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E.S.Dergal, O.T.Kudrevatykh, N.O.Quinn

Oles Honchar Dnipro National University

A DILATOMETER FOR THE CARBON FIBER COMPOSITE TUBES

Розроблено прилад та метод вимірювання коефіцієнта теплового розширення композитів, заснований на цифровому запису лазерної плями. Спеціальними утримувачами для фіксації тестового об'єкта і оптичним розташуванням дилатометра пропонується вимірювати деформації вуглецевого волокна армованих композитних трубок за рахунок ефекту різниці температур. До переваг методу відносять високу чутливість і здатність з високою точністю досліджувати композитні трубки різної довжини (від 0,2 м до 2 м). Розроблена спеціальна теплова система для зміни температури в об'єктах, що вивчаються, на основі провідності вуглецевого волокна. Чутливість дилатометра може регулюватися в залежності від розміру об'єкта, що вивчається.

Ключові слова: *композитні матеріали, вуглецеве волокно, посилене пластиком, дилатометр, коефіцієнт теплового розширення, компоненти аерокосмічної інженерії, оптичний метод.*

Разработан прибор и метод измерения коэффициента теплового расширения композитов на основе цифровых записей о смещении лазерного пятна. Специальными держателями для фиксации испытательного объекта и оптическим расположением дилатометра предлагается измерить деформацию углеродного волокна усиленных композитных труб из-за действия перепада температуры. Преимущества метода включают высокую чувствительность и способность с высокой точностью исследовать композитные трубки с различной длиной (от 0,2 м до 2 м). Разработана специальная тепловая система для изменения температуры в исследуемых объектах на основе проводимости углеродного волокна. Чувствительность дилатометра может регулироваться в зависимости от размера исследуемых объектов.

Ключевые слова: *композитные материалы, углеродное волокно, усиленное пластиком, дилатометр, коэффициент теплового расширения, компоненты аэрокосмической инженерии, оптический метод.*

A device and method for measuring the coefficient of thermal expansion of composites based on digital recordings of the indicating laser spot displacement has been developed. Specific holders for support of the test object and an optical arrangement of the dilatometer are proposed to measure the deformation of the carbon fiber reinforced compositetubes due to temperature changes. The advantages of the system include high sensitivity and the ability to examine composite tubes with varied length (from 0,2 m to 2 m) with high accuracy. A special heating system for temperature changes in examined objectsbased on conductivity of carbon fiber has been developed. The sensitivity of the dilatometer can be adjusted in according to the size of examined objects.

Keywords: *composite materials, carbon fiber reinforced plastic, dilatometer, thermal expansion coefficient, aerospace engineering components, optical method.*

Introduction

Composites have gained widespread use in aerospace and transport industries. Almost 80% of Boeing 787 Dreamliner body are made of composites. The booster body, thermal protection for the payload fairing, solar cell substructures, primary structure for the space telescopesare made with use of the composite materials (CM).The rapid growth in the use of CM is confirmed by expert assessments of the market leaders. According to the forecast, the volume of the world market of CM for the period from 2016 to 2022 should grow by almost 60%, from 72,58 billion dollars to 115,43 billion US dollars [1].

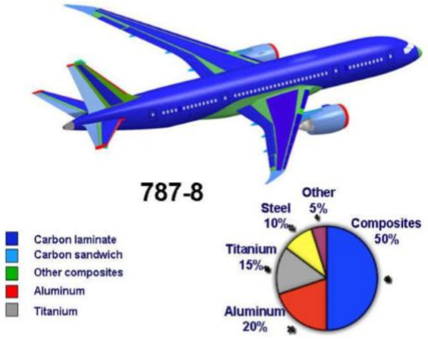


Fig.1. The use of composites in the Boeing 787 Dreamliner [2]

The outstanding feature of the composite materials is that they are not a monolithic material in the classical sense of the word, for example, metals. CM is de factoformationcreated in the manufacturing process. Depending on the matrix material distinction is made between polymeric, metallic, ceramic, carbon, and other composite materials. By selecting and proportioning filler and matrix, choosing orientation of the reinforcing fibers, it is possible to obtain materials with predetermined performance characteristics, such as robustness, rigidity and thermal stability [3].

However, the physical and mechanical properties of CM products are largely dependent on the technological excellence of the CM production process.

In the process of manufacturing CM structural elements experience a variety of technological impacts particularly thermal and mechanical.The imperfection in the technological process and equipment or human errorslead to defects formation exceedingthe permissible requirements of design documentation andcause product failures.The physical, mechanical and strain-strength properties of composite materials and products can be significantly affected by the binding substance and reinforcement structure divergency, discontinuity in the reinforcing fiber, porosity in the bonding adhesive, localized air blisters andviolations of the molding process[4].For example, $\underline{+}2^{0}$ deviation in the fiber layup drives up thermal deformation of the carbon fiber reinforced CM by 18% [5].

The stability of linear dimensions over a wide range of temperatures is an indispensable requirement in the manufacturing of load-bearing structures for precision equipment of space vehicles, such as antennas, control systems and space-based telescopes. Thus, it is necessary to design equipment and methods for testing composite materials, as well as elements of the spacecraft structures, intended to assess the value and homogeneity of the thermal deformation.

The main characteristic of the thermal deformation is the coefficient of thermal expansion (CTE). It measures increase in the size of the test object per degree in temperature change [6].

The section of physics and metrology that studies the dependence of the size change on temperature, pressure, humidity, electric and magnetic fields, ionizing radiations, etc. is called dilatometry.

An analysis of the current state of the problem solving

Presently manufacturers and researchers offer a wide range of equipment for dilatometry[7-15].

Depending on the method of obtaining informative parameters used for determination of the changes in test object dimensions the industrial and scientific dilatometers can be divided into several basic groups (table 1).

Table 1

Basic dilatometer types

Dilatometer type	Primary informative parameter	Sensitivity, m
Optical:		
- comparative	Displacement of the test object edge controlled by microscope	10^{-6}
- mechanical	Displacement of the light spot reflected by the mirror attached to the test object	10^{-5}-10^{-7}
- interferometric	Displacement of the interference fringes caused by distance changes between mirrors in Michelson interferometer one of which is attached to the test object	10^{-8}
- shadow	Change in the shadow dimensions of the test object caused by heating	10^{-6}-10^{-7}
Capacitive	Change in the capacitance of the parallel plate capacitor with one stationary and one moveable plate where moveable plate is attached to the test object and moves when object is heated	10^{-12}
Inductive	The change in the mutual inductance of the coils due to a change in their mutual disposition	10^{-11}
Radio-resonance	The change of the resonance frequency of the cavity resonator made from tested material caused by heating	10^{-14}
X-ray	Parametric variations in crystalline structure of the test object caused by heating	10^{-10}
Push-rod	Difference in expansion of the specimen and quartz or ceramic rode with well-defined CTE due to heating process	10^{-7}

It is worth noting that commercially available dilatometers and CTE measurement standards [6, 16-22] provide the opportunity to determine the CTE of the tested materials based on test data for the small samples (up to 0,05 m).

For example, according to [20] the determination of the CTE for carbon fiber reinforced composite materials is carried out by the thermal loading of the samples with a diameter of 30 ± 0,1 mm and a length of 40 ± 0,1 mm, which must be cut from the manufactured batch of products.

Upon that, strict requirements regarding the quality of the samples must be met, namely:

- cracks and chips are not allowed on samples;
- the end surfaces of the samples should be parallel and flat, the deviation from flatness should not exceed 0,01 mm.

The same requirements are in demand for determination of the CTE for composite materials used in aerospace industry accordingly to [21].

The CTE of the carbon fiber reinforced composite materials does not exceed 10^{-5} K^{-1},therefore the efforts of researchers in recent years are devoted to the development of highly sensitive optical methods such as speckle interferometry [23] and digital image correlation(DIC) [24]. Speckle interferometry dilatometer allows to determine the CTE through the registration of the speckle structure displacement due to heating process. The digital image correlation method allows the determination of the CTE using the correlation between pixel intensity array subsets on two or more corresponding images, which gives the integer translational shift between them dueto heating process. Nevertheless, both dilatometers can also be used only to determine the CTE of small samples (no more than 60 mm in length).

Problem definition

The mechanical properties of the carbon fiber reinforced polymer structures (CFRP) significantly depend on the orientation of the fibers, the number of layers, layup technology and other factors.The unique feature of CFRP is the anisotropy of thermal expansion determined by the laying pattern of reinforcing fibers, namely the CTE is minimal along the fiber and maximum in the direction perpendicular to the fiber [25]. The increase in the number of reinforcing layers and the optimization of their reinforcement scheme make it possible to minimize thermal deformations of the construction. For example, for CFRP with one layer of a reinforcing unidirectional matrix, the CTE can vary in a temperature range about $15x10^{-6}$-$30x10^{-6}$ K^{-1}, namely twice, but for the quasi isotropic CFRP in this temperature range CTE remains approximately constant at nearly 3 $x10^{-6}$ K^{-1} [26].

The thermal anisotropy in composite materials leads to a special selection of test samples, namely, the samples should be cut along the main axes of anisotropy so that the sample axis coincides with the axis of anisotropy and the CTE for anisotropic materials should be determined for each anisotropy axe. Thus, the process of determining the CTE of composite materials is very material-intensive and time-consuming.

At the same time, the slightest deviations from the manufacturing technology lead to the significant difference in the thermo-mechanical characteristics of the finished product from those provided by the design documentation.

Thus, the purpose of the research is to solve the problem of creating equipment and testing methods to determine with high accuracy the CTE of a finished CRFP product.

Research overview

Research was conducted with use of the CRFP square hollow sections such as those used in the manufacturing of truss structures of the space-based telescopes (fig.2).

Fig. 2. Space frame

Coefficient of thermal expansion (CTE) α for the CRFP samples can be defined as:

$$\alpha = \frac{\Delta l}{L\Delta t} , \qquad (1)$$

where Δl – section length change caused by heating; L – distance between fastening points; ΔT – temperature change.

Simple calculation shows that raising temperature by 1^0 for the samples with length in range 0,2 – 2 m and CTE nearly $10^{-7}K^{-1}$their extension be as large as 20 – 200 μm, based on initial length of the test object. Proceeding from this, the main technical requirements for the dilatometer under development were defined:

- sensitivity to displacements of the tube extension indicator should be no less than 1 μm;
- the accuracy of determining the sample temperature should be within$0,1^0$C;
- homogeneity heating and temperature stabilizing for the sample with accuracy within at least $0,2^0$C should be provided for at least 10 minutes;
- dilatometer protection against possible external vibrations should be provided.

Based on the technical requirements, we developed an optical dilatometer, consisting of two main units - a heating block and a measuring unit.

The heating of the test object was performed by using conductive properties of the carbon fiber.The sample was connected through collectors on its edges to a heating control unit consisting of an industrial thermostat using the RC113M-220V-250V2A PID-controller to ensure feedback to be carried out between the measuring unit and the heating block. The temperature control was carried out using a DS18b20 digital temperature sensor with a resolution of 0,0625 ° C/LSB at 12-bit mode connected to the control unit via the Arduino board.

The dilatometer design is shown in fig. 3.

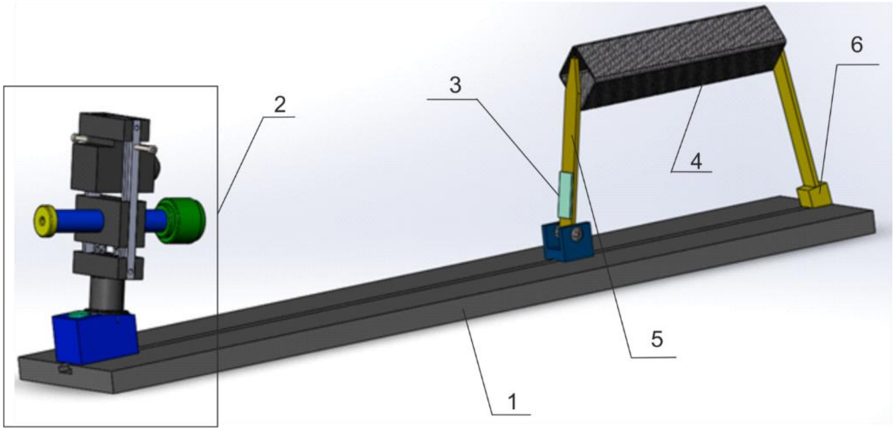
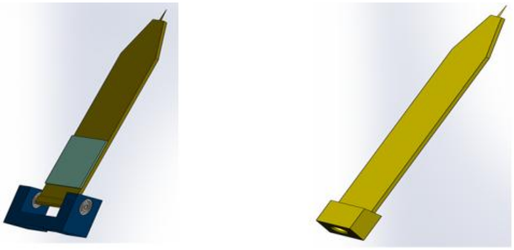


Fig. 3. Dilatometer for CRFP square hollow section:
1 – guide rail; 2 – laser-optical unit; 3 – mirror; 4 – test object;
5 – movable rack; 6 – rigid rack

The laser-optical unit combines a laser source (a 1 mW SSD laser) and a digital image recording unit based on a CCD array with a pixel size of 2,57 μm (fig. 4). The test object is placed on two racks with bases rigidly fixed on the guide rail.

Fig.4. Laser-optical unit

The rear rack is absolutely rigid, and the front rack is fixedly attached to the hinge (fig. 5a), so that its upper end is free to move when the test object expands due to heating. Racks have needle-shaped tips, on which the pipe is "suspended". A flat mirror attached to the front rack reflects a laser beam which forms a displacement indication spot on the CCD array.



a) b)

Fig. 5. Movable (a) and rigid (b) racks for test object placement

When the tested object is heated, it expands, causing inclination of the hinge rack. Such a change in the orientation of the rack causes the laser beam to change its direction after reflection from the fixed mirror on the rack. As a result, the indicating laser spot moves in the plane of the CCD array of the image recorder. The magnitude and direction of the displacement varies with length change of the heated section.

The computational model of the dilatometerallows to establish the relationship between the section length change *Δl*, the height of the rack*h*, the distance between movable rack and the CCD array*H*and the indicating laser spot displacements (fig. 6).

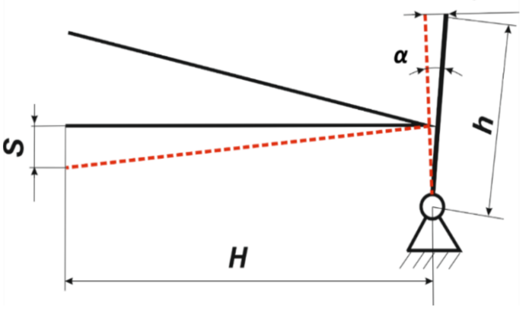


Fig.6. Computational model of the dilatometer

The change of the section length

$$\Delta l = \frac{h}{2H} * S \,, \tag{2}$$

where *h* – the height of the rack, H – the distance between movable rack and CCD array; S – the indicating laser spot displacement on CCD array.

Magnitude of *S* defines by

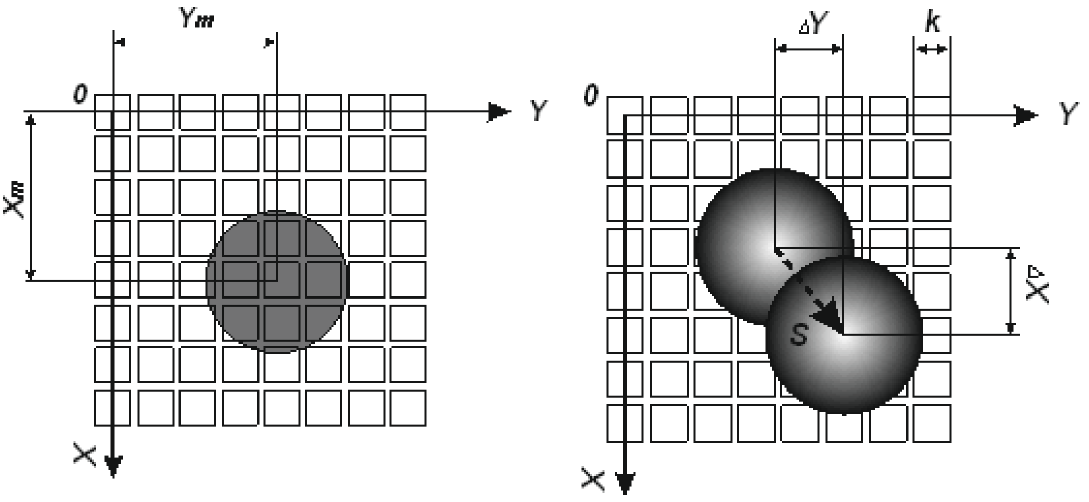
$$S = \frac{1}{2} k \left(\sqrt{X_{m2}^2 + Y_{m2}^2} - \sqrt{X_{m1}^2 + Y_{m1}^2} \right) \,, \tag{3}$$

where *k* – size of one pixel, X_m, Y_m– geometric coordinates of the indicating laser spot center before and after displacement (fig.7):

$$X_m = \frac{1}{N} \sum_{i=1}^{N} X_i \,, \tag{4}$$

$$Y_m = \frac{1}{N}\sum_{i=1}^{N} Y_i \,. \qquad (5)$$

In the course of computational experiments, it has been established that the displacement of the indicating laser spot in CCD array plane is in the range of 0,2 – 4μm for sections with 0,2 – 2 m length. The laser spot positioning the on CCD array plane can be defined with accuracy up to 0,01 of pixel size [27]. Therefore, the dilatometer makes it possible to determine the CTE of the CRFP square hollow sections within a length range from 0,2 m to 1,5 m by use of the CCD array with a pixel size of 2,57 μm. An increase in the distance from the CCD array plane to the movable rack allows increase accuracy of the CTE determination, since it leads to a proportional increase of the indicating laser spot displacement in the CCD array plane.



а) *б)*

Fig.7. Geometric center (a) and displacement (b) of the indicating laser spot

Conclusion

The results obtained in the analytical and experimental studies confirmed the operability of the developed dilatometer. The accuracy of determining the CTE for a CRFP product for a given dilatometer is comparable to the accuracy of dilatometers based on optical interferometry and digital correlation methods.

Compared to known dilatometers thedeveloped device provides information on the integrated thermal deformation of a CM parts.It provides possibility to improve the quality of aerospace equipment by sorting out components that do not meet the design requirements at the premanufacturing stage. Thus, the reliability of aerospace products, production process efficiency and external competitiveness may be increased.

It would be helpful to use the developed dilatometer for the fine-tuning of CM manufacturing technologies for aerospace products with extreme thermostability requirements such as space telescopes and antennas.

Taking in to consideration the high dependence of CRFP thermal deformation on the moisture saturation, it is worthwhile to use the developed dilatometer as a tool for examining deviations in mechanical properties of the structural components duringa climatic test.

During the follow-up study it is planned to reratethe CTE determination accuracy under the influence of such parameters as:

- the environment parameters (temperature, pressure, humidity),
- the image compression ratio,
- the image quantization bit rate and quantization noise.

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