APPLICATION OF ELECTRONIC SPECKLE PATTERN INTERFEROMETRY TO MEASURE THERMAL STRAINS OF THIN LAYERED STRUCTURES

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Abstract. Applications of the Electronic Speckle Pattern Interferometry (ESPI) for the determination of the coefficient of thermal expansion (CTE) and thermal behaviour of a thin layered foils is investigated in this paper. A heating system was designed for applying thermal load and ESPI technique delivers the full-field thermal deformation fields of the test sample due to the change in temperature. The normal strain is calculated for full-field analysis of thermal expansion of the specimen. For validation, the CTE of an aluminium sample is determined and compared with the textbook value, validating the proposed experimental set-up and the sensitivity and accuracy of the applied experimental technique. The CTE and stress concentration at interface due to thermal loads of a layered thin structure consisting of two different materials is measured. The results reveal that the ESPI is a proper and effective tool for full-field thermal behaviour analysis and CTE measurement.

Key words: speckle interferometry, thermal strain, coefficient of thermal expansion.

1. INTRODUCTION

The coefficients of thermal expansion (CTE) are extremely important for parts where two different materials join, such as printed circuit boards and ICs (metals are bonded with epoxy resin). Ideally, the difference in thermal expansion coefficients between the two materials should be as small as possible. For other many layered thin structures such as flex circuits, flexible printed circuit boards, strain gauges or bonded foil gauges for pressure transducers matching the value of the thermal expansion coefficient (CTE) between materials play a key role in components design, in structure response or in the final decision-related materials selection. Thermal expansion for such structures from materials or components with different thermo-mechanical behaviour can be properly evaluated if the investigation method is highly accurate and ensures full field visualization of strain distribution in the materials or components under thermal loads.

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Conventional CTE experimental point measurement technique for homogeneous materials such as thermo-mechanical analyser (TMA) is not well suited for the effective CTE measurement because of a point-to-point CTE variation within the component. Full-field optical techniques like moiré interferometry for CTE measurement of flexible substrates and its application to a glass fiber/epoxy composite ply is presented in [1]. Successful application of digital image correlation (DIC) technique to determine the CTE of thin films was reported in [2]. A high-resolution digital image correlation (HRDIC) platform for measuring small thermal deformation of film specimens has eliminated some negative factors which may affect the measurement accuracy, such as image noise, heat radiation and out-of-plane deformation was developed by Wang [3]. Digital speckle correlation method for coefficient of thermal expansion (CTE) measurement of film was developed by Zhanwei Liu [4]. A new non-contact optical method (IIC, infrared image correlation) for the determination of the coefficients of thermal expansion of solid materials was presented by Montanini [5]. Compared to other optical methods the DIC has a simple set-up, easy post-processing of the measured data, and no limits on the temperatures and strains than can be reached but limited accuracy in the small field deformations. A comparison in terms of accuracy between DIC and interferometric techniques in the field of very small displacements is definitively in the favour of interferometry [6–8]. As an interferometric method Electronic Speckle Pattern Interferometry (ESPI) has a high sensitivity, the displacement measurement range and the displacement resolution are of the order of 10 nm to 10 μm and 10 nm per loading step respectively. These characteristics are very well adapted to the general requirements of experimental measurements of thermal behaviour of layered structures subjected to small thermal gradients. ESPI proved to be well suited to analyse the thermal expansion behaviour and to determine the coefficients of thermal expansion (CTE) for thermally isotropic as well as anisotropic solid materials [7, 8]. The drawbacks of ESPI methods consist in its high sensitivity to environmental and complexity of the measurement set-up.

In this paper it is investigated the thermal behaviour of a layered thin structure of two different materials by the experimental method of ESPI. The work discusses in the first part the principles of the experimental technique, CTE calculation of isotropic materials and describes the developed measuring setup and heating system for applying the thermal load. Measurement results for a thin layered foil, a commercial strain gauge solder terminal, are presented in the second part of the paper. For validation, the CTE of an aluminium sample is determined and compared with the textbook value, validating the proposed experimental set-up and the sensitivity and accuracy of the applied experimental technique. An assessment of the method performance and resulting conclusions are made at the end of the paper.

2. MATERIALS AND METHOD

In its simplest form, the coefficient of linear thermal expansion (CTE) of any solid material can be defined as the change in length (linear dimension) per unit rise in temperature. The most general definition is the mean or average coefficient of thermal expansion as given by [9]:

$$\alpha_m = \frac{(L_2 - L_1)/L_0}{T_2 - T_1} = \frac{1}{L_0}\frac{\Delta L}{\Delta T} = \frac{\varepsilon}{\Delta T}. \quad (1)$$

The CTE is related to the slope of the chord between two points on the curve of change in length against temperature, which represents the expansion over the particular temperature range from T_1 to T_2, with initial length L_0 defined at a reference temperature T_0. According to the previous expressions, determination of the average coefficient of thermal expansion requires the measurement of two physical quantities, strain and temperature, which can be accomplished by means of experimental methods.

For the experimentally determination of CTE is important that the strain field within the sample to be caused only by the thermal loads and no mechanical restraints on the sample, either external or internal, such that no stresses arise in the body during thermal expansion or contraction. For thermal strain measurement the method of in-plane one dimensional electronic speckle pattern interferometer was employed. Accurate measurement and controlling of the sample temperature was done by a self-designed heating device based on a thermoelectric module.

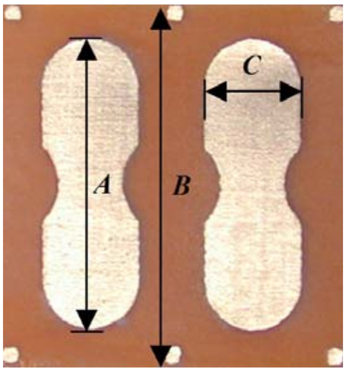


Fig. 1 – Thin foil specimen: strain gauge solder terminal.

The sample was a commercial strain gauge solder terminal (Micro-Measurements, USA) which is usually installed between the connecting cable and the strain gauge itself. The terminal (Fig. 1) is made a 0.036 mm thick copper foil, laminated on either of two types of backing material. Preferred general purpose backing material is a polyamide film 0.08 mm thick. Polyamide film backing combines high-temperature capability, resistance to soldering damage and good electrical properties. The dimensions of the terminal is A=8.4 mm, B=6.35 mm and C=2.54 mm.

ESPI is an optical measuring technique that allows rapid and highly accurate measurement of deformations. It can be applied to any material provided that the surface is sufficiently rough and the laser light is diffusely reflected. ESPI can be used for one step measurement or for a series of measurements, thus is suitable both for low or high loading.

In the in-plane speckle interferometer set-up, also called double illumination set-up, the speckle pattern is produced by simultaneous illumination of the sample with two laser waves directed symmetrically to the observation direction (Fig. 2).

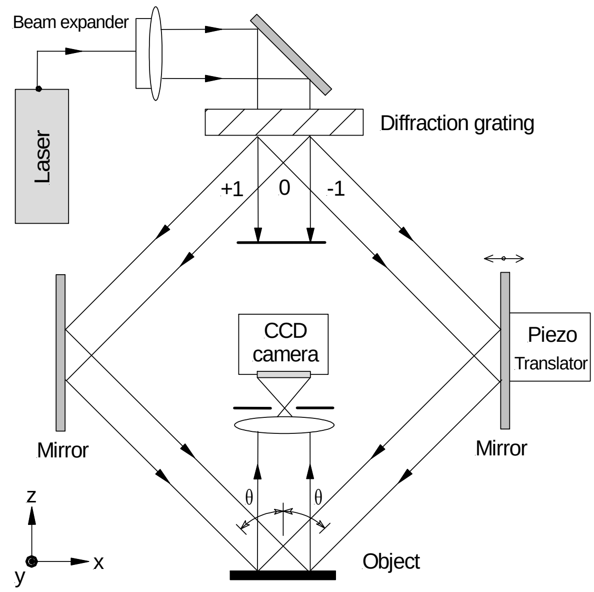


Fig. 2 – Optical arrangement for in-plane displacement sensitive speckle pattern interferometer based on a dual-illumination method .

The laser beam is split in two beams at an angle of 2θ using a beam splitter (e.g. diffraction grating). These two object beams generate their own speckle patterns which are added coherently and form a resulting subjective speckle at the detector of a CCD camera. The interference intensity in this speckle pattern is given by

$$I_1(x,y) = I_0(x,y) + I_M(x,y)\cos\phi(x,y)\,, \tag{2}$$

where $I_0(x,y)$ is the background intensity, $I_M(x,y)$ is the intensity modulation of the speckle interference pattern, $\phi(x,y)$ is a random phase and (x,y) are the spatial co-ordinates in the reference frame of the image.

Deformation of the object changes the relative phase $\phi(x,y)$ of the interference patterns, thus another speckle pattern is formed and the intensity recorded in the deformed state becomes

$$I_2(x,y) = I_0(x,y) + I_M(x,y)\cos\left(\phi(x,y) + \Delta\phi(x,y)\right), \tag{3}$$

where $\Delta\phi(x,y)$ is the phase change caused by the deformation. Subtraction of the actual intensity $I_2(x,y)$ from the stored intensity $I_1(x,y)$ by image processing produces the real-time correlation fringes distribution [8], according to Eq.

$$\Delta I(x,y) = \left|I_2(x,y) - I_1(x,y)\right| = \left|2I_M(x,y)\cdot\sin\left(\phi(x,y) + \frac{\Delta\phi(x,y)}{2}\right)\cdot\sin\frac{\Delta\phi(x,y)}{2}\right|, \tag{4}$$

where $\sin\left(\phi(x,y) + \Delta\phi(x,y)/2\right)$ represents the speckle noise with random variation.

Equation (4) describes the modulation of the high frequency noise by a low-frequency interference pattern related to the phase difference term $\Delta\phi(x,y)$.

For such a double illumination arrangement, correlation fringes represent contours of equal in-plane displacement component parallel to the plane containing the two illumination beams. The phase change $\Delta\phi(x,y)$ is related to an object movement in the direction of the sensitivity vector **S** ($\Delta\phi = \mathbf{S}\cdot\mathbf{u}$). It can be shown [8] that the resultant sensitivity component for an in-plane arrangement (Fig. 1) is given by

$$\underline{S} = \left(S_x, 0, 0\right)^{\mathrm{T}}, \quad S_x = \frac{4\pi}{\lambda}\sin\theta, \tag{5}$$

where θ is the illumination beam's angle of incidence to the surface normal.

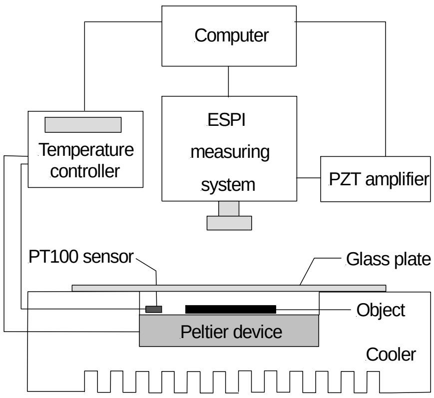
Measurement of the in-plane component u_x requires that the illumination beams are arranged parallel to the *x*-*z* plane. The presence of the term $\sin\theta$ in Equation (5) enables changing the in-plane sensitivity by modifying the illumination direction. The displacement can be calculated when the phase change $\Delta\phi(x,y)$ is known according to the formula

$$u_x(x,y) = \Delta\phi(x,y)\cdot\frac{\lambda}{4\pi\sin\theta}. \tag{6}$$

By counting the number (*N*) of fringes at every object point, the deformation of the object's surface in fractions of the laser wavelength is obtained. The measuring direction is orthogonal to the viewing direction in the plane which is produced by the two illumination directions. If the illumination directions are produced by parallel light beams, the measuring direction is constant in the whole measuring field.

Instrumentation for the in-plane, one dimensional ESPI set-up includes typical components: a Nd:YAG laser, output power 100 mW, wavelength 532 nm and optical elements presented in Fig. 2. The beam splitter used was a diffraction grating with 1 200 lines/mm, zero order being absorbed and the "+1" and "–1" orders representing the two illumination beams for the in-plane ESPI, measuring field was about 20×20 mm. The image processing system consists of a CCD camera with FireWire technology, 8 bit, 1024×1024 pixels resolution and self-developed software for image acquisition and automated evaluation of interference images.

Figure 3 shows the experimental set-up developed to measure in-plane thermal strain of the carbon fibre specimens. It consists of two main parts: the ESPI measuring system and the heating/cooling device with temperature controller.



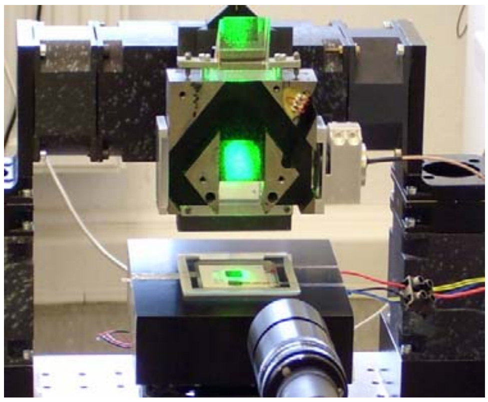


Fig. 3 – Measuring setup for measuring the CTE and thermal behaviour.

Heating/cooling of the thin layered foil was achieved in a small temperature chamber operating between $5 \div 70$ °C and based on a Peltier device (thermoelectric module). The Peltier device was driven by a highly accurate temperature controller. The advantages of no moving parts, no noise, no vibration, very small size, fast temperature response, long life, capability of precision temperature control, make thermoelectric devices very suitable in applications with speckle interferometry.

Uniform heating/cooling of the specimen and precise determination of its temperature at the measurement time proved to be a critical point in connection with computation accuracy of the CTE. There are certain parameters which have to be taken into consideration, such as thermal conductivity and the heat transfer from the Peltier device to the specimen. Several tests with an infrared thermography system demonstrated that a uniform temperature field can be assumed in the thin specimens during heating and cooling periods. Other tests revealed only very small differences between indications of a resistance thermometer (PT 100) attached on the Peltier device surface as well as on the thin foil surface.

Stationary conditions required during the ESPI phase shifting procedure can be easily achieved using the adequate control routine of the thermoelectric module. Real time observation of the correlation fringes during the thermal expansion is desirable and very helpful because certain fringes and phase perturbations can occur at temperatures higher than 50 °C. This effect is introduced by the thermal convection currents flowing around the specimen. Thermal currents can change the refractive index of the air surrounding the measuring object and hence introduce phase changes in the laser beam propagating through it. The problem can be overcome by preventing fresh air coming into the surroundings of the specimen.

3. EXPERIMENTAL RESULTS

The specimens were positioned on the surface of Peltier element without any fixation. Friction is minimized by a thin film of heat transfer paste. This procedure guarantees a free expansion and avoids any mechanical stresses within the specimen. As a disadvantage, a small rigid body rotation can occur. The specimen's surface was coated in fine white powder to increase the contrast of the ESPI fringes. A spray-on developer used for crack detection is ideal.

Validation of experimental technique above described was done by application to a sample with known thermal proprieties. A reference flat sample made of aluminium (EN AW 5754) with sides of 10×10 mm and 2 mm thick was investigating in order to determine the CTE.

In-plane deformations due to thermal expansion at different temperatures were measured by ESPI. Measurements were carried out during heating-up periods, in the interval 20 °C to 60 °C with temperature steps of 5 °C. Temperature at the measurement step was recorded with the thermo-resistance, after reaching the stationary conditions. This could be easily observed looking at the live correlation fringes. The experimental results of one measurement step can be observed in Fig. 4. Figure 4a presents the image of the sample illuminated by ambient light. Speckles image is presented in Fig. 4b and the phase map obtained as difference between a reference state and a loaded case state corresponding to a temperature change of 5°C is shown in Fig.4c. For eliminating the noise a phase filter is applied (Fig. 4d). Unwrapping of modulated phase map and introducing of sensitivity value explained in Eq. (5) lead to the in-plane deformation in the horizontal direction as shown in the Fig. 4e. Because the reference point (zero displacement) was placed in the middle of the specimen, as in reality, the free expansion produces symmetrical displacements about this point. As expected, in the ideal case of no rigid body rotations, the isolines of x displacements are parallel with y-axis. Thermal strains are generated by differentiation as shown in the Fig. 4f.

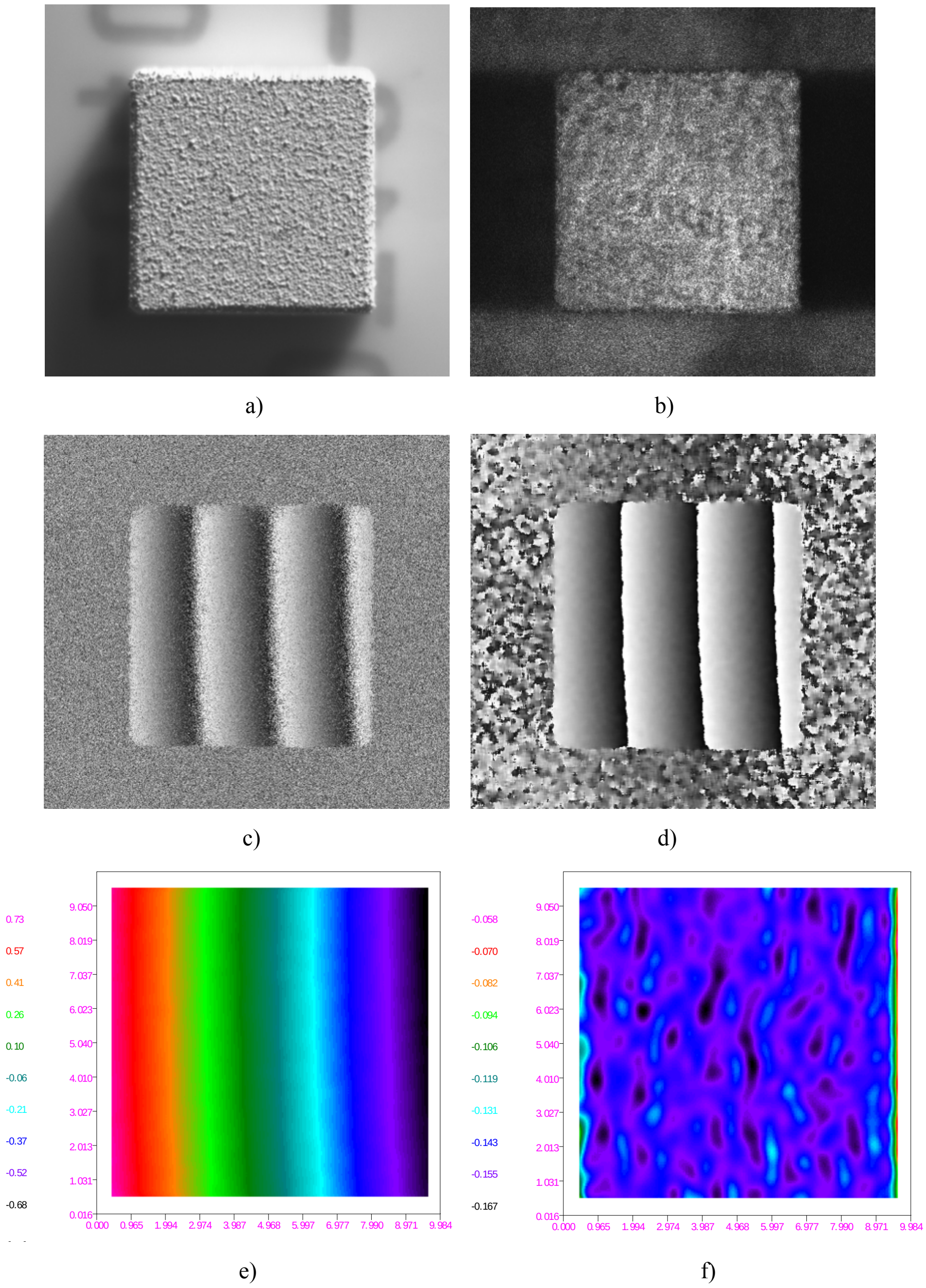


Fig. 4 – Thermal expansion of an aluminium sample measured by ESPI:
a) sample view; b) speckle pattern; c) phase map; d) filtered phase;
e) displacements (u_x), f) strains (ε_x).

The strain value of one measurement step was obtained by averaging the full field values over the specimen area, using a special software function called “gauge” that enables to get values over a defined polygonal area. Dividing the thermal strain to the temperature change the CTE can be calculated. An accurate result is obtained by calculating the slope of the curve strain to temperature range.

The calculated CTE mean value of 24.6×10^{-6} /°C is in very good agreement with the existed textbook value for aluminium alloy of 23.9×10^{-6} /°C. The relative deviation under 3% proves that the method of ESPI to get the thermal strain is valid and can be successfully used to complex structures of different materials.

The above described technique has been applied for a thin layered foil of two different materials, a commercial strain gauge solder terminal. The experimental results can be observed in Fig. 5. Figure 5a presents the image of the solder terminal after the surface preparation. The specimen was placed of the Peltier device surface in such way that one of its symmetry axis is aligned with the measuring direction of the speckle interferometer. This simplifies the results understanding and reduces the post-processing operations to get the thermal strain. Filtered phase map obtained as difference between a reference state and a thermally loaded state corresponding to a temperature change of 5°C is shown in Fig. 5b. After phase unwrapping the in-plane deformation in the x direction is obtained as shown in the Fig. 5c. In case of two materials with different thermal expansion non-uniform displacements field is measured. The difference in slope can be noticed in Fig. 5d (the zero displacement point was set in the middle of the specimen). Thermal strains (ε_x) are generated by differentiation as shown in the Fig. 5e. A horizontal profile (dashed line) shows the different thermal behaviour of two materials and the thermal strain concentration that occur at their interface. The measured value of the CTE for the two materials was: $\alpha_{Cu}=19.6\times10^{-6}$ /°C for copper alloy and $\alpha_{PA}=42.4\times10^{-6}$ /°C for polyamide backing. Textbooks values for copper alloy (constantan) give a value of $\alpha_{Cu}=18.8\times10^{-6}$ /°C and between $25\div80\times10^{-6}$ /°C for polyamide depending on producer and type. A good agreement with the existed textbook values can be noticed in this case too.

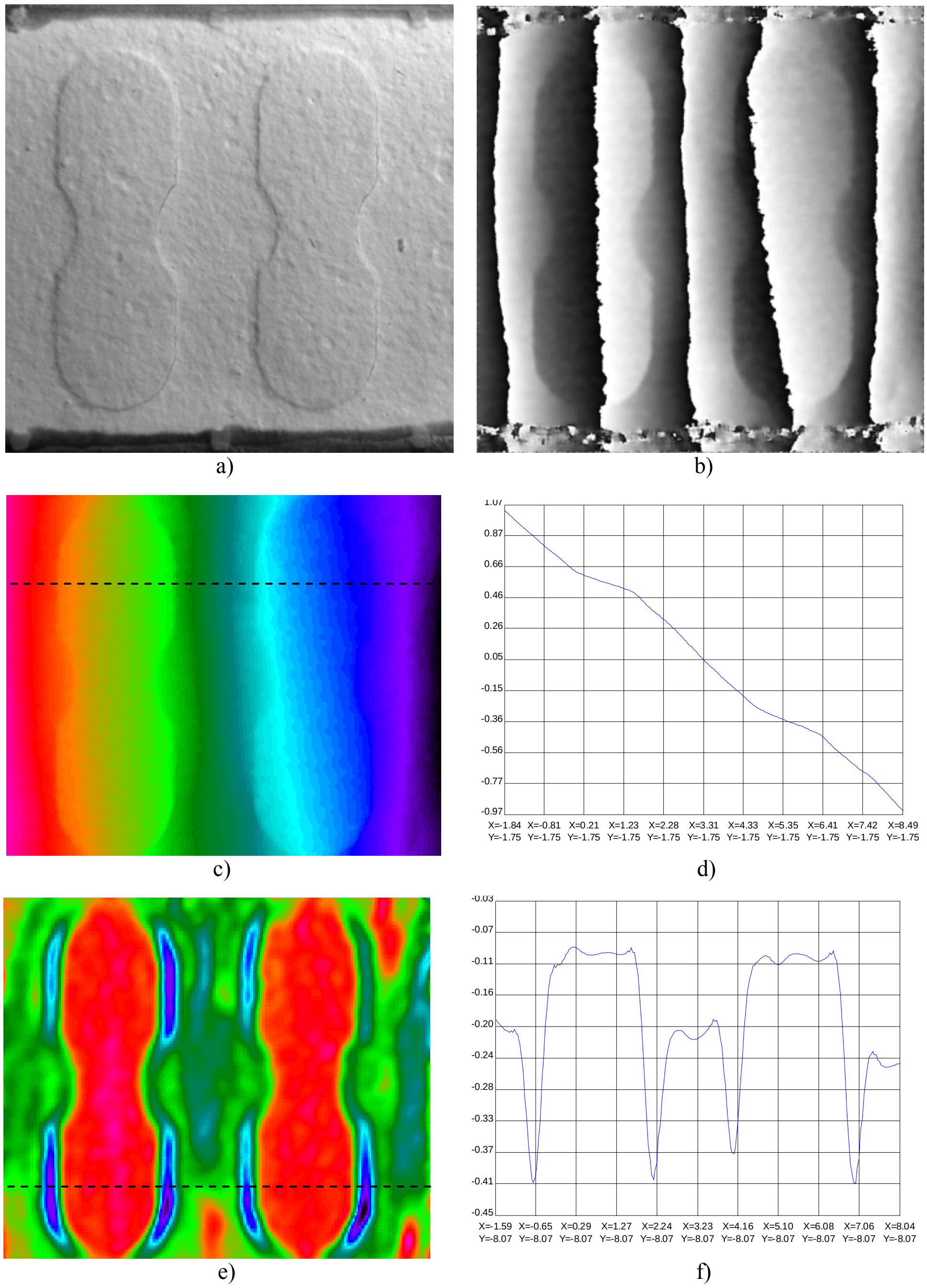


Fig. 4 – Thermal expansion of a layered foil of different materials measured by ESPI: a) sample view; b) filtered phase map; c) displacements (u_x), d) horizontal profile of displacements; e) strains (ε_x); f) horizontal profile of strains.

4. CONCLUSIONS

In this paper it has been shown that the full-field and non-contact technique of the ESPI is well suited to analyse the thermal expansion behaviour and to determine the CTEs for layered foils build of different materials. The determination method of CTE was validated on an isotropic specimen made of aluminium. It could be proved that the optical method of ESPI has special advantages for the investigation of thin (<1 mm) and small (<10 mm) specimens, for which other methods cannot be applied. Another advantage is that the correlation fringes or phase maps give important information about the uniformity or non-uniformity of the strain field in the specimen as for example of thin layered structures. The overall accuracy of the CTE measurement by the suggested method was estimated at 0.1×10^{-6} [1/°C]. Conditions for such a high accuracy is the precise measurement of the thermal strain and the precise temperature measurement and control.

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