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Thermal Strain Analysis of Composite Materials by Electronic Speckle Pattern Interferometry

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This study discusses a non-contact optical technique(electronic speckle pattern interferometry) that is well suited for thermal deformation measurement without any surface preparation and compensating process. Fiber reinforced plastics($[0]_{16}$, $[0/90]_{8S}$) were analyzed by ESPI to determine their thermal expansion coefficients. The thermal expansion coefficient of the transverse direction of a uniaxial composite is evaluated as 48.78×10^{-6}(1/℃). Also, the thermal expansion coefficient of the cross-ply laminate $[0/90]_{8S}$ is numerically estimated as 3.23×10^{-6} (1/℃) that is compared with that measured by ESPI.

Key Words : Electronic Speckle Pattern Interferometry(ESPI), Image Processing, Composite Material, Thermal Expansion Coefficient, Classical Lamination Theory(CLT)

1. Introduction

When materials are used at a high temperature atmosphere, the material properties must be matched with temperature conditions. However, it is very difficult to measure thermal strain in structures with strain gages, because the instrument used for the strain measurement is also influenced by the temperature. Although temperature effect can be eliminated by the dummy gauge hear the active gauge. The resistance of strain gauges is effected by the temperature (Balbas et al., 1989; Malmo et al., 1987). But this procedure (temperature compensation technique) is not reliable where there is a temperature gradient. Furthermore, if the strain field is transient, (e.g. thermal shock) this method is not applicable at all. Instead, the in-plane moirē method has been used successfully to measure the thermal strain. However, one must place a grating on the surface of the specimen for the techinque.

Because, mechanical or electronic measuring methods are in general not applicable, many non-contact (optic) methods have been introduced. Some researchers (Shchepinov et al., 1996; Kim et al., 1998; Løkberg et al., 1985) proposed an electronic speckle pattern interferometry method (ESPI) that can measure displacements without the preparation of the structure surface. In this study, we used ESPI to measure the thermal strain at high temperature. Also, we presented the results of a simple experiment to explore the capability of a laser speckle interference method as the measurement of thermal strain of the fiber-reinforced composite materials.

Composite materials have made startling progress in astronautics industry. As materials for

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aeronautics, composite materials undergoe serious environment, high temperature, air friction, and vibration etc. Fibrous composites are hybrid materials of which the composition and internal architecture are varied in a controlled manner. Therefore, the basic mechanical properties must be accurately measured in order to match their performance to the most demanding structural roles (Wang and Choi, 1979; Reddy, 1996). Especially, it is very important to determine the thermal strain.

A recent paper (Aswendt and Hofling, 1992) related to thermal strain analysis studied on the various kinds of laminates by ESPI and only experimentally determined properties. However, it is necessary to know each thermal property in manufacturing and designing laminates. In this study, the thermal strain of the composite materials are numerically estimated and confirmed experimentally. We use composite material specimens with the fiber orientations of [0°] and [90°] to determine the thermal expansion coefficients of the fiber direction (α_L) and the transverse direction (α_T). Also, using the values of the uniaxial composite, the thermal expansion coefficient (α_{yy}) of cross-ply laminate $[0/90]_{8S}$ is estimated by classical lamination theory(CLT) and compared with that by ESPI.

2. Determination of In-plane Displacement

The photons emitted from a laser take the same frequency, progressive direction, and polarization to make the same phase and velocity. It means that the laser light makes spatial coherence and temporal coherence. Based on these specific characters, the techniques of the holography interferometry and the speckle interferometry have been developed with the computer science that allows to do real-time measurement and sampler processing work (Lϕkberg, 1980). Recently, the electronic speckle pattern interferometry(ESPI) developed from the speckle interferometry has been applied to composite materials for measuring in-plane and out-of-plane deformation(Vikhagen and Lϕkberg, 1990). The optical arrangement is according to the displacement direction; and the optical arrangement for y-direction (gravity direction) displacement measurement is handled in experiment of this study.

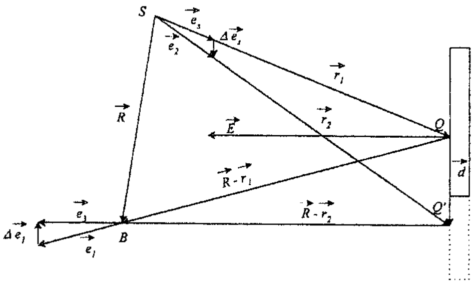


Fig. 1 Relationship between the displacement vector of surface point and phase difference

Also, the quantitative determination of the object surface displacement fields by the interference fringe pattern is one of the main tasks in ESPI. To this end, it is necessary to establish the relations between the fringe parameters and the surface displacement components of a strained object. One way for reaching this objective involves the application of the geometrical model.

A diagram for the illumination and the observation of the corresponding point Q and Q' on a surface before and after its deformation is shown in Fig. 1. The virtual image reconstructed through a double exposure method can be considered as two simultaneously images-existing surface and strained object.

The case involves the phase difference of light waves from the displacement of the point Q on the object surface. The phase difference δ between two interfering lights can be written:

$$\delta=\frac{2\pi}{\lambda}(SQ'B-SQB) \tag{1}$$

where λ is the wavelength of laser light;

$SQ'B$ is the optical path from the light source S through Q' to point B; SQB is the analogous optical path of Q.

The optical path can be presented with vectors as the following way:

$$SQ'B=\vec{e}_2\vec{r}_2+\vec{e}_3(\vec{R}-\vec{r}_2) \tag{2}$$

$$SQB=\vec{e}_S\vec{r}_1+\vec{e}_1(\vec{R}-\vec{r}_1) \tag{3}$$

where $\vec{r}$, $\vec{r}_2$, and $\vec{R}$ are the vectors of the point

Q, Q' and B from S respectively; $\vec{e}_S$, $\vec{e}_1$, and $\vec{e}_2$, $\vec{e}_3$ are the unit vectors of illumination and observation of the points Q and Q', respectively.

In this optical system, the distance from the light source to the object is much greater than the displacement value $|\vec{d}|$:

$$|\vec{d}| \gg |\vec{r}_1| \cong |\vec{r}_2|$$

For the relative vector directions we can assume

$$\Delta\vec{e}_s \perp \vec{r}_2, \ \Delta\vec{e}_1 \perp (\vec{R}-\vec{r}_2)$$

Substituting Eqs. (2) and (3) into Eq. (1), if this assumption is valid, the phase difference δ is formed:

$$\delta=\frac{2\pi}{\lambda}(\vec{e}_1-\vec{e}_s)\,\vec{d} \tag{4}$$

Bright interference fringes will be observed when

$$\delta=2\pi n \qquad n=0,\ 1,\ 2,\ \cdots \tag{5}$$

and dark ones when

$$\delta=2\pi\left(n-\frac{1}{2}\right) \qquad n=1,\ 2,\ \cdots \tag{6}$$

where n is the absolute order of the bright or dark fringes at the surface point under consideration.

Substitution of Eqs. (5) or (6) into Eq. (4) leads to the following equation for the bright fringes:

$$(\vec{e}_1-\vec{e}_s)\,\vec{d}=n\lambda \qquad n=0,\ 1,\ 2,\ \cdots \tag{7}$$

and for the dark ones

$$(\vec{e}_1-\vec{e}_s)\,\vec{d}=\left(n-\frac{1}{2}\right)\lambda \qquad n=1,\ 2,\ \cdots \tag{8}$$

In this paper, only Eq. (7) will be considered.

In order to determinate α_L and α_T, unidirectional laminates are investigated. Starting at room temperature, the thermal expansion coefficients are obtained from the in-plane strain caused by a temperature increase or decrease (ΔT). A first speckle pattern is recorded at the temperature T_1 and the fringe formed at T_2 are evaluated by computer to provide the strain value ε_{yy} associated with ΔT. Then, the coefficient of thermal expansion is given by

$$\alpha_{ij}=\frac{\varepsilon_{ij}}{\Delta T} \tag{9}$$

The fringes spacing is inversely proportional to the thermal expansion rate of the specimen, and the fringe orientation is perpendicular to the in-plane displacement produced by the thermal expansion. Also, the thermal expansion coefficient of $[0/90]_{8S}$ composite material laminated is numerically evaluated (Kobayashi, 1993); and the results are compared with those measured by ESPI.

3. Analysis of Interferometric Fringe

The fringe patterns produced on the composite material by heating are analyzed in vertical direction for measuring the in-plane displacement. But the images of fringe patterns are not clear in contrast and in visibility compared with those of the holographic interferometry by using the smoothing reference beams. To enhance the fringe patterns and to remove the speckle noise, a series of image processing, such as the enhancement of fringe patterns, smoothing, thresholding, expansion-contraction, thinning, and labeling are performed; and the enhanced fringe image is compared with the original interferometric fringe image.

The distribution of the processed image intensity is thinned by the linear interpolation (Kim et al., 1998). Suppose two adjacent thinned fringes of n and $n+1$ order, and the displacements u of each fringes are given by

$$u_n=\frac{n\lambda}{2\cos\theta} \tag{10}$$

$$u_{n+1}=\frac{(n+1)\lambda}{2\cos\theta} \tag{11}$$

And the difference between two displacements of the adjacent fringes Δu is given to as follow;

$$\Delta u=\frac{\lambda}{2\cos\theta} \tag{12}$$

As the above equation is applied to a general fringe pattern on the surface, a normal strain ε_{yy} may be interpreted as follows;

$$\varepsilon_y=\frac{\Delta u}{F}=\frac{\lambda}{2F\cos\theta} \tag{13}$$

where F is a fringe spacing.

4. Image Processor and Optical Arrangement

The ESPI technique has been used in the various fields of optical tests and measurements. In ESPI method, the lenses and the films used in the speckle pattern interferometry have replaced a CCD camera (resolution 480×512) and a TV monitor.

The development of computer science takes electronic signals to produce the interference fringe patterns with real-time by displaying on a TV monitor without any photographic processes. The block diagram for the image processing system of this study is described in Fig. 2.

The frame grabber takes the reference image before deformation with 256 gray level to record the memory. And then, the reference image is compared with the live image under deformation every 1/30 sec through electronic subtraction process.

In order to achieve the objective, the configuration of an optical path must be differently considered. The optical path for the measurement of thermal strains, which are intended to expand to y-direction (gravity direction), is shown in Fig. 3. The Ar^+ Laser (the wave length, 514.5 nm) is used as a source. To make a plane wave from the spherical wave that is generated by a beam expander, the collimate lenses are positioned. The mirrors 6 and 7 illuminate the surface of object upward and downward, respectively. The vertical mirrors inclined at 35 degree (to the observation direction) are positioned adjacent to the specimen. To validate this ESPI system, the pure copper (30×30 mm) (the thermal expansion coefficient $16.5\times10^{-6}(1/℃)$) is used as a specimen. The results measured by ESPI agree with that of the strain gage within 10%.

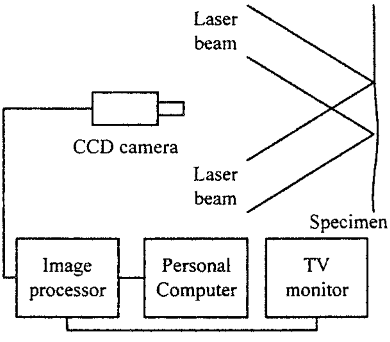


Fig. 2 Image processing system

5. Specimen

Investigations are described on the thermal strain of the continuous fiber composites. Measurements were carried out with the samples of the carbon fiber reinforced plastics (denoted by CFRP) of different angles $[0]_{16}$, and $[0/90]_{8S}$.

The material property and geometry of the specimen are listed with table 1. The specimen size is 170 mm by 20 mm and the thickness of 2 mm. In order to increase the degree of reflection, object surfaces are uniformly coated with white color. The specimen is fixed on a heating plate,

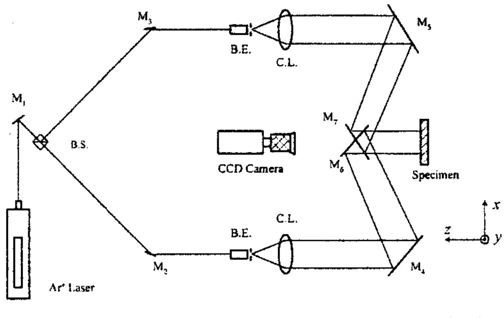


Fig. 3 Optical arrangement for in-plane displacement measurement
M : Mirror, B. S. : Beam splitter, B. E. : Beam expander, C. L. : Collimate lens

Table 1 Material property and geometry of specimen

Longitudinal moduli E_L	Transverse moduli E_T	In-plane shear moduli G_{LT}	Poisson's ratio ν_{LT}
134 GPa	7.5 GPa	5.12 GPa	0.31
Gage length	Num. of ply	Ply thickness	Laminate thickness
150×20 mm	16	0.125 mm	2 mm

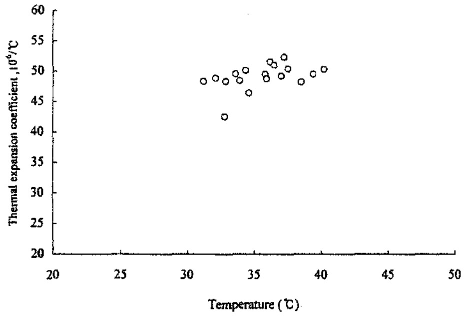
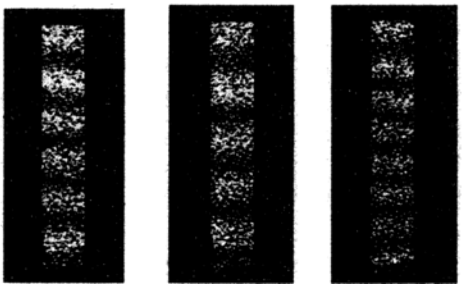
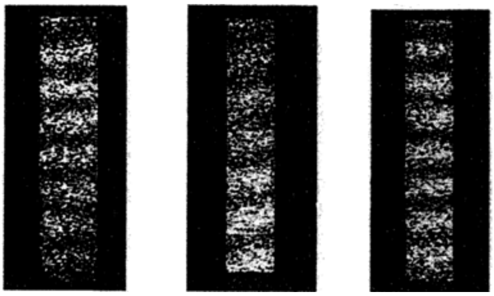


Fig. 4 Thermal expansion coefficient (α_T) vs. temperature



29.7-30.0(℃) 36.0-36.4(℃) 37.0-37.4(℃)

Fig. 5 Interferometric fringe patterns of composite materials $[90]_{16}$



33.2-39.4(℃) 35.2-38.2(℃) 41.5-47.4(℃)

Fig. 6 Interferometric fringe patterns of composite materials $[0/90]_{8S}$

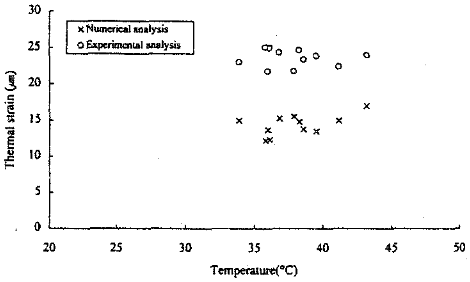


Fig. 7 Thermal strain (ε_y) vs. temperature for $[0/90]_{8S}$

which is controlled with a voltage regulator. As the upper side of the specimen with tab (20 mm) is restricted. The free thermal expansion is allowed to y-direction. To control the temperature, the primary and secondary voltage regulators are used. α_L and α_T of the unidirectional laminate are firstly investigated. The thermal expansion coefficients are obtained from the in-plane strain caused by a temperature change.

6. Results

This study analysed the thermal strain of composite materials laminated by $[0]_{16}$, $[90]_{16}$ and $[0/90]_{8S}$. Using composite material $[90]_{16}$, α_T with CFRP manufactured by SK Chemical Co. (USN 125) can be evaluated as 48.78×10^{-6} (1/℃), which is the average of data between 30 and 40℃ obtained by ESPI method. But, using the composite material $[0]_{16}$, α_L can not be measured with the ESPI system, because the thermal deformation is infinitesimal due to small temperature change. Therefore, α_L is assumed as zero. Refering to similar data, the value is record as -0.7×10^{-6}(1/℃) at 21℃ (Reinhart at al., 1989). But, the data vary according to manufacture.

The results of α_T are shown in Fig. 4. Also, Fig. 5 is the fringe patterns of the composite materials $[90]_{16}$ obtained from the ESPI method at each temperature change (about ±0.4℃).

α_L and α_T obtained from the unidirectional laminate are used in a numerical analysis program to estimate the thermal expansion coefficient of symmetric laminates (supposing that α_L is zero). α_y of the cross-ply laminate $[0/90]_{8S}$ was estimated as 3.23×10^{-6}(1/℃) between 30 and 40℃. Fig. 6 shows the fringe patterns of composite materials $[0/90]_{8S}$ obtained from the ESPI method by a temperature variations (about ±5℃). The results by the numerical analysis are compared with experimental results shown in Fig. 7. There exist errors between experimental and numerical results. However, note that both distributions are very similar.

7. Conclusion

In order to determine the thermal expansion coefficient, ESPI method is used in this study. This paper presents the results of a simple experiment to explore the capability of a laser speckle interference method for measuring of the thermal strains of the carbon fiber reinforced composite materials — $[0]_{16}$, and $[0/90]_{8S}$.

Using unidirectional laminate $[90]_{16}$ manufactured by SK Chemical (USN125), α_T is evaluated as 48.78×10^{-6}(1/℃), which is used as that of the transverse direction and the thermal expansion coefficient of the cross-ply laminate $[0/90]_{8S}$ is numerically estimated as 3.23×10^{-6} (1/℃), that is compared with those obtained by ESPI. But, compared with the numerical data based on CLT, the data show some error. It is believed that the error is caused by the experimental condition (air distribution and heating).

Also, the transverse thermal expansion coefficient is several times the axial expansion and the difference in the thermal expansion coefficient will generate sufficiently high residual stresses during cool-down.

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References

Kobayashi, A.S., 1993, *Handbook on Experimental Mechanics Second Revised Edition*, VCH Publishers, pp. 829~904.

ASM INTERNATIONAL Handbook Committee, 1989, "Engineered Materials Handbook," *ASM International*, Vol. 1 pp. 49~54.

Reddy, J. N. 1996, *Mechanics of Laminated Composite Plates Theory and Analysis*, CRC Press, pp. 23~48.

Malmo, J. T., Lϕkberg, O. J. and Slettemoen, G. A., 1987, "Interferometric Testing at Very High Temperatures by TV holography (ESPI)", *Experimental Mechanics*, pp. 315~321.

Kim, Koung-Suk Jung, Hyun-Chul, Kang, Ki-Soo Lee, Jong-Kook Jang, Soon-Suck and Hong, Chung-Ki, 1998, "In-plane Strain Measurement by using the Electronic Speckle Pattern Interferometry," *KSME International*, Vol. 12, No. 2, pp. 215~222.

Balbās, M. Fraile, D. Gascon, F. Varade A. and Vilarropig, P. 1989, "Thermal Expansion Tensor Measurement by Holographic Interferometry," *Applied optics*, Vol. 28, No. 23, pp. 5065~5068.

Lϕkberg, O. J. Malmo, Jan T. and Slettemoen, Gudmunn A. 1985, "Interferometric Measurements of Tigh Temperature Objects by Electronic Speckle Pattern Interferometry," *Applied Optics*, Vol. 24, No. 19, pp. 3167~3172.

Lϕkberg, O.J. 1980, "Electronic Speckle Pattern Interferometry," *Physics in technology*, No. 11, pp. 16~22.

Aswendt, P. and Hofling, R. 1993, "Speckle Interferometry for Analysing Anisotropic Thermal Expansion-Application to Specimens and Components," *J. of Composites*, Vol. 24, No. 8, pp. 611~617.

Shchepinov, Valery P. Pisarev, Vladimir S. Novikov, Sergey A. Balalov, Vitaly V. Odintsev Igor N. and Bondarenko, Mikhail M. 1996, *Strain and Stress Analysis by Holographic and Speckle Interferometry*, John Wiley and Sons, pp. 122~196.

Vikhagen. E. and Lϕkberg O. J., 1990, "Detection of Defects in Composite Materials by Television Holography and Image Processing," *Mater. Eval.*, No. 48, pp. 244~248.

Wang, S. S. & Choi, I., 1979, "Boundary Layer Thermal Stress in Angle Ply Composite Laminates," *Modern Development in Composite Material and Structures*, J. R. Vinson, Ed., pp. 315~341.