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Measurements with thermoelastic technique from infrared microscopy on random trabecular structures

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ABSTRACT

In this paper it is proposed a measurement technique based on differential thermal microscopy based on the application of a thermoelastic measurement system and an infrared zoom optics to analyze stress distribution on a random lattice structure realized by stereolitographic additive techniques. Lattice structures, because of the possibility to be actually easily realized by additive manufacturing techniques, see a growing interest and a lot of application in engineering and medical fields. The possibility to experimentally analyze stress conditions by new full field and non-contact measurement techniques is fundamental to correctly design components made of it, predict its life, optimize performances.

KEYWORDS:*thermoelastic technique, lattice structure, stereolitographic additive techniques, trabecular structures.*

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I. INTRODUCTION

Lattice structures can be realized by repeating a single geometric element called cell, along selected directions. This method lead to a symmetrical and repetitive lattice structure. Trabecular structures have random distribution and their behavior is one of the hottest topic currently tackled by manufacturing community. The trabecular structures were partially designed in nTopology and futher processed using SolidWorks. The trabecular structure here analyzed was realized by an additive manufacturing stereolitographic process, using a Formlabs Form 2 3D printer. The material chosen id the “clear” resin, provided by Formalbs. The printer and the additive manufacturing process is illustrated in figure 1.1

Figure: 1.1: SLS additive process of a Formlab Form 2 3D printer.

A laser beam from the UV transparent bottom of a tank cure in its focal point a liquid resin that locally became solid. The laser beam is moved on the points of the solid layer to build by two mirror, once the layer is completely realized the building plate moves up and a second layer can be realized connected to the first, below it. The solid component realized grows from the first layer on the building plate to the bottom, so upside down. With this technology detailed component, with resolution up to 25 microns and very complex structures, like lattice structures, can be realized with many engineered materials, mainly plastics but actually also ceramics.

II. THE THERMOELASTIC MEASUREMENT PRINCIPLE

The Thermoelastic Stress Analysis (TSA) is a technique for the indirect non-contact measurement of the stress field un the surface of a mechanical component [1]. Every substance present in nature, if subjected to a variation in volume due to external forces, undergoes a reversible gradient of temperature directly proportional to the volume variation that accompanies the deformation[2].

The thermoelastic effect was studied by Lord Kelvin, who described it through the following relation, valid for a homogeneous solid, with elastic and linear isotropic behavior, which undergoes a reversible adiabatic transformation[3]:

$$\Delta T = -\frac{T\alpha}{\rho C_p}\left(\Delta\sigma_{xx} + \Delta\sigma_{yy}\right)$$

where:

α is the coefficient of thermal expansion;

Cp is the heat capacity at costant pressure;

ρ is the density;

T is the ambient temperature;

($\Delta\sigma_{xx}+\Delta\sigma_{yy}$) are the time changes in surface stress in two orthogonal directions.

From this equation we can see how the temperature variation in time ΔT due to the thermoelastic effect depends on the thermophysical characteristics of the material, its absolute temperature and the stress changes in time ($\Delta\sigma_{xx}+\Delta\sigma_{yy}$). The thermoelastic effect is very slight and transient, due to the heat flow through the solid that lead to a uniform temperature field[4].

The measurement systems here used is composed of a thermal camera, a lock-in system and a specific software for image processing in order to have a so called DC thermographic system. It is not possible to use the standard thermography (DC thermography) to make stress measurements, it is necessary to use an AC differential thermography were a high frame rate IR-camera with high resolution and low noise is needed in order to measure the very little temperature variation in time ΔT generated by the thermoelastic effect. The differential thermography used in the TSA instruments, therefore, is able to detect the slights temperature fluctuations in time due to the thermoelastic effect[5].

The problem related to the use of thermoelasticity lies in the fact that the measuring instruments must be so sensitive to detect very slight temperature variations in the presence of a high level of background noise[6]. The resolution of the thermal imaging cameras used in differential thermography is very high, of the order of 1 mK, and the best thermographic systems have typically a noise equivalent temperature (NET) that is around 10 mK, characterized by a white noise distribution; therefore, it is very difficult to measure temperature variations due to the thermoelastic effect around few mK.

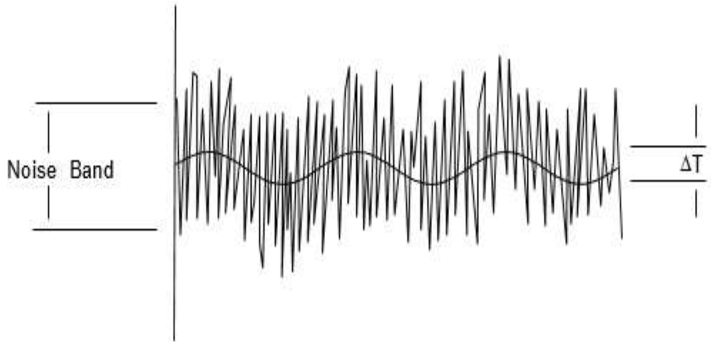

Figure: 2.1: Temperature signal disturbed by noise.

For these reasons it is necessary to filter the temperature variation signal ΔT by using the lock-in data processing technique.

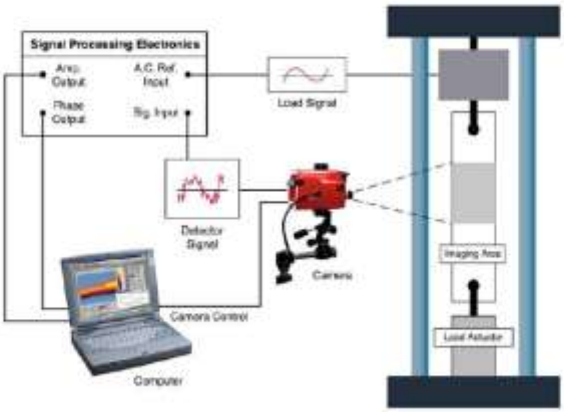

Figure: 2.2: Thermoelastic measurement system.

The lock-in technique consists in correlate the time signal coming from each pixel of the camera with another reference signal R synchronous with the load that generate the stresses in the mechanical component. Normally a sine excitation signal is used for optimize the results and used as reference signal for lock-in signal processing[7].

$$R(t) = R_o \cdot sen(\omega t)$$

The signal R is transformed into two square waves oscillating between -1 and +1 with the same frequency:

$$F(t) = square(\omega t)$$
$$G(t) = square\left(\omega t + \frac{\pi}{2}\right)$$

F(t) and G(t) functions are then used to create two sine waves, having the same pulse ω and $\frac{\pi}{2}$out of fase, f(t) and g(t) respectly.

$$f(t) = cos(\omega t)$$
$$g(t) = cos(\omega t + \frac{\pi}{2})$$

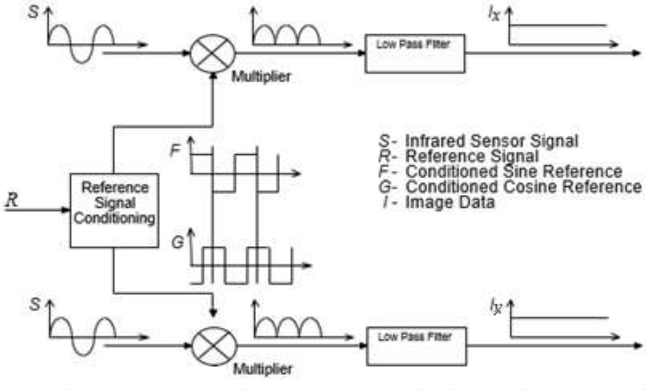

Figure: 2.3: Signal processing and processing with the Lock-In Signal Processing.

Considering the temperature fluctuation ΔT on a point of the body surface, ΔT is a sine wave whose frequency is equal to the frequency of the reference signal. The S(t) signal, output from each camera pixel, contains the measurement of temperature T(t) on a small region of the body surface plus a lot of noise.

$$S(t) = K_{sens}\ T_{ampl}\ \cdot sen(\omega t + \theta) + Noise$$

Where T_{ampl} is the amplitude of temperature sine wave due to the thermoelastic effect and K_{sens} is the sensitivity of the sensor. By correlation between the signal S(t) and the functions f(t) and g(t) it is possible to isolate the temperature fluctuation from the background noise. Integration time around typically twenty second lead to good S/N ratio. The values I_x and I_y which contain the information on the module and phase of the body temperature fluctuation:

$$I_x = \frac{1}{t}\int_0^t S(t) * f(t)$$

$$I_y = \frac{1}{t}\int_0^t S(t) * g(t)$$

Indeed:

$$\Delta T(t) = I_x \cdot \cos(\omega t) + I_y \cdot sen(\omega t\ )$$

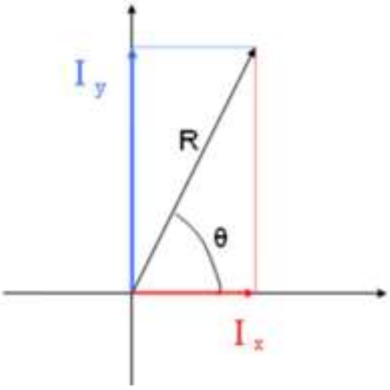

Figure: 2.4: Temperature fluctuation ΔT from Ix and Iy.

Amplitude ΔT_{max} and phase θ of the thermal fluctuation are evaluated with the following relationships:

$$\Delta T_{max} = \sqrt{I_x^2 + I_y^2}$$

$$\tan(\theta) = \frac{I_y}{I_x}$$

This is performed for each pixel time history S(t) of the thermal film recorded, therefore from the thermal film a complex image is calculated in terms of its amplitude and phase image that is the so called differential thermography, proportional in its amplitude image to the stress level accordingly to the previous illustrated Kelvin equation.

III. TEST BENCH SET-UP

A test bench suitable for the measurement process to be carried out has been set up. A small electro dynamical shaker (10 N force) is used to apply a sinusoidal compression load to the specimen, the random trabecular structure: a frame of 8x8 cm of plastic clear resin of Formlabs printer, constrained into a steel frame. A signal generator and a signal amplifier are used in order to drive the electro dynamical shaker. The signal generator output is also used as reference for lock-in signal processing.

Figure: 3.1: Test bench.

The Deltatherm 1560 system, realized by StressPhotonics, consists of an NIR infrared thermal imaging camera with a resolution of 320x256 pixels and a lock-in signal processing unit. In order to evaluate the distribution of temperature (and therefore stress) in detail of the complex structures of the specimen, a two-position zoom was used that allowed to analyze an area of 14.3x11.4 mm^2 or 2.8x2.24 mm^2. The zoom allow to make thermal measurement with a resolution up to 112µm or 22µm, so up to the same order of magnitude of the 3D printer used to realize the trabecular structures tested.

Figure: 3.2: Test bench, infrared camera and zoom setup.

IV. ANALYSIS OF THE RESULTS

The prototype was subjected to two different load conditions at a frequency of 100 and 200 Hz, respectively.

Below are the images, resulting from the acquisitions, related to the response of the prototype to the different load frequencies. Results are expressed in terms A/D, which means Analog to Digital conversion. Valued expressed in A/D units are proportional to IR radiant energy measured by CCD sensor array and proportional to temperature through Stefan-Boltzman emission law.

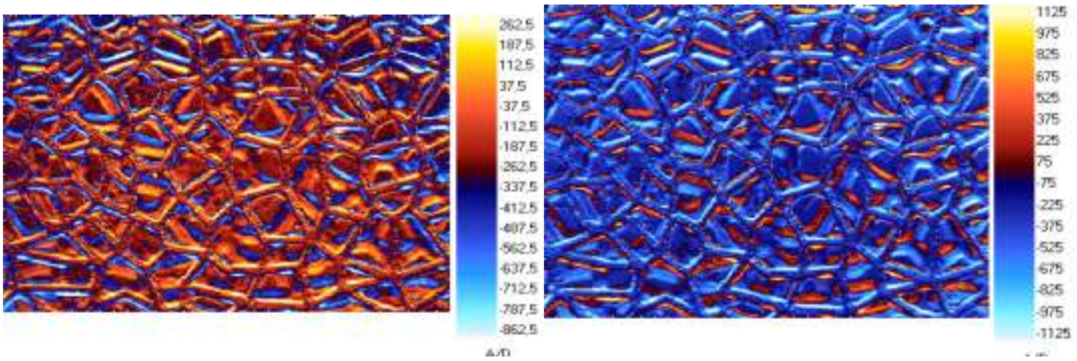

Figure: 4.1: Differential thermography Ix and Iy with at 100 Hz.

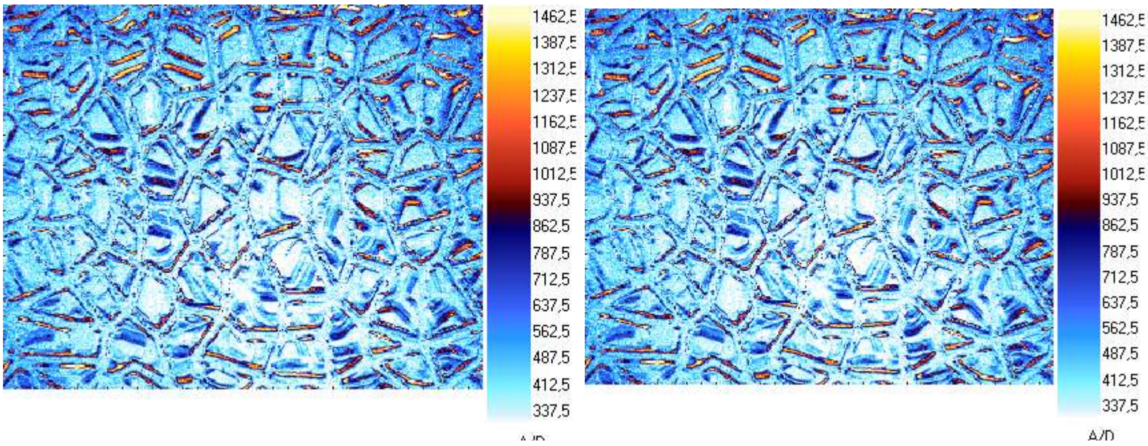

Figure: 4.2: Differential thermography R and phase at 100 Hz.

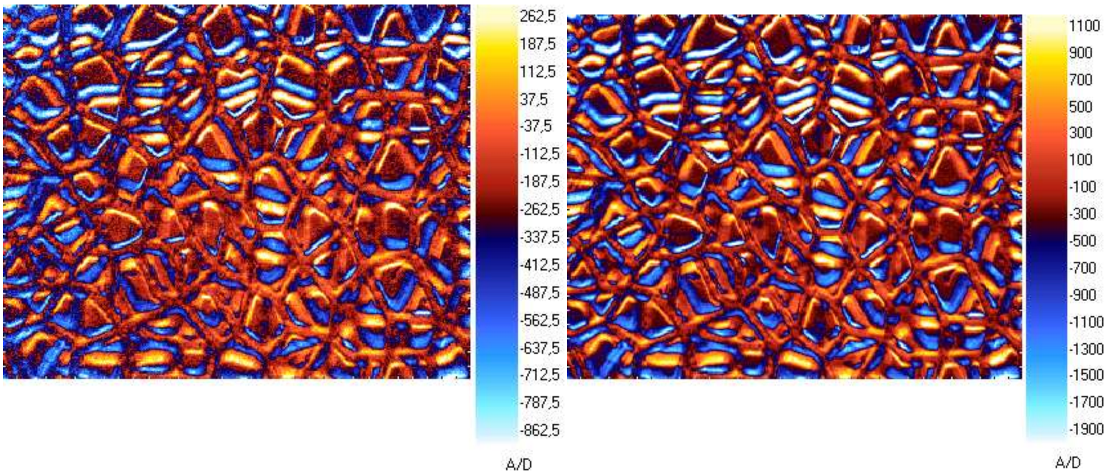

Figure: 4.3: Differential thermography Ix and Iy with at 200 Hz.

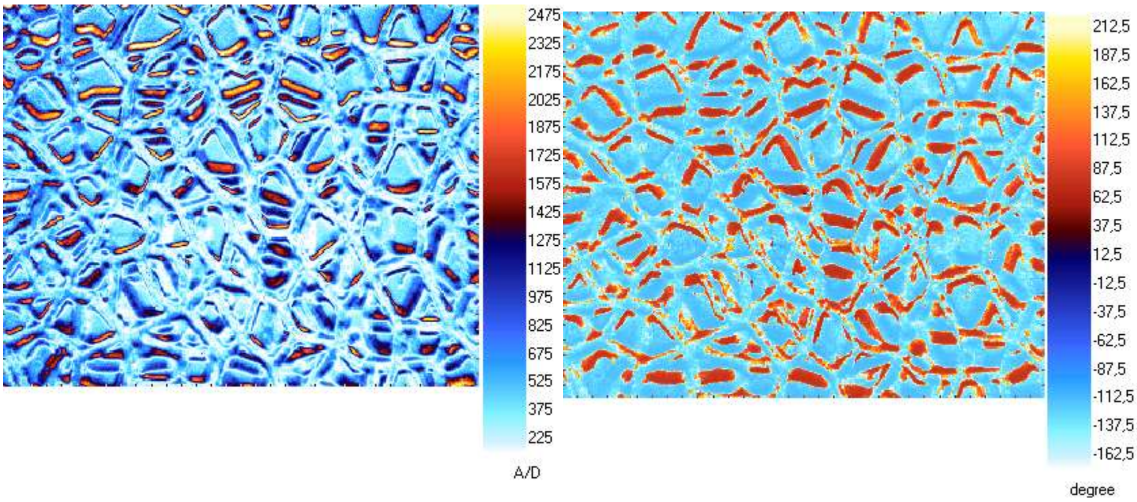

Figure: 4.4: Differential thermography R and phase at 200 Hz stress.

As has been described, the values Ix and Iy contain information on module (R) and phase of the temperature fluctuation on the surface of the body. In fact, the image R represents the distribution of ΔT_{max} on the surface of the piece, proportional to the stress field. Results shown in previous figures show a typical edge effect, due to the displacement of the specimen which undergoes of load. The edge effect generates false temperature fluctuation because the same pixel of the IR camera in focused alternately on the specimen and on the background. Processing software of the Deltatherm measurement system allows to make a special processing of the thermal image in order to remove the effect. This motion compensation tool creates two sets of thermal images acquired at maximum load (reference images) and minimum (moved images) load respectively and all images of a set can be transformed by shift and rotation in order to obtain the edge overlay on the two sets of thermal images, using a built-in Procrustes algorithm. This tool is very effective using a large Field Of View (FOV) images, because displacement field can be considered as rigid and deformation is neglectable if compared with spatial resolution. This condition is not well achieved on small FOV where the deformation of the specimen lead to a non-rigid transformation. Motion compensation can be applied yet, focused on a specific and chosen point P of the reference image, but edge effect afflicts the results, with increasing intensity moving away from point P.

By applying the motion compensation on previous results, focused on center image point, the result became that of the following figures, where stress concentration on the trabecular structures are clearly visible.

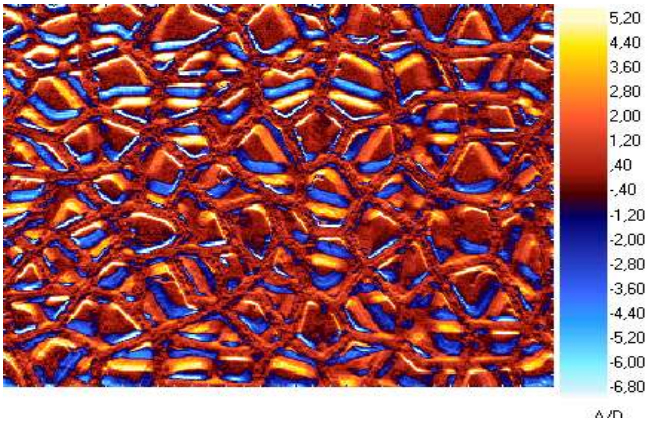

Figure: 4.5: Results with motion compensation processing at 100 Hz.

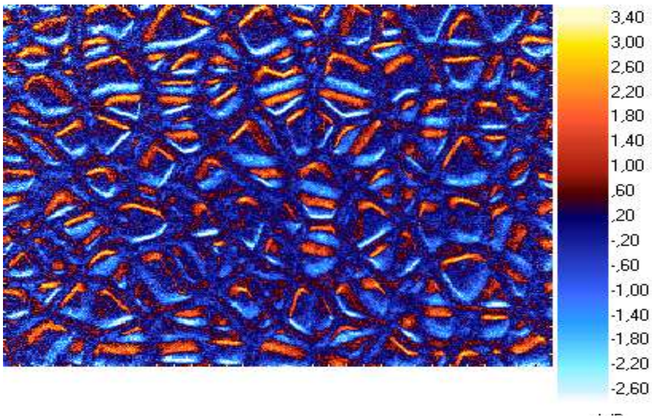

Figure: 4.6: Results with motion compensation processing at 200 Hz.

V. CONCLUSIONS

A first test of microscopy thermoelastic measurement technique applied to the stress analysis of a random plastics trabecular structures has been performed. Encouraging results has been obtained and the fact that high loading frequency and motion compensation techniques must been used. Auto adaptive compensation tool could be studied in order to compensate the edge effect on a large portion of the image.

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