have a good sensitivity of about (-30 dB) but requires adaptive delay-lines with the main disadvantage of reflection echoes in the silica delay-line structure generating noise. PVDF transducers do not have delay-line but their sensitivity is poor (-70 dB). Typical C-scans obtained with a 60

MHz quartz transducer having a 12.5 mm focal length in water, and mapped with acquisition steps ranging from 0.01 mm to 0.1 mm are shown in Figures 1 and 2.

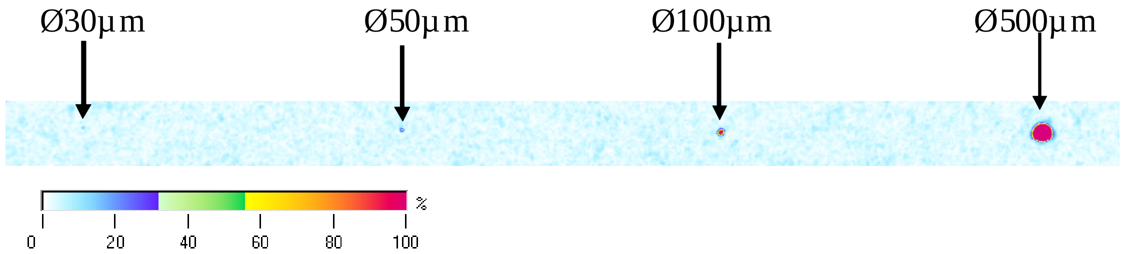

Figure 1. Acoustic microscopy images of FBHs in a 3 mm thick titanium sample at 60 MHz.

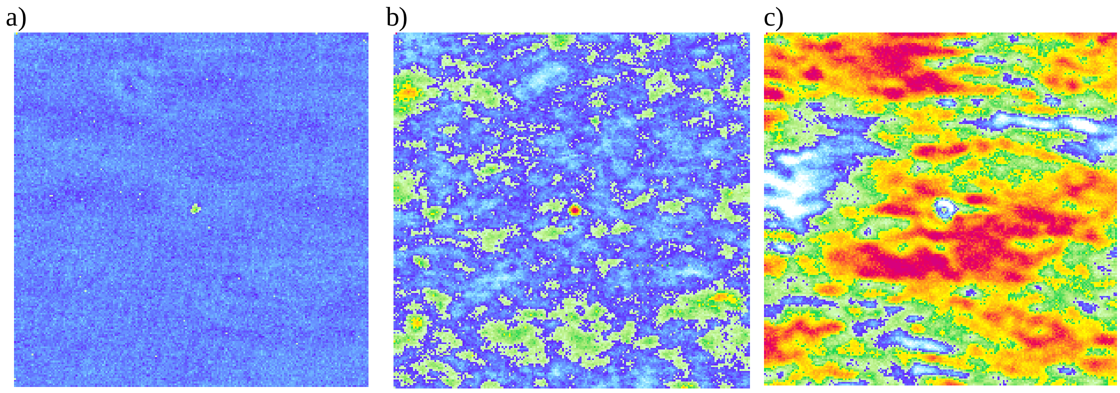

Figure 2. C-scans over a 30 µm FBH in a 3 mm thick titanium sample obtained by acoustic microscopy at 60 MHz. The pulse echo C-scans are located at a depth of a) 1.25 mm, b) nearly 3 mm and c) 3 mm, imaging the backwall echo.

As shown in figures 2, acoustic microscopy with ultrasonic frequencies as low as 60 MHz enables the detection of flat bottom holes of 30 µm diameter and even of smaller size. However, acoustic microscopy is very sensitive to surface aspect; usually surfaces are polished down to a RA better than 0.8.
A specific phenomenon appears on samples repaired by Electron Beam Welding (EBW) and Laser Beam Welding (LBW). The C-scan obtained from the measurement of the attenuation of the backwall echo in Figure 2c shows the metallurgical structure resulting from the process which masks the isolated defects. The limitation of the actual technique is that it does not enable the detection of defects close to the top and bottom surfaces due to the dead zone (width of the front wall and back wall echoes). Work is undertaken to reduce this dead zone, firstly by using higher frequencies and secondly by signal processing.

3.2 Laser ultrasonics

Laser ultrasonics is a non-destructive technique that uses lasers to both generate and detect ultrasound. Laser ultrasonics operates without contact and at a distance from the materials and can be used on surface of complex geometry. Also relevant to this application, the laser-ultrasonic frequency content is determined by the laser pulse duration and can easily extent in the few hundred MHz range. The laser-ultrasonic setup used for these tests is shown in Figure 3. The sample was a 2.88 mm thick titanium plate with 30, 50 and 100 µm diameter FBHs drilled on it. The laser spot sizes on the titanium plate are about 50 µm diameter. Laser-ultrasonic frequencies up to 150 MHz are generated and detected, corresponding to wavelengths larger than 40 µm in titanium. Two-dimensional laser-ultrasonic scans were taken above the FBH and the laser-ultrasonic data was then processed by a Fourier domain SAFT algorithm [3]. The results are shown in Figures 4 and 5.

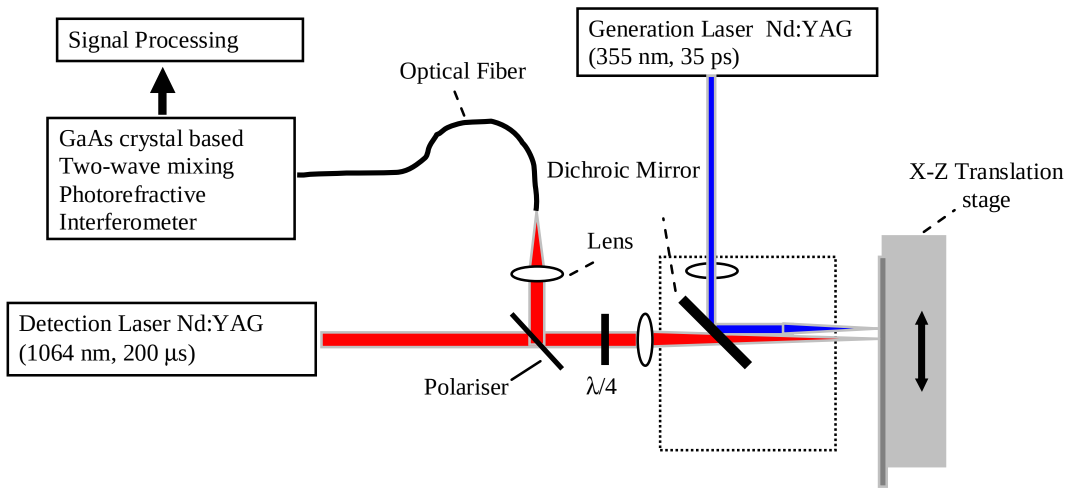

Figure 3. Laser-ultrasonic setup.

Figure 4 shows C-scans, B-scans et profiles for holes of a) 100 µm diameter, 100 µm depth, b) 100 µm diameter, 250 µm depth, c) 50 µm diameter, 250 µm depth. The scan step size is 50 µm and the total scan size is 5 mm x 5 mm. All the FBHs are properly detected with a good signal-to-noise ratio as shown in the profiles. The 100 µm diameter FBH are properly sized while the 50 µm appears larger to a size of about 85 µm. Figure 5 shows C-scans, B-scans and profiles for holes of a) 50 µm diameter and b) 30 µm diameter, both of 250 µm depth. The scan step size is 50 µm and the total scan size is 3 mm x 3 mm. The 50 µm diameter FBH is seen with a better signal-to-noise ratio than in Figure 4c. This FBH is also better sized with a measured diameter of 75 µm. Ultrasonic image of the top of the 30 µm diameter FBH is not visible, only the shadow of this hole can be seen using the echo in the bottom of the part. However, no bottom echo is expected from a properly welded interface. It is expected that 30 µm FBHs can be detected using a laser ultrasonic detection system with a broader frequency bandwidth. Detection of smaller size defects is possible, but ultimately limited by the attenuation due to ultrasonic scattering by the titanium grain size. As acoustic microscopy, laser ultrasonics presents a dead zone that forbids the detection of defects located near the inspected surface. Again, a broader frequency bandwidth is expected to reduce this dead zone within 30 µm of the inspected surface. A slight but acceptable

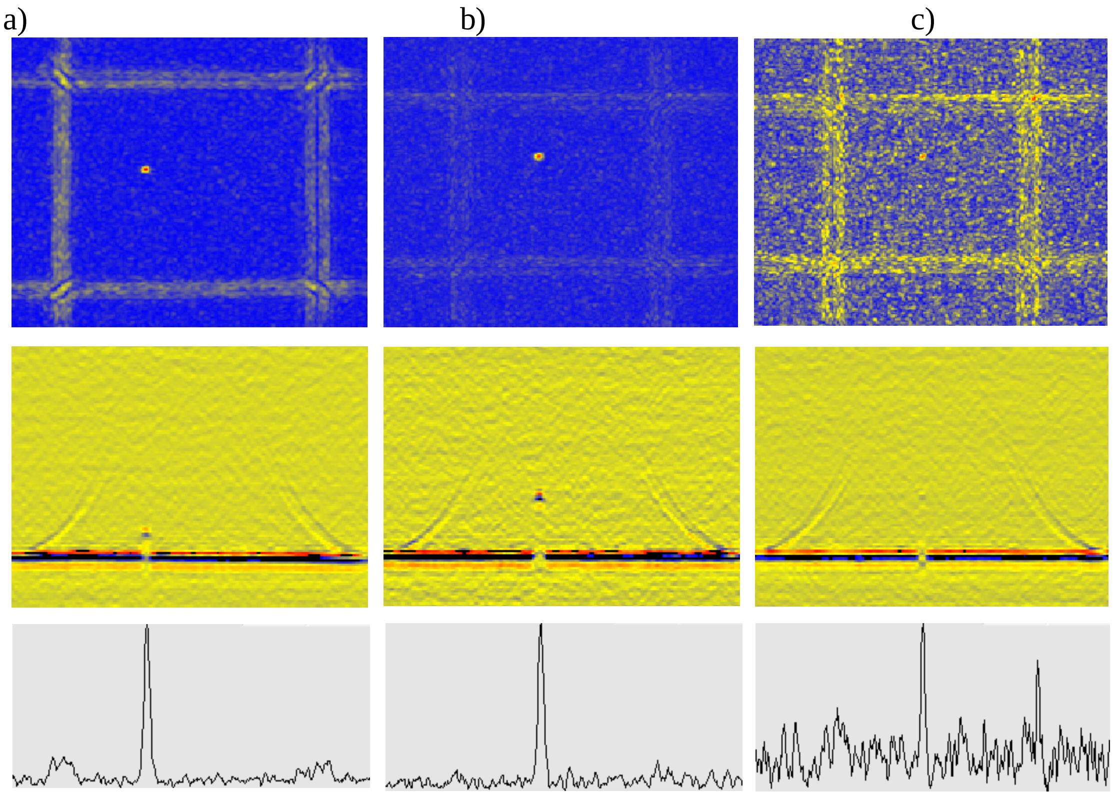

Figure 4. Laser-ultrasonic C-scan (top), B-scan (middle) and profile (bottom) for FBHs of a) 100 µm diameter, 100 µm depth, b) 100 µm diameter, 250 µm depth, c) 50 µmdiameter, 250 µm depth. The scan step size was 50 µm and the total scan size is 5 mm x 5 mm.

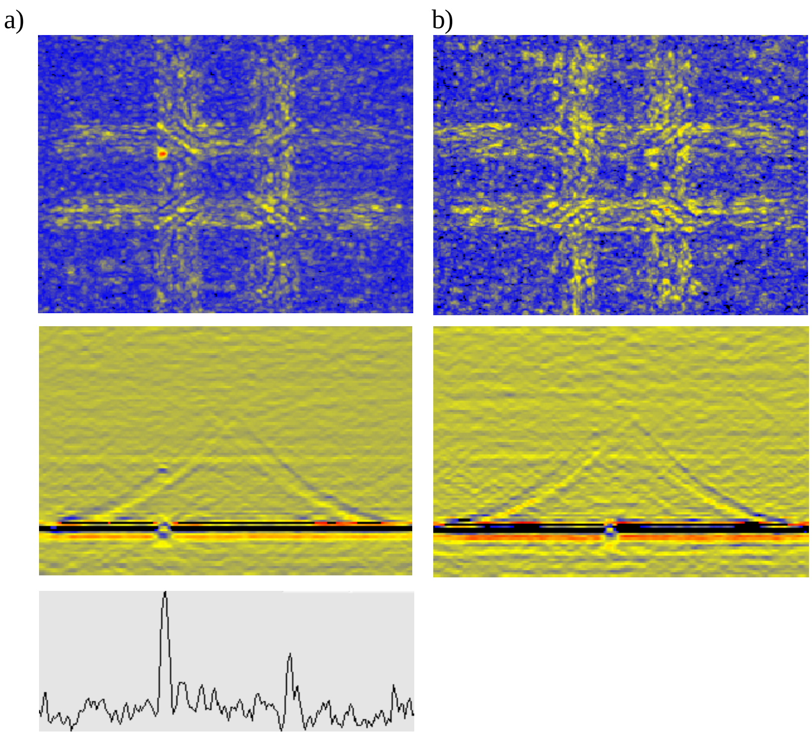

Figure 5. Laser-ultrasonic C-scan (top), B-scan (middle) and profile (bottom) for FBHs of a) 50 µm diameter, 100 µm depth, b) 30 µm diameter, 250 µm depth, c) 50 µm diameter, 250 µm depth. The scan step size was 25 µm and the total scan size is 3 mm x 3 mm.

drawback of laser ultrasonics is that small marks are left on the surface by laser ablation. If not acceptable, the scan can be made in the thermoelastic regime with the drawback of a lower signal-to-noise ratio.

3.3 Eddy current

A theoretical and experimental study was carried out by the GREYC Group of the University of Caen in France. The experimental set-up used a standard eddy current detection system, however the probes were giant magnetoresistors integrated by the GREYC group [4]. Specific FBHs were drilled in the reference sample, with the diameter equal to the depth of the simulated defect. The results were disappointing with respect to the simulation, only the 1 mm^3 FBH could be detected.

3.4 X-Ray Computed Tomography

Computed tomography with micro and nano focus systems has been used to detect similar defects. Good results and good correlation have been obtained on the tested samples, however its application is too cumbersome for the real parts targeted.

4. Conclusion

FBHs of diameter down to 30 µm have been detected by acoustic microscopy. FBHs of diameter down to 50 µm have been detected by laser ultrasonics and only FBHs of 100 µm have properly located and sized. Better signal-to-noise ratio and higher frequencies are required to see such small defects and are now investigated. Signal processing will also be used to improve the temporal resolution to detect the defects close to the surface and to distinguish them from the structural noise. While X-ray computed tomography can be of a valuable help, eddy currents do not seem appropriate for that type of defect. The investigation of available inspection methods for the detection of defects as small as 10 µm will help tackling the challenges provided by the new metallic material processing technologies.

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