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Suitability Assessment of Ethylene-Vinyl-Acetate (EVA) as a Material for Dynamic Photoelastic Coating

Soumen Mandal

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Abstract

The basic objective of the paper is to assess the suitability of ethylene-vinyl-acetate (EVA) as a material for dynamic photoelastic coating applications. Suitability is judged by calculation of optical, mechanical and thermal parameters. The Young's modulus, stress optic coefficient, stress wave velocity, density and glass transition temperature (T_g) are explored. The stress wave velocity is determined from Young's modulus and material density. The Young's modulus is experimentally assessed using a universal testing machine (UTM). The glass transition temperature (T_g) is found using differential scanning calorimetry (DSC). The stress wave velocity is determined experimentally using a poledioscope. Finally these assessed parameters are presented together with a justification of suitability of EVA for dynamic photoelastic coating application. It is concluded that EVA stands as a potential material to be used as photoelastic coating under dynamic conditions.

Keywords

Ethylene-Vinyl-Acetate (EVA), Photoelasticity, Glass Transition Temperature, Stress Wave Velocity, Polariscope

Introduction

Photoelasticity is a well-known photomechanical phenomenon exhibited by materials like plastics, glass, transparent rubber, calcite etc by virtue of property called birefringence. Birefringence is the ability of a material to exhibit double indices of refraction under induced stress[1]. This phenomenon is tactically exploited by engineers to evaluate stress on a material. The instrument used to do so is known as polariscope. A polariscope consists of two sections- a polarizer and an analyser. There are numerous types of polariscope in the literature and available commercially – such as a linear polariscope, circular polariscope, grey field polariscope, poledioscope etc. While a description about the instrument is irrelevant here, there is a similarity between all of these types in that they contain one or more polarizing filters in their polarizer and analyser section, a light source of known wavelength in the polarizer and a camera to capture the images (fringes generated due to stress) in the analyser portion. A schematic of a poledioscope as depicted in [2] and used here for experimental testing of a photoelastic material is shown in Figure 1.

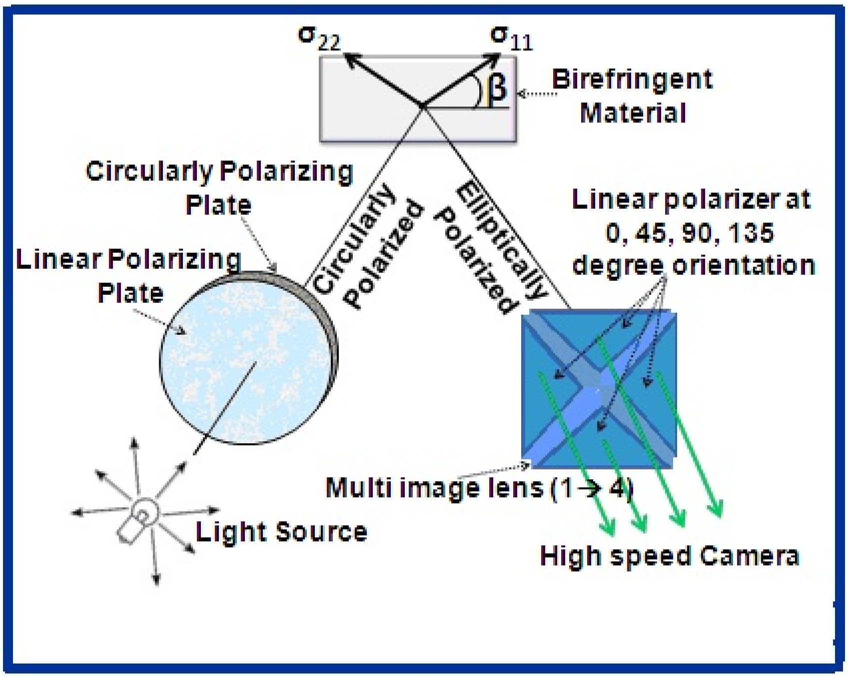

Figure 1. Schematic diagram of a typical poledioscope.

For stress testing using photoelasticity, a material should essentially be birefringent. However metals and ceramics which are the prime materials undergoing stress testing in this era do not exhibit this phenomenon. In order to tackle this problem, such materials are coated with a thin layer of photoelastic material, which becomes rigidly bonded to the sample material to be tested [3]. A myriad of such coating materials exist, depending on specific application and the testing environment. Examples of few commonly used materials include araldite (epoxy based resins), catalin, urethane, synthetic rubber etc. Araldite and catalin are materials possessing high Young's modulus in the range 3000-4000 MPa. Whereas high Young's modulus materials in the range 1000 -7000 MPa are suitable for static photoelastic experiments i.e. static loading, materials with low Young's modulus in the range 0.01-10 MPa [4] are used in dynamic photoelasticity. The reason behind this is that velocity of stress wave propagation through a material is equal to the square root of the ratio of Young's modulus and density. The density of the materials mentioned above used as photoelastic coatings does not vary much and lies in the range 900-1200 kg/m^3. Thus Young's modulus becomes the deciding factor for the value of stress wave velocity in such materials and hence its high value leads to greater stress velocity. In photoelastic experiments the velocity of stress wave propagation in the material is seen as photoelastic fringes. In dynamic applications, if the fringes (image patterns) generated due to stress or load change fast, compared to the frame rate of the camera of the polariscope, the images captured by the camera become blurred. So in dynamic applications, it becomes mandatory to use materials which possess low stress wave velocity of order 200m/sec as stated in [5, 6]. This condition is satisfied only if the Young's modulus of material used for photoelastic coating is low. Examples of commonly used low Young's modulus materials are urethane and synthetic rubber. Urethane has poor machinability. The photoelastic sensitivity of synthetic rubber is poor and is quantitatively not defined. Thus materials commonly used today for stress testing applications have some limitations like poor machinability, poor photoelastic sensitivity, high cost etc which are not desired and hence introduces difficulties in testing and also affects analysis results in terms of accuracy. In order to confiscate the existing limitations and to ensure accurate stress testing under dynamic situations, authors were encouraged find some suitable material which does not bear these limitations thus rendering dynamic photoelastic stress testing process to be more accurate and industrially reliable.

EVA, a copolymer of ethylene and vinyl acetate is a transparent rubbery plastic which is exclusively used in the electronics industry for packaging, sealing and as an adhesive. It is readily available, inexpensive; it can be easily moulded or formed into a desired shape and possesses good machinability. However, the use of this material as a dynamic photoelastic coating is not cited or established in the literature. And, commercially, this material still does not find its application as a photoelastic coating material. Due to the fact that EVA does not bear the limitations present in existing dynamic photoelastic coating materials, authors tested and validated the effectiveness and suitability of EVA for use in dynamic photoelastic applications.

Experiments Conducted

Experiments were conducted to measure the required parameters of EVA in order to check its suitability as a dynamic photoelastic coating material. There are a number of vendors in the market supplying ethylene-vinyl-acetate copolymer. They include Bamberger Polymers, Bostik, Westlake Chemical Corporation, and others. Each supplier markets a number of types of the product with variable monomer content.

Properties of EVA Used in the Experiment

We used a poly-EVA sample supplied by Westlake Chemical Corporation, viz. grade-EF437 containing 2.5% vinyl-acetate. This grade was specifically chosen because it possesses excellent optical properties and high tensile strength of break bearing a numeric value equal to 24 MPa according to company specifications.

The EVA material was heated to 82°C for 120 seconds inside a microwave oven. Under these conditions the EVA sample melts down to liquid form. EVA in liquid state was poured into a cylindrical die of height 5 cm and inner diameter 1.1 cm. The die was subjected to rapid cooling under refrigeration facility with temperature set to 10°C for 4 minutes. Rapid cooling of the molten EVA to convert it into solid form is the key factor in determining its applicability in photoelastic coating applications. It was observed that if these conditions were not followed, and molten EVA solidifies gradually, the colour of processed EVA changes slightly towards milky white which affects its transparency. The solid cylinder so obtained by this process was used in a universal testing machine (UTM) to evaluate the Young’s modulus of EVA and subsequently the stress wave velocity as described in later sections. Similar processing condition was used to coat a metallic disk required for evaluation of the stress optic coefficient. To maintain integrity of the experimental process EVA processed by above mentioned conditions was used in evaluation of the glass transition temperature.

Procedure for Evaluation of Stress Wave Velocity

The stress wave velocity is related with dynamic Young’s modulus and density by equation 1 [7].

$$E_D = v^2 \rho \tag{1}$$

Where

E_D is the dynamic Young’s modulus.

v is the stress wave velocity.

ρ is the density of material.

In order to access the dynamic Young’s modulus, the cylindrical specimen of material was loaded on a universal testing machine (UTM) and the relationship between stress and strain was obtained using the ASTM D638 standard method. The experimental set up is depicted in Figure 2. The density of same EVA rod was evaluated using the liquid displacement method. The EVA rod was dipped into a measuring gauge containing kerosene. The increase in liquid level corresponds to the volume of sample. The density was accessed taking the ratio of mass and volume of the EVA rod under consideration.

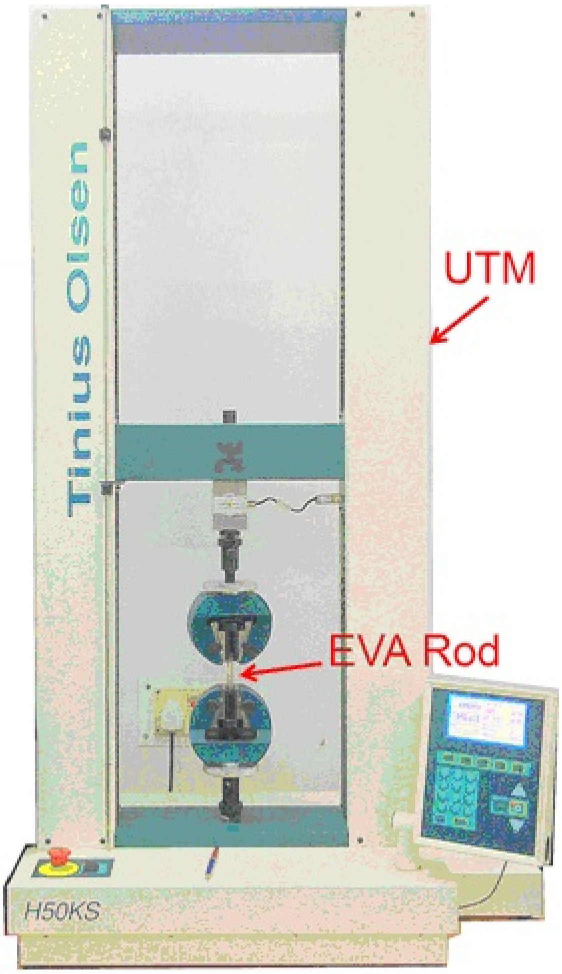

Figure 2. Experimental set up to evaluate stress strain relationship of EVA sample.

Procedure for Evaluation of Glass Transition Temperature (T_g)

Differential scanning calorimetry (DSC) was used to determine the glass transition temperature T_g. This is a crucial parameter as it is the temperature at which the material changes from hard brittle state to soft rubbery state [8]. Due to this transition the material properties changes abruptly when the states are switched. Scientific backgrounds to determine T_g using DSC are depicted in [9-11].

Procedure for Evaluation of Stress Optic Coefficient

In order to determine the stress optic coefficient of the EVA polymer, the method suggested in [12] was used. A circular disk with diameter 8.930 cm and thickness 1.76 mm, coated with an EVA material layer of thickness 1.36mm was subjected to compressive loading under a load of 4.55 N. The loaded disk schematic under compressive loading is shown in Figure 3.

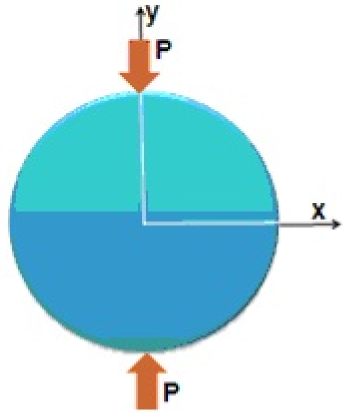

Figure 3. Schematic diagram of loaded disk.

From the theory of elasticity [13], the solutions for the normal stresses along the horizontal diameter mathematically are given by equations 2 to 4.

$$\sigma_x = \sigma_{11} = \frac{2P}{\pi h D}\left(\frac{D^2 - 4x^2}{D^2 + 4x^2}\right)^2 \quad (2)$$

$$\sigma_y = \sigma_{22} = -\frac{2P}{\pi h D}\left(\frac{4D^4}{\left(D^2 + 4x^2\right)^2} - 1\right) \quad (3)$$

$$\sigma_{11} - \sigma_{22} = \frac{8P}{\pi h D}\left(\frac{D^4 - 4D^2x^2}{\left(D^2 + 4x^2\right)^2}\right) \quad (4)$$

where, P is the applied load, h and D are the sample thickness and diameter respectively.

Four images were obtained for four different analyser orientations i.e. for 0, 45, 90 and 1350 respectively on a single camera shot using a poledioscope while the disk was under loaded conditions. It was possible to capture four images in a single shot as a poledioscope uses a multi image lens (beam splitter) or a kaleidoscope in its analyser section. For a grey field polariscope or a poledioscope (which is combination of a grey field polariscope and a kaleidoscope) the measured value of light intensity from the image/ image detection unit is given by equations 5 and 6 [14]

$$I = \frac{a^2}{2}\left(1 + \sin\Delta \sin 2(\alpha - \beta)\right) \quad (5)$$

$$I = I_a + I_{c\alpha}\cos 2\alpha + I_{s\alpha}\sin 2\alpha \quad (6)$$

where

I is the intensity of the image pixel under consideration from the detection unit of the polariscope.

$I_a = a^2/2$ is the average light intensity collected by the detector unit.

α is the orientation of the linearly polarizing plates in the analyser.

$$I_{c\alpha} = -\left(\frac{a^2}{2}\sin\Delta\right)\sin 2\beta \quad (7)$$

$$I_{s\alpha} = \left(\frac{a^2}{2}\sin\Delta\right)\cos 2\beta \quad (8)$$

where
a is the amplitude of the circularly polarized light.
β is the orientation of the fast axis or equivalently the orientation of the first principal strain with reference.
Δ is the amount of phase lag for the slow axis compared to the fast axis.

For each of these values of α (i.e. 0, 45, 90, 135 degree), equation 2 can be rewritten as equation 9 to 12.

$$I_1 = I_a\left(1 - \sin\Delta \sin 2\beta\right) \quad (9)$$

$$I_2 = I_a\left(1 + \sin\Delta \cos 2\beta\right) \quad (10)$$

$$I_3 = I_a\left(1 + \sin\Delta \sin 2\beta\right) \quad (11)$$

$$I_4 = I_a\left(1 - \sin\Delta \cos 2\beta\right) \quad (12)$$

Solving these equations the values of Δ and β can be stated as equations 13 and 14.

$$\Delta = \frac{1}{2I_a}\left(\left(I_3 - I_1\right)^2 + \left(I_4 - I_2\right)^2\right)^{1/2} \quad (13)$$

$$\beta = \frac{1}{2}\tan^{-1}\left(\frac{I_1 - I_3}{I_4 - I_2}\right) \quad (14)$$

This equation is particularly suited for sub-fringe photoelasticity where it is difficult to identify individual fringes due to the low value of induced stress. The phase lag (retardation) Δ is given by equation 15 [15]:

$$\Delta = \frac{2\pi C(2t)}{\lambda}\left(\sigma_{11} - \sigma_{22}\right) \quad (15)$$

where,
C is the stress optic coefficient.
t is the specimen thickness. (2t is used as light travels through the coating twice in reflection photoelasticity).
σ_{11} and σ_{22} are the principal stresses.
λ is the wavelength of the light source used (here 590 nm).

Results and Discussion

Results for Stress Wave Velocity

The stress strain relationship obtained using UTM set up is shown in Figure 4. The Young's modulus, which is the slope of the stress strain curve within the elastic limit, was found to be approximately 0.0105 GPa. The material density was found to be 9.254 X 10^2

kg/m^3. Hence using equation 1 the value of stress wave velocity is 106.542 m/sec. Materials with stress wave velocity of this order are suitable for use in dynamic photoelasticity.

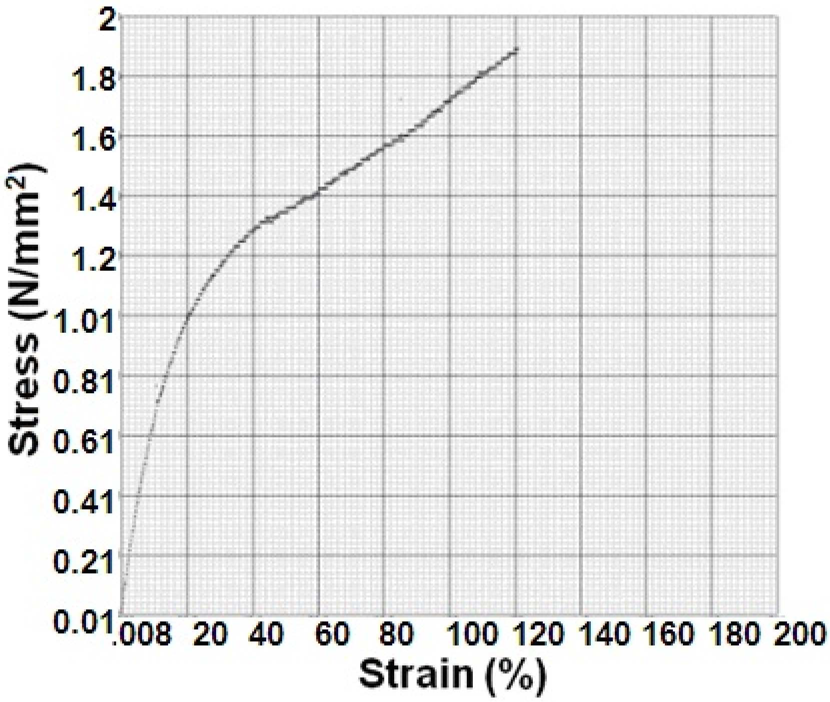

Figure 4. Relationship between stress and strain for EVA obtained using UTM.

Results for Glass Transition Temperature

The glass transition temperature for the sample under test was found to be -25°C during heating and -20°C during cooling. The plot obtained using DSC is depicted in Figure 5.

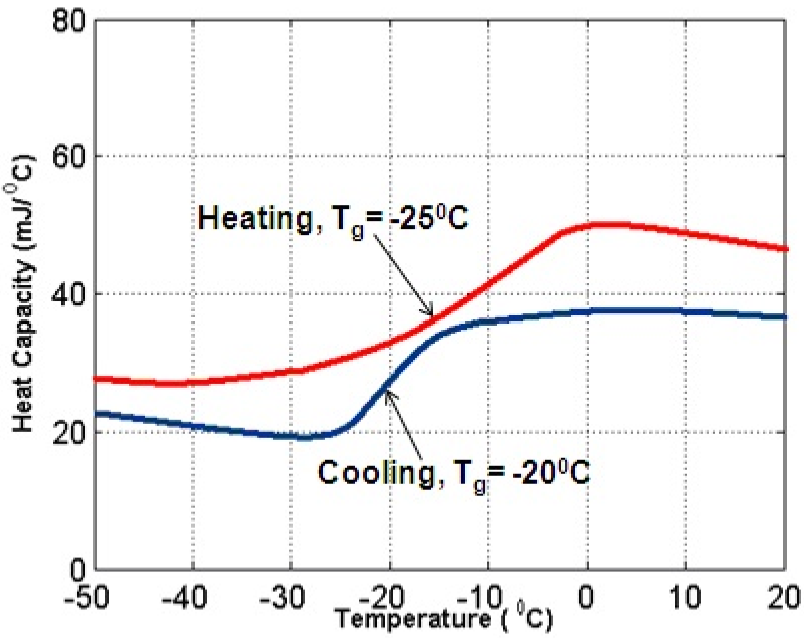

Figure 5. Relationship between heat capacity and temperature for EVA obtained using DSC at heating/cooling rate of 10°C/min.

Results for Stress Optic Coefficient

In order to evaluate the stress optic coefficient, the value of (σ_{11}- σ_{22}) from equation 4 was used in equation 15 and the value was found to be 2.8 X 10^{-10} Pa^{-1}. Figure 6 shows birefringence in EVA coated metallic disk.

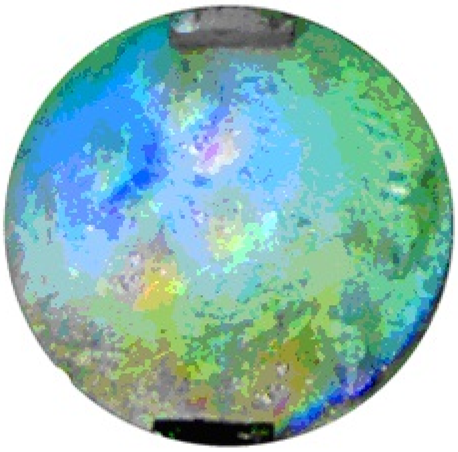

Figure 6. EVA coated metallic disk exhibiting birefringence under experimental conditions

The results are summarized in Table 1.

Table 1. Summarized results of conducted experiments.

Young's modulus (GPa)	Density (Kg/m^3)	Stress Wave Velocity (m/sec)	Glass Transition Temperature (°C)	Stress Optic Coefficient (Pa^{-1})
0.0105	9.254 X 10^2	106.542	-25 (Heating)/-20 (Cooling)	2.8 X 10^{-10}

The results infer the fact that EVA coating with 2.5% vinyl-acetate content processed with the mentioned methodology is an apt choice for use in stress testing using dynamic photoelasticity due to the following reasons:

- It possesses fairly low value of stress wave velocity. A value of stress wave velocity less than 200 m/sec signifies the fact that it is possible to capture good quality unblurred images during dynamic stress testing using a high speed camera present in polariscope, as materials with stress wave velocity of such order is suitable for dynamic photoelastic stress testing applications.
- The value of T_g lies in a zone which is far from reach under normal environmental and experimental condition. This factor adds to the fidelity of calculated parameters and it can be assured that under normal laboratory testing conditions the assessed values of stress wave velocity and stress optic coefficient will not undergo large transition.
- A significantly high value of stress optic coefficient bearing a numeric values equal to 2.8 X 10^{-10} Pa^{-1} marks the fact that EVA shows a higher amount of birefringence than other commonly used materials as dynamic photoelastic coating. Thus under low values of stress or loading clear and distinct fringes can be observed which adds to the sensitivity of the test set up.

The validity of using 2.5% EVA as material for dynamic photoelastic coating is applicable as long as the melting and solidification processes and the conditions mentioned in this paper are followed.

Conclusion

It is very well understood from the calculated parameters that EVA with 2.5% vinyl-acetate content has potential to be used in dynamic photoelastic coating applications. Furthermore, soft and malleable nature, abundant availability, low cost, and good transparency makes it a promising material for the desired application.

References

1. Krevelen D.W. and Nijenhuis K.T., "Properties of polymers: their correlation with chemical structure; their numerical estimation and prediction from additive group contributions", Elsevier, pp. 299-301, 2009.

2. Lesniak J., Zhang S.J. and Patterson E.A., “Design and Evaluation of Poledioscope: A Novel Digital Polariscope”, Society for Experimental Mechanics, 44 (2), 128-135, 2004.
3. Hearn E. J., “Mechanics of materials: an introduction to the mechanics of elastic and plastic deformation of solids and structural materials” Volume 1, Butterworth- Heinemann, 454-455, 1997.
4. Ganesan T.P., “Model Analysis of Structures”, Universities Press, 123- 125, 2005.
5. Asundi A. K. and Sajan M.R., “Low-cost digital polariscope for dynamic photoelasticity”, Optical Engineering, 33(9), 3052-55, 1994.
6. Durelli A. J. and Riley W.F., “Introduction to photomechanics”, Prentice Hall, New York, 33(9), 123- 135, 1965.
7. Gray J. D., Grushecky S.T. and Armstrong J.P., “Stress wave velocity and dynamic modulus of elasticity of yellow-poplar ranging from 100 to 10 percent of moisture content”, Proceedings of the 16th central hardwoods forest conference, West Lafayette, 139- 142, 2008.
8. ISO 11357-2 catalogue-Plastics, “Differential scanning calorimetry (DSC) - Part 2: Determination of glass transition temperature”, 1999.
9. Schawe J.E.K., “Principles for the interpretation of modulated temperature DSC measurements. Part 1. Glass Transition”, Thermochimica Acta, 261, 183 -194, 1995.
10. Kalichevsky M.T., Jaroszkiewicz E.M., Ablett S., Blanshard J.M.V., Lillford P.J., “The glass transition of amylopectin measured by DSC, DMTA and NMR”, Carbohydrate Polymers, 18(2), 77-88, 1992.
11. Verdonck, E., Schapp, K., Thomas, L.C., “A discussion of the principles and applications of Modulated temperature DSC (MTDSC)”, International Journal of Pharmaceutics, 192(1), 3-20, 1999.
12. Horn G., Lesniak J., Mackin T. and Boyce B., “Infrared grey-field polariscope: A tool for rapid stress analysis in microelectronic materials and devices”, Review of Scientific Instruments, 76, 045108, 2005.
13. Dally J.W. and Riley W.F., “Experimental Stress Analysis”, McGraw Hill, New York, 1991.
14. Pin W. and Asundi A., “Phase shift polarimetry for non-invasive detection of laser-induced damage”, Ninth International Symposium on Laser Metrology, Proc. of SPIE Vol. 7155, 715511, 2008.
15. Khan A.S. and Wang X., “Strain measurements and stress analysis”, Prentice Hall, 149-170, 2001.

Contact Details

Soumen Mandal

Central Mechanical Engineering Research Institute- Council of Scientific and Industrial Research- India.

Microsystems Technology Laboratory,

CMERI-CSIR,

Durgapur, India- 713209

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