

Non-Destructive Testing by Ultrasonic and Thermal Techniques of an Impacted Composite Material

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Abstract— The aim of this work is to control the state of the structure of a composite material after low velocity impact. In fact, the impact damage is one of the most critical flaws that can reduce the intrinsic characteristics of a composite structure drastically. The diagnostic of composite laminates in this case will be very difficult, because during impact several modes of failure appear (matrix cracking, delamination and fiber breakage), and it can be often not visible on the surface. For this reason it will be necessary to use the non-destructive techniques (NDT) of control to make sure of the state of the material without damaging it. This paper presents some methods of control to detect and characterize defects appeared after low velocity impact on a hybrid composite plate of epoxy resin reinforced with carbon fiber. The methods used in this work are considered among the most used in the control of composite material. Indeed, each technique has advantages and disadvantages. Therefore, the use of several control techniques ensures the diagnosis, so we talk about the complementarity of techniques. For this reason, the following methodology is followed. First of all, a quick and general control is performed of the whole specimen to designate the damaged area using the infrared technique. After that, the ultrasonic technique (phased array) is performed in the previously localized area for finer results. Finally, for validating the precision of the results obtained by the ultrasonic technique a metallurgy study is used. The methodology followed in this work will allow us a fast and precise control.

Keywords— composite laminates; low velocity impact; diagnostic; NDT; Infrared; ultrasound; metallurgy.

I. INTRODUCTION

The damage, impact is one of the most found defects in composite structure, it represents around about 80% in service damages [1]. The low-velocity impact, the origin of which is due to the fall of tools during the manufacturing phase or in the use. It can drastically reduce their residual characteristics while leaving a mark often not visible on the surface [2], [3]. However, the anisotropic nature and the architecture of composite reduce the propagation of defects produced during impact in components [4]. Then a visual inspection is insufficient. It will be necessary to use the non-destructive techniques to ensure an efficient monitoring.

Several techniques of control have been proposed to investigate the defects, possibly produced after damage caused in composite materials. However, pulsed eddy current [5], acoustic emission [6], X-Ray [7], thermography [8], ultrasonic testing [9], represent the commonly used techniques. These techniques allow the examination of the integrity of components, and the detection of defects without

damaging the parts inspected during the production, either during use or in the context of maintenance.

The aim of this study was to investigate the structural integrity of composite material after low velocity impact, by giving information about non visual impact damages. For this reason ultrasonic and infrared technique are used. The phased array ultrasonic technique is widely used due to its advantages, such as speed of scanning, good resolution and sensitivity flaw detecting capabilities thanks to beam focusing, imaging, traceability or also fast execution of an inspection, etc.

On the other hand, thermography has become a relatively recent addition which represents a non-contact, non-destructive technique that is quick and simple to implement. Such as, this technique is performed to control a large area in short time. All bodies at a different temperature from 0° K emits a certain amount of infrared energy which can be detected and recorded by thermal cameras.

In this experimental study the control starts with the use of the infrared thermography technique for the reason to

obtain general information on whole component in a single control and in short time. The first test helps just to locate the defect, so for more accurate information the ultrasound technique is applied locally in the altered zone [10]. Finally, a destructive test is performed (metallurgy study) on the specimen, whose the results obtained are compared with those obtained by the ultrasonic technique.

II. MATERIAL AND METHOD

Two different NDT techniques are used in this study, namely ultrasonic testing and thermography, which are described in more detail in a later section.

A. Material

The component used in this work is a hybrid composite material constructed with a carbon fibers in an epoxy matrix. It's a stacking of two different sequences, woven and laminate (unidirectional plies) presented in the fig.1 . The lamination sequence was $(0/90)_6$ with a ply thickness of 0.217 mm and a total thickness of 5mm.

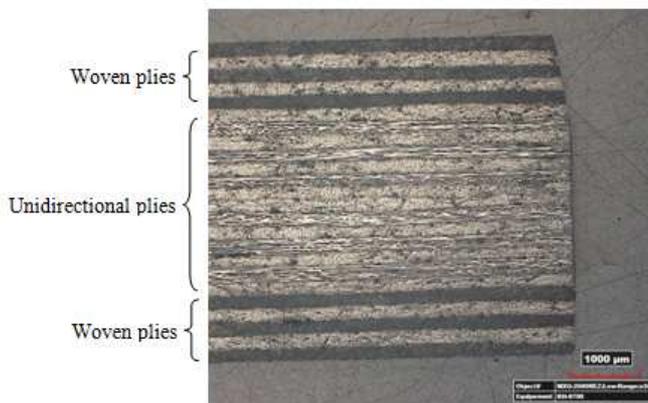


Fig. 1 View of the structure of composite material.

The component is damaged by a low velocity impact event. The impact test is performed manually using a hammer. Noted that, the impact did not penetrate at the bottom of the specimen as present in the figure 2.

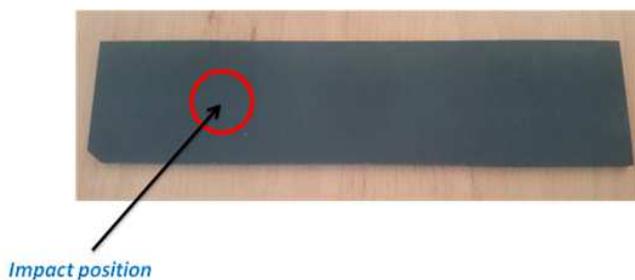


Fig. 2 Composite component after low velocity impact.

B. Impact

An impact is generally characterized by its velocity. So it can be classified according into two broad categories: low-velocity impacts and high-velocity impacts [3], [11]. High velocity impact is characterized by penetration into the sample or its perforation, accompanied by fiber breaks [12].

The most common test technique is the ballistic impact test [13]. The focus will be making it on the categories of low velocity, which is considered the most dangerous [14]. For this reason, it is important to understand the mechanisms of damage after impact. This type of impact produces several modes of damage arising inside, the material thickness without any perception on the impacted side, these damages are involved due to the heterogeneity and the anisotropy of composite materials. These are matrix cracking, delamination and fiber breaks.

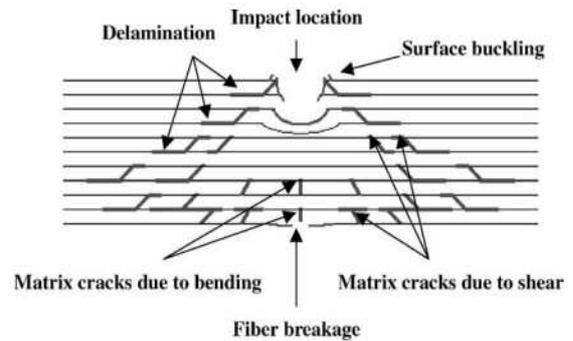


Fig. 3 Schematic representation shows typical impact damage for laminated composite [15].

The damage starts by matrix cracks which propagates in the matrix and reaches the interface, but it does not generally pass through the latter and the reinforcements are therefore not damaged. Rather, the crack changes direction and follows the interface. These various cracks will then cause initiations of delamination at the level of the upper and the lower interfaces of the fold concerned. They can then develop during the impact. In fact, the delaminations represents the most serious problem, which is the non visual damage it lowers the mechanical properties. After these two modes of damage mentioned before, generally the rupture of fibers takes place under the impact of a composite. So, when the fibers under the contact zone between the impactor and the specimen undergo a stress, greater than their tensile strength, they break.

C. Methods of control

1) *Thermography Infrared Technique:* During the thermography inspections two different approaches are possible for measuring the infrared radiation in NDT. A passive approach [16]; Or an active approach [17]. In this study the active approach is used. The principle of active thermography is based on the measurement of the flux emitted by the excited body via an external source, usually of thermal or ultrasonic origin. The infrared camera allows visualizing the thermal radiations and representing them as thermograms (thermal image), where temperature gradients along the surface are shown as image bright contrasts. The presences of defects inside of the material structure affect the thermal flow, which leading to temperature gradients on the surface.

In this work, the inspection is carried out according to the mode of transmission. One projector of 500 W is used to apply an external excitation heating source. A thermal camera FLIR T440 is used in the aim to record the emitted flux and transform it in the thermal image.

To ensure the experience the following protocol is followed:

- Extinguishing the lights, the experiment is performed in a dark room.
- Heating the component 14 seconds on average.

2) *Ultrasonic Phased Array Technique*: Phased array technology is among the non-destructive ultrasound controls that has proven itself in recent years [18]. Thanks to, the possibility of deflections in different directions and / or focusing a beam at different depths with one and the same multi-element sensor as shows in the Fig. 4. The principle of phased array relies on the use of a translator decomposed into individual elements that can be controlled independently [19]. These elements allow the conversion of an electrical signal into mechanical vibration and vice versa. So, The equipment like the Omniscan SX allows the excitation of the elements of the transducer (probe) with an adequate delay. It also allows to receive the signals and put them in the form of different representations (cartography) :A-Scan, B-Scan, S-Scan, C-Scan...etc. The cartography represents an important point to visualizing and interpreting the information collected by the translator.

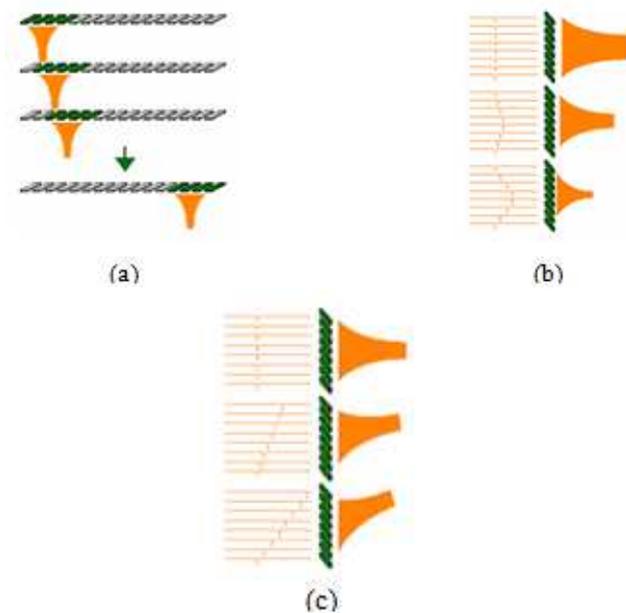


Fig. 4 (a) Electronic scanning, (b) Electronic Focus, and (c) Electronic deflection.

This technique provides a precise through thickness damages informations, which are useful for determining the depth, size and distribution of internal delaminations.

In this study, a 5L32 multi-element transducer connected to an Olympus Omniscan-SX ultrasonic system is used to analyze the defects produced after the impact event. The center frequency of the used transducer was 5 MHz (32 active elements). As high frequency waves do not propagate in air, a gel couplant is applied to insure the maximum transmission of the waves in the component. The used equipment produces S and C-scan images, which provides through thickness the damage information: position, size and orientation.

Other, characteristics of the used translator :

- The width of the probe: 22 (mm)

- Wave type: longitudinal (L)
- The speed of propagation of the L waves in the specimen is: 3000 (m / s)

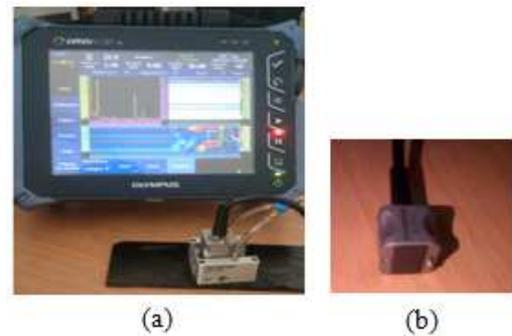


Fig. 5 (a) OmniScan SX, (b) phased array probe of 32 active elements.

An electronic scan has been performed, which involves spatially moving a beam by sequentially activating different active apertures, with a step of one element. In order to increase the ultrasound beams, energy and decrease its angle of divergence, 16 elements are used to generate each single beam.

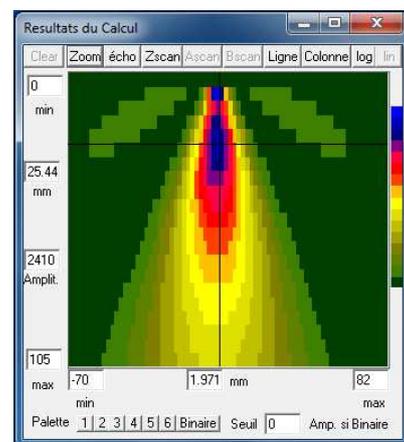
The choice of a large number of excited elements allows obtaining a clear focus and therefore a good resolution (Fig. 6). Such as, the focal width is given by:

$$d = \lambda F / D$$

when the diameter of the set of active elements of translator increases (D), the focal width decreases (d), which getting a good lateral resolution.

In the illustration of the beam profile above, red and blue represent high energy areas, while green and yellow represent areas of low energy.

The Fig. 6 represents simulation of an ultrasonic beam generated each time by the excitation of different groups of elements. We extract that the augmentation of the excited elements provides a beam of small width that allows us a clarity and reliability. These last results confirm what has been mentioned before.



(a)

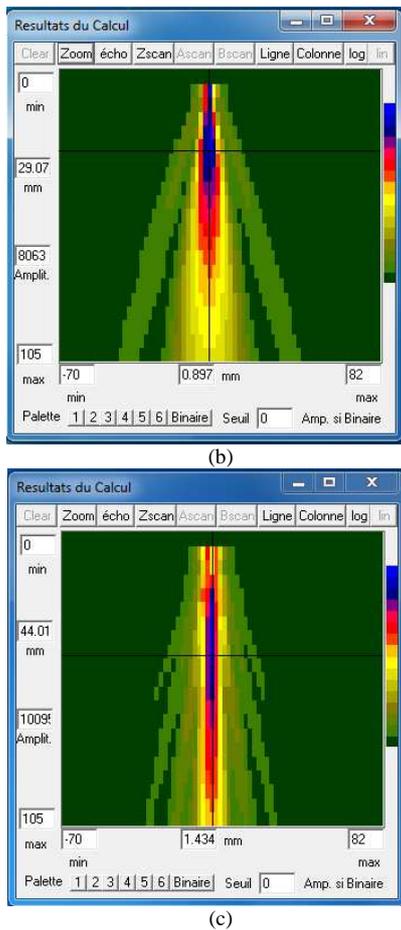


Fig. 6 Simulated ultrasonic field obtained by the excitation of different active elements groups [(a): 4active elements, (b): 8 active elements, (c): 16 active elements], using Atlas Sound software.

3) *Metallurgy study*: A scanning, digital microscopy is used to observe the structure of the specimen, interface, and crack initiation and also propagation mechanisms after the impact event. It's used in order to verify the results obtained from the ultrasonic technique.

Thanks to a digital microscope KH-8700, it is possible to extract and record fastly and with a high quality the three dimensional shape of the surface as well as the damages left by the impactor on the whole specimen (Fig. 7).

The software allows, for extracting the chosen section in order to get the information about the profile and in our case to measure the indentation left after the impact event.



Fig. 7 Digital microscopes / 3D display microscopes.

The Fig. 8 represent a surface recorded after the impact event, with a high precision of the surface reconstruction.

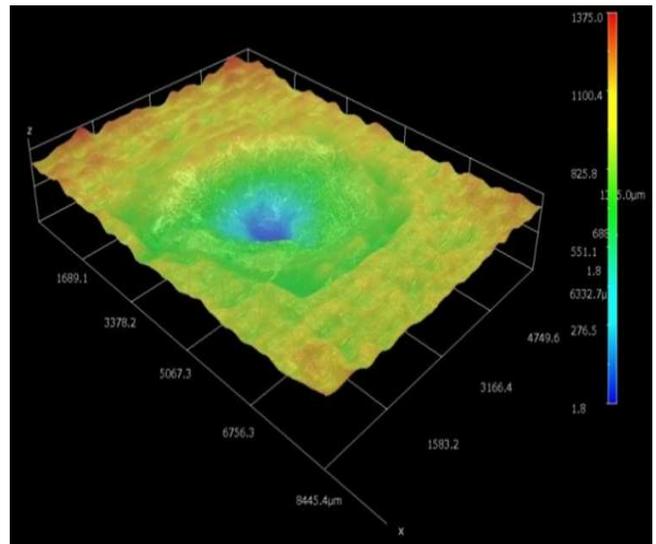


Fig. 8 Image 3D of the surface of the composite part recorded by the digital microscope after the impact test.

III. RESULTS AND DISCUSSION

Two different NDT are used to detect the defects produced after the impact event in composite material used in this study and also to reveal the size of the affected area.

Damage evaluation and determination are realized by means of the visual methods, thermography and the S&C-Scan process. The results obtained by the ultrasonic technique are compared to the one obtained by the metallurgy (digital microscope).

We start the experience by a global visualization of the whole specimen in order to localize the position of defects fastly and easily. For this reason the thermography is applied.

Fig. 9, show an increase in temperature, indicating the presence of defect which is probably a delamination between the folds. In addition, the increasing of the excitation time amplifies the response in the surface of the specimen. Indeed, the central zone reaches saturation for 42s, while the undamaged zone heat more slowly Fig. 10.

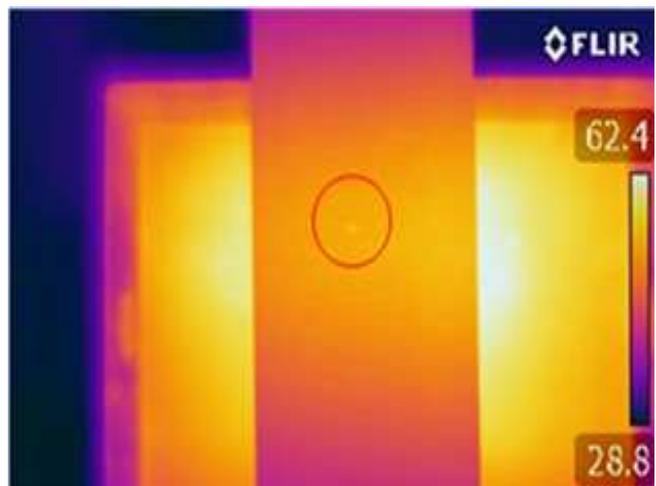


Fig. 9 Thermogram in transmission mode.

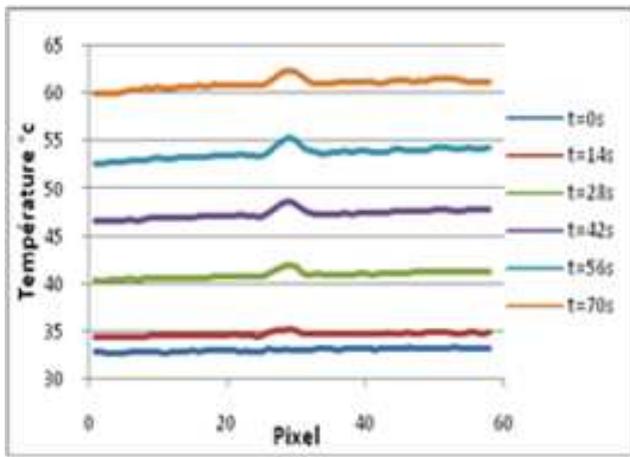


Fig. 10 Diagram representing the thermal evolution of impact as a function of time.

Then, the ultrasonic technique is applied locally in the damaged area for a finer analysis. A manual scanning is performed, for the purpose of obtaining cartography of the damaged area shown above in the Fig. 11. C-Scan cartography provides an aerial view of the controlled area. Indeed, this technique shows the impact damage throughout the specimen, and it allows us to measure the size of the damaged area.

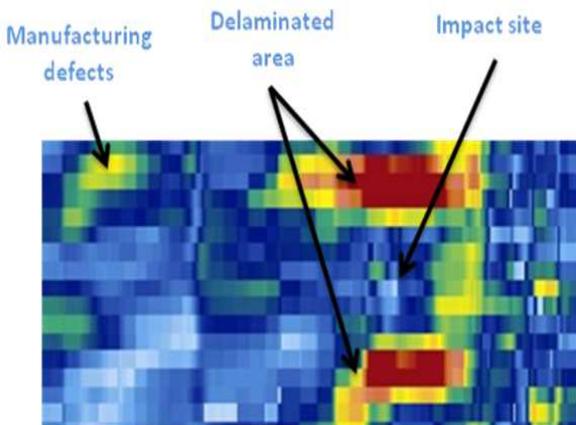


Fig. 11 C-Scan cartography.

Fig. 12 represent the S-scans, which indicate the depth damage after the impact and allows us to give information about the thickness of the part (we extracted 5mm in the thickness which is in agreement with the real measurement of the piece). A very strong attenuation of the ultrasonic beam is observed, which is resulting from the anisotropy of the material and its structure (the orientation of the fibers, the stacking of the layers). In addition, it can be seen that the amplitude of the surface echo decreases in the impacted area (the thickness of the surface echo in the contact zone between the impactor and the part is small compared to the rest of the echo). There is also the appearance of the detachments between the folds in other words delamination, which is characterized by a conical shape (the origin of this cone is at the contact region between the impactor and the specimen). As can be seen, a discontinuity of the echoes under the damaged place (impact site). Indeed, these results are due to the impactor, which deformed the surface (concave shape). This deformation caused the diffusion of

the ultrasonic beam which explains the discontinuity of the echoes.

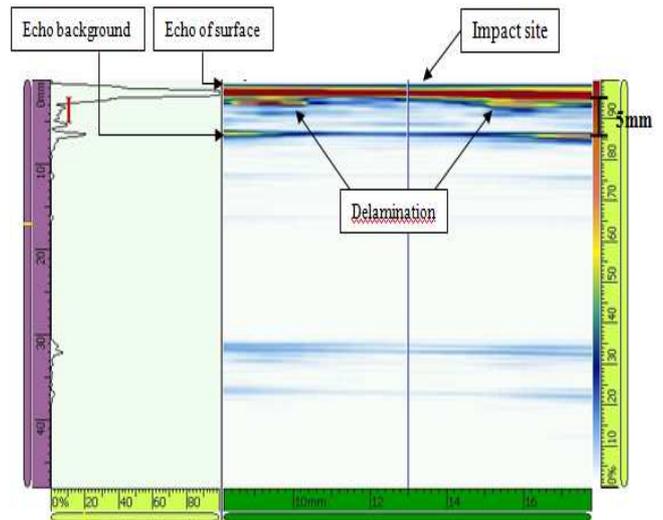


Fig. 12 A&S-Scan cartography of the damaged area.

After the NDT controls, the specimen is examined under scanning, digital microscopy to investigate their microstructure, the interface and also the failure mechanisms. A conical shape in the thickness direction in the upper folds is observed (Fig. 13).

Generally, the observations revealed macro-cracks in the material, located in the conical zone observed previously. So, three kinds of internal damage were observed: fiber breakage, matrix cracking and delamination.

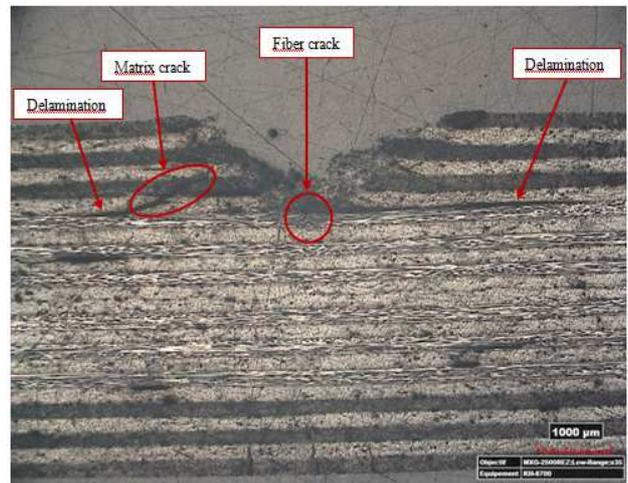


Fig. 13 Metallography photograph shows damage produced after the impact event at the impacted area.

The first type of mechanism observed is matrix cracks. This type of crack is systematically linked to interface cracks (fiber / matrix decoheres) or to initial manufacturing defects. These cracks are due to transverse shear and appear in the first folds at some distance from the impacted area (Fig. 14(a)). They are inclined at 45° and propagate in the direction of the fibers (Fig. 13).

These various cracks will then cause delamination initiations at the upper and lower interfaces of the fold concerned (Fig. 13 & Fig. 14(b)).

Finally, after matrix cracking and delamination appears the rupture of the fibers (Fig. 14(c)). They are located under the impactor in a region where matrix cracking and delamination are observed (Fig. 13).

Other defects are present in the specimen shown in the Fig. 13, they can be interpreted as porosity (manufacturing defect).

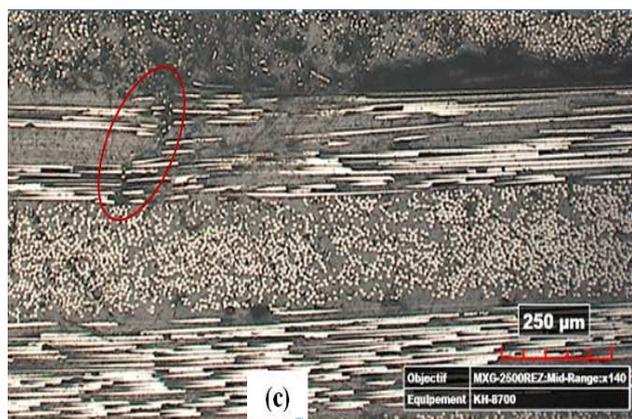
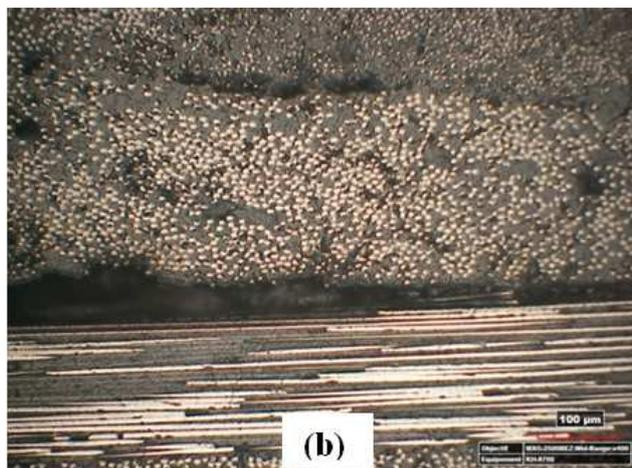
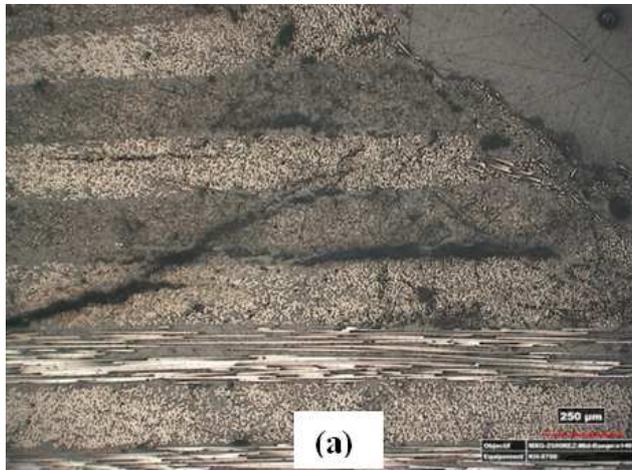


Fig. 14 Scanning electron micrographs showing (a) matrix cracking, (b) delamination between the layers and (c) cracking of the fibers.

The results found in this work are encouraging, there is a correlation with other research [20], [21], [22].

IV. CONCLUSION

In the present work, the monitoring of composite material is ensured by two non-destructive testing techniques.

The methodology followed in this experiment has allowed us a precise control in a short time. It starts with the localisation of defects using thermography of the whole specimen in few seconds and in non contact mode. Then the ultrasonic technique is applied locally in the designated area to get finer analysis. It appears quite clearly that there is a complementary of methods.

A good agreement between the results obtained with both the ultrasonic technique (NDT) and the digital microscope (DT) are noticed. It proves the reliability and accuracy of the ultrasonic technique used.

NOMENCLATURE

F focal focus mm
D the diameter of the set of active elements mm

Greek letters

λ wavelength mm

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