NON DESTRUCTIVE EVALUATION OF COMPOSITE MATERIALS WITH NEW THERMAL METHODS

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Abstract

In this work a microwave sources were used to heating the water inside composite materials in order to detect with thermographic technique the damaged area of materials. The tests were performed with traditional thermographic techniques and the new technique proposed on CFRP and GFRP damaged specimens. A new algorithm was developed to processing the thermographic data obtained by microwave stimulation in order to evaluate in automatic mode the damaged areas of analyzed component. A microwaves lock-in thermography was carried out to detect the impact damages on composite material specimen using a algorithm based on FFT analysis.

1 Introduction

Nowadays new materials such as composite materials are used in many applications and the researchers are interested to develop new non destructive techniques to monitoring the structural integrity of materials. In particular, in the aerospace industry well established non destructive techniques such as, ultrasound and x-ray, are used together new techniques such as thermography and shearography. Stimulated thermography techniques (pulsed, lock-in and ppt thermography) allow to detect the defects without contact and with a full field set-up [1], [2], [3], [4]. Interesting results were obtained using the TSA (Thermoelastic Stress Analysis) on composite materials. In this case the cracks are detected by means a dynamic load applied on materials [5], [6].

The thermographic techniques cited above, have some limitations in detecting of very small defects placed at depths greater than 10 mm and many problems can occur in the case of automatic detection of defects.

In this work have been used the microwaves as alternative heating source to detection the defects in composite materials. The aim is detect the defects that the thermographic techniques that use traditional heating source are not able to detect. Small defects e.g., defects due to impact damage, can cause the penetration of water inside the composite structures. The temperature and pressure during the flight may freeze the water with the possible size increase of defects [7].

This means that detecting the moisture inside the composite components, is important for predict irreversible damage of the components. Moreover, the water presence, allow to detect the small defects placed also at high depth.

The aim of this work is develop a new thermography microwaves techniques in order to analyze wide areas of components with low tests time respect to the traditional thermography techniques.
The tests have been carried out on composite material specimens, in particular preliminary tests have been carried out to optimize the experimental set-up on CFRP specimens manufactured with resin film infusion technique. To quantitative analysis of defects have been used impact damaged CFRP specimens.
On the same specimens were carried out a microwave lock-in thermography and pulsed microwave thermography tests. A new algorithms were used to data processing in order to obtain the phase and the amplitude data of the thermal signal and to detect in automatic mode the defect.
The specimens have been heated using a commercial microwave oven suitably modified. In particular, microwaves sensors have been used to measure leaks from microwave oven during the test.
Comparison among the new termographic technique and other non destructive techniques such as x-ray have been shown a good agreement of the results obtained and promising advantages in term of time of tests and the possibility to detect defects at high depth.

2 Experimental set-up

The tests have been carried out on specimens in composite material, in particular, CFRP specimen manufactured with RFI technique (Resine Film Infusion) and a sandwich specimen in sintattic foam, “Henkel Syncore 9872.1, K40”.
The RFI specimen was subjected to impact test with 30 J impact energy. After the impact the specimen was tested to measure the residual strength, according to standard ASTM, causing a break on the right side as shown in fig. 1.
The sandwich specimens were obtained with foam layers assembled CFRP with preimpregnated layers. For high impact energy (E=70 J) the laminate layers in carbon fiber undergo matrix breaks also in sub superficial layers and delaminations can create also between layers. The specimen used for tests has following dimension: width 76 mm, length 76 mm and thickness 8 mm.

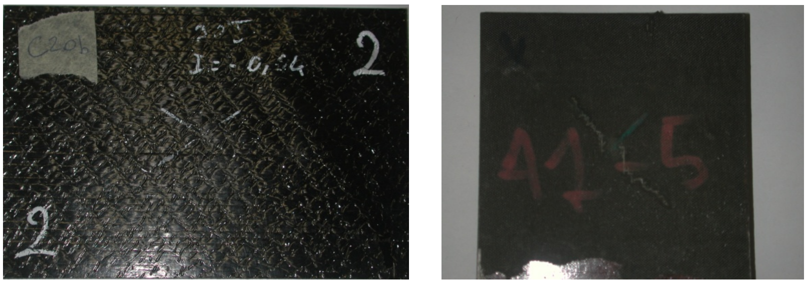

Figure 1. RFI (left) specimen and sandwich specimen (right)

Thermographic tests have been carried out by means commercial domestic microwaves oven. (power 750 W, frequency 2450 Hz, capacity 20 l). The microwave oven was modified to improve the tests performance, in particular the internal lamp was removed because during the test it overheated e became a heat source. After preliminary tests and when only cooling phase was recorded, the oven protection glass was removed in order to recording the temperature trend of specimen during heating phase. A copper grate permits a totally reflection of microwaves coming to the inside of the oven and allows the protection of instrumentation, such as the thermocamera, placed in front of the oven. The domestic

microwave oven produce 2,45 Ghz frequency waves suitable to excite water molecule and at length of about 12 cm, much more greater than the copper grate knit.
During preliminary tests various measurement have been carried out to evaluate possible microwaves leakage using electromagnetic sensors placed in various positions close to oven fig 2.

Figure 2. Electromagnetic waves evaluated in various point on the front door of the microwaves oven

The thermography data have been acquired via two different thermocameras, in particular for the early tests have been used a 160x120 microbolometer detector ThermoVision A20 M, which work in the long wave of the infrared spectrum between 7 μm and 14 μm (NETD<55 mK). These tests have been used to identify the possible optimal set-up. After, the tests have been performed by differential IR camera DeltaTherm 1560 (DT) made by StressPhotonics (USA) with thermal sensitivity (NETD) < 18 mK and based on a InSb photonic detector with 320×256 pixels. With both thermocameras were acquired thermographic sequences at 50 Hz frequency with Flir A20 and at 100 Hz frequency with DeltaTherm 1560.
In order to obtain the optimal set-up was taking in account the following parameters: specimen position in oven, presence of a water container in oven, position of a water container in oven, heating time and position of thermocamera.
The specimen was positioned in the centre of oven in order to receive the great part of microwave coming from magnetron and to obtain a short heating time. In fact different temperatures were measured changing the position of the specimen in the microwaves oven.
In the pulsed microwaves thermography tests the heating time has been chosen considering that elevated heating time can cause high temperatures that can damage the composite material, while, low heating time doesn't allow to obtain sufficient thermal contrast to detect defects. In this case a 5 second heating time has been used for the tests without the presence of water container in the oven.
The thermocamera has been positioned at 15 cm from grate to permits to focus and to frame the whole specimen and to avoid damage due to possible microwaves leakage from oven fig. 3.

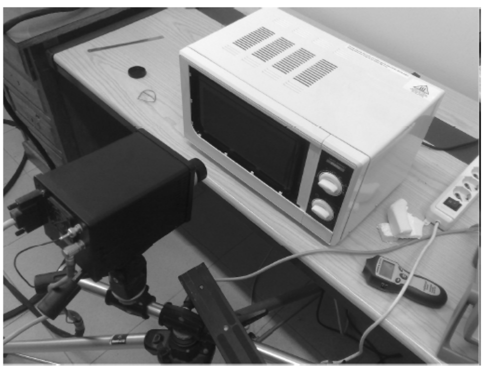

Figure 3. Experimental set-up used for microwaves thermography

In the lock-in microwaves thermography tests was used a microwave oven controlled by a function generator and power relay. A 0.1 Hz excitation frequency was used and 7 excitation cycles were acquired and processed with new software developed in Matlab environment.
The x-ray images (fig. 4) shows the presence of delaminate zone near the impact zone in the superficial composite layers. In the impact zone there are delaminations in deep areas of the specimen that involve the foam also.

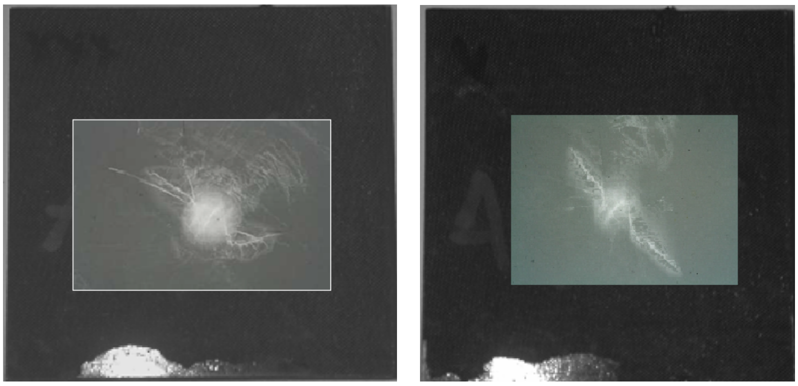

Figure 4. X-ray digital images of sandwich specimens

3 Results

3.1 Microwaves pulsed thermography tests

The aim of this work is use an innovative heating technique using microwaves to detect deep defect in composite materials with thermography.
The substances have an electric dipole and tend to align their angular momentum to electric field produced by microwaves. This alignment causes an elongation of dipolar atoms and this movement, causes friction between atoms with positive charge and atoms with negative charge, creates heating.
The water is a dipolar substance hence, the objects that contain water can be heated using microwaves. In the damaged zones of material there is a moisture accumulation, therefore the microwaves can represent a valid tool to investigation of wet zones (Swiderski W., 2002).
The presence of a grid between specimen and thermocamera tends to filter the infrared radiation directed towards the thermocamera. In order to evaluate the effective temperature of the specimen has been necessary to compute the trasmittance value τ of the grid in the temperature range of test. The τ value has been calculated using a reference blackbody (Hart Scientific 4180 Fluke) in order to obtain a trasmittance curve which allows to obtain the specimen real superficial temperature in function of the apparent temperature measured.
Monitoring the heating and the cooling curve of specimen, a different behaviour between undamaged zone and damaged zone of the specimen was observed. In particular, in undamaged zone the heating curves present an initial linear trend. The slope of the linear curve increases with amount of microwaves received by specimen.
After the heating phase, the temperature slight decreases, due to heat diffusion phenomena probably towards deeper undamaged zone, which are less heated by microwaves. The temperature tends to stabilize towards a constant value in the last phase of cooling (fig. 5).
On specimen surface are evident two delaminations in the central zone on the side of impact zone and there are cracks in the carbon fibers along the fibers direction.
In the delamination zones, the heating of the material occurs in a very sudden manner with a curve heating slope much higher respect to undamaged zones.

At the end of the heating there is a very rapidly cooling phase and a subsequent temperature increment. In fact in the central damaged zone of the specimen, there are sub superficial defects caused by impact test and then there is a temperature increase caused by the heat coming to damaged zones placed in more deep thickness of the specimen (fig 6). These defects are placed in the interface between carbon fibers laminate and Syncore resin. In this case the heating curve is less linear than undamaged and damaged superficial zones. At the end of the heating there is a short cooling followed by a temperature increase up to achieve a constant value fig 7.

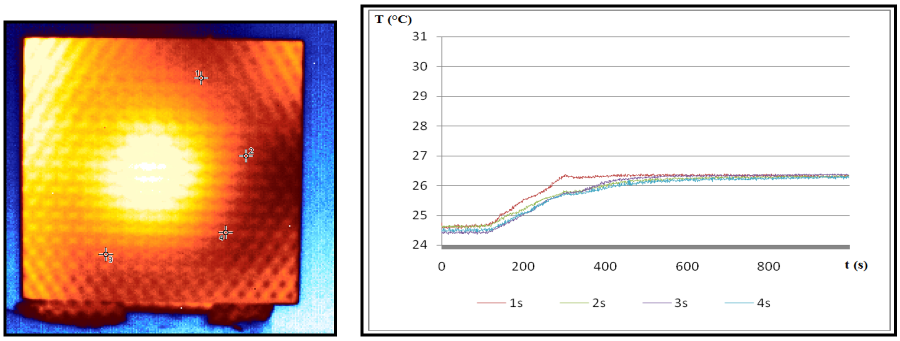

Figure 5. Temperature-time graph for 4 point on undamaged areas

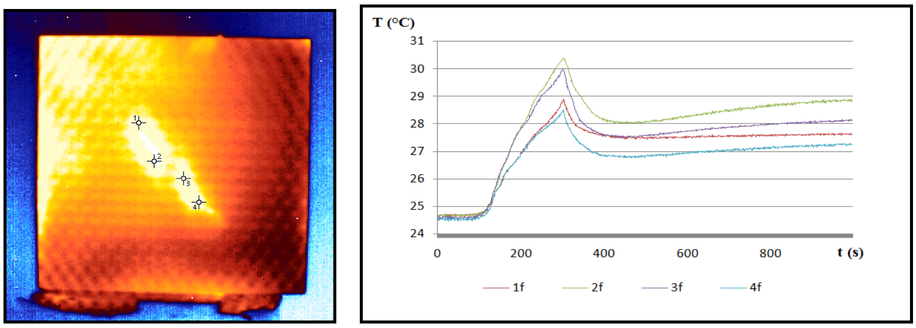

Figure 6. Temperature-time graph for 4 point on delaminations areas

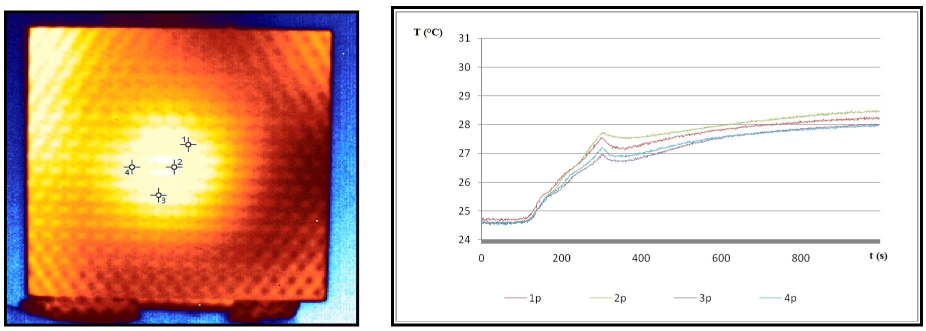

Figure 7. Temperature-time graph for 4 point on impact areas

An innovative algorithm was developed to detect in automatic mode, different defects typology placed in different deep of material.

The algorithm is based on hypothesis that the most points of the specimen are undamaged. The data analysis is based on the average behaviour of all points of specimen over time. The defected points have a different behaviour over time respect to the average behaviour previously evaluated. In particular, the damaged zones are identified considering two criteria: the maximum achieved temperature and the slopes of the heating and cooling phase during the test. Figure 8 show a generic curve of one point obtained during the test characterized by a

first phase (phase 1) due to heating of the material until to the maximum value of temperature (Tmax), by a second phase (phase 2) subsequent to the switch off of the magnetron of the oven and by a third phase (phase 3), different point by point, that provides important information on the defects typology.
The algorithm developed in Matlab®, acquires a thermografic sequence, calibrates the thermal data in order to obtain the temperature values considering the trasmittance coefficient of the grid, evaluates for each point of specimen, the temperature-time curve, the maximum temperature and the curves slope of each phase.
Figure 9 (left) shows the slope matrix evaluated during the heating phase (phase 1). The superficial damaged zones are visible in the central part and on top of the specimen. The superficial damage points have a very steep slope heating curve respect to undamaged points.

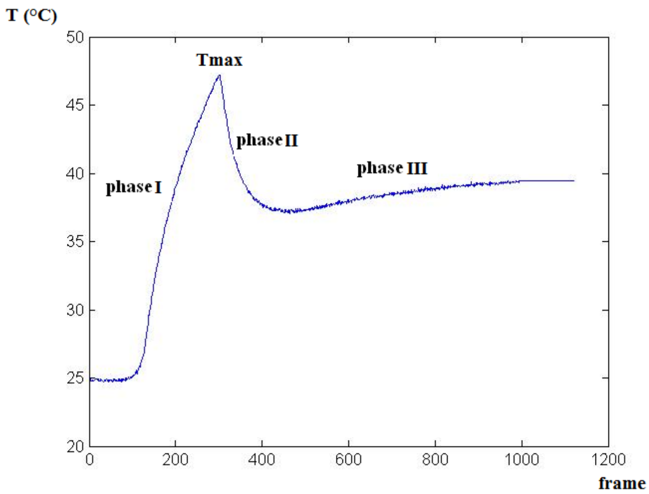

Figure 8. Temperature trend over time and 3 phase obtained during the tests

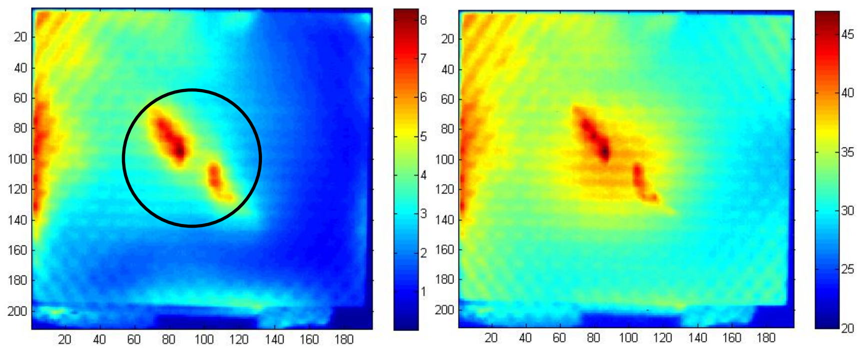

Figure 9. Slope matrix evaluated during the heating phase (phase 1, left) and matrix of maximum temperature (right)

Figure 9 (right) shows the matrix of maximum temperature for each point. In this case is possible have information also on the presence of deeper defects. In particular in this case is present in the central zone of the specimen a circular damaged zone due probably to break among core and CFRP laminate. The images show also an anomalous heating on the edge of the specimen due to non-uniform heating produced by microwaves oven.
A comparison with x-ray technique has been carried out to validate the new procedure adopted. In order to obtain a quantitative data analysis has been considered an equivalent defect area determined by a circular area with diameter equal to maximum dimension of the defect area obtained by NDT tests. Figure 9 shows the circular area adopted to quantitative analysis (black circle) [8]. The measurement of this area has been made applying maximum

contrast method [9], on thermographic image, known mm/pixel ratio. The evaluation on x-ray images have been carried out using digital images and digital ruler.
Table 1 summarizes the obtained results. The value of the equivalent area are comparable using the two NDT techniques. The quantitative data analysis confirms the possibility to use the microwaves as thermal source to non-destructive control of composite materials.

NDT Technique	Equivalent Area [mm^2]
Microwave thermography	1693
X-ray	1385

Table 1. Microwave thermography vs. X-ray

3.2 Microwaves lock-in thermography.
Lock-in thermography is based on thermal waves generated inside the specimens by submitting them to periodic thermal stimulations. In the case of a sinusoidal temperature stimulation of a specimen, highly attenuated and dispersive waves are found inside the material [1], [2], [3], [4]. More specifically, measurement of temperature evolution over the specimen surface permits to reconstruct the thermal wave and to establish the amplitude and the phase of the thermal signal.
The set-up used to microwave lock-in thermographic test is the same used to pulse microwave tests. in this case a power relay controlled by a function generator, commands the switch off/on of the oven. the excitation frequency (0.1 Hz) was choose in order to obtain an high thermal contrast and to avoid high temperature that could damage the specimen.
Figure 10 shows the superficial temperature of the specimen during the tests. The temperature evolution over time presents a strong drift due to the low velocity of heat diffusion and to low thermal conductivity of composite material.

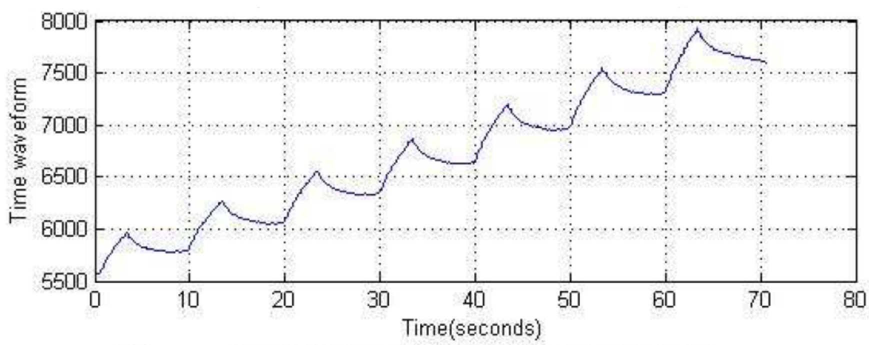

Figure 10. Temperature evolution during lock-in test

The thermographic data were processed with a new algorithm based on the FFT (Fast Fourier Transform) analysis. The algorithm acquires frame by frame and pixel by pixel, the thermal signal on the surface of the specimen and processes the thermal signal over time by means a Fourier transform in order to obtain the amplitude and the phase signal.
Figure 11 shows the amplitude and phase images obtained by the algorithm used to data processing. The images present some problem on the edges of the specimen. In fact, the interaction among electromagnetic field and specimen geometry provides an high temperature near the edge of the specimen. However, the impact damaged zone is clearly evident.

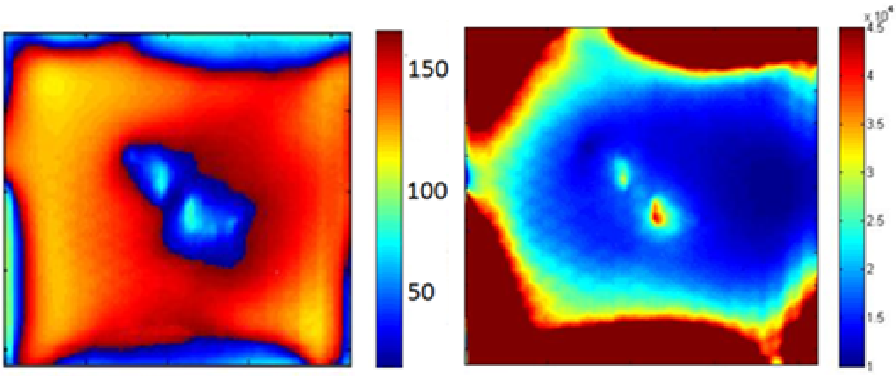

Figure 11. Lock-in phase image (left) and lock-in amplitude image (right) obtained using microwaves

4 Conclusions

In this work a new thermographic technique has been used to assess the damaged zones in composite material by means to a microwaves source. The tests have been carried out on previous damaged composite materials using the innovative thermographic technique and x-ray. A modified microwaves oven has been used to heating the specimens in order to acquire thermal data by thermocamera.

In the first part of this work a preliminary tests have been carried out in order to determine the best set up in term of best heating time and specimen position in the microwave oven. A pulsed and lock-in thermographic tests were carried out using microwaves. In the first case, an innovative algorithm for the data analysis has been developed to evaluate in automatic mode the damaged areas and the various defects typology. The lock-in thermography data were processed using an innovative algorithm based on the Fast Fourier Transform analysis.

The results obtained with microwaves thermography have been compared with x-ray. Quantitative analysis of the damaged areas show a good agreement among results obtained with microwaves thermography and x-ray.

The microwaves thermography technique provides advantages in term of time of tests and the probability to detect defects at high depth. Future works will focus on experimental setup in particular will be evaluated the use of microwave antenna in order to obtain a uniform microwave beam to avoid non uniform heating of analyzed specimens.

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