Polymer Testing 71 (2018) 329–334

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Test Method

On the reliability of residual stress measurements in polycarbonate samples by the hole drilling method

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ARTICLE INFO

Keywords:
Residual stress
Polymer
Polycarbonate
Hole drilling
Environmental stress corrosion

ABSTRACT

The present study introduces a procedure to analyze residual stresses in polymer materials using the hole drilling method. This method is widely applied in metallic materials, however its application in polymer materials is not straightforward. In previous work [1, 2], the experimental set-up was improved to gain reproducible results, however, in-depth analysis of the reliability of measurements was not conducted. In order to gain appropriate information, a known loading stress was introduced in bending samples made of polycarbonate. By measuring the total stresses in the samples and comparing them with theoretical expectations, it is shown that the hole drilling method delivers reliable results and has a high potential for residual stress analysis in a variety of polymer materials. Based on this approach, it is shown that the resistance to environmental stress cracking of polycarbonate can be significantly improved by introducing compressive residual stress states.

1. Introduction

In polymer materials, residual stresses are usually minimized as they can cause different detrimental effects, e.g. warpage of structures. On the contrary, it is a common procedure to use well-defined residual stress states to improve component properties in metallic materials. As an example, introducing compressive residual stresses at the surface of components by means of shot peening or deep rolling is a powerful way to increase the lifetime of products, e.g. gear shafts or turbine blades. In a similar way, by introducing compressive residual stresses in polycarbonate samples, e.g. by quenching, it is possible to improve the fatigue life of polycarbonate components by a factor of 10 [3]. Consequently, the reliable measurement of residual stresses is necessary to better understand and predict the actual behavior of components.

In Refs. [3] and [4], residual stresses were determined using the slitting method and the photoelastic residual stress analysis method. In the same works, attempts to measure residual stresses with the hole drilling method were not successfully accomplished and, thus, this method was estimated to be less accurate. Certainly, the hole drilling method has obvious advantages in comparison to the slitting and photoelastic methods. Firstly, the photoelastic stress analysis does not provide absolute residual stress values, but only the difference between both principal residual stress components. Thus, it cannot determine residual stresses in the presence of an equibiaxial residual stress state. Secondly, photoelastic stress analysis determines the average of residual stresses over the cross section of the samples. Therefore, this method is mostly suited for uniform and uniaxial residual stress analysis. Thirdly, the hole drilling method can locally determine both principal stresses with far less restrictive geometry constraints than the slitting method, as shown in Ref. [5]. For these reasons, the hole drilling method should be the method of choice to measure residual stresses locally also in polymer materials. In Ref. [6], measurements were made in polycarbonate samples under 4-point bending with the hole drilling method applying an optical system for strain analysis. The hole drilling method showed an accuracy of about 1 MPa. However, little information is available about influencing parameters, and thermal strains are also mentioned to have potentially influenced the results. In previous works [1,2], it was shown that the experimental set-up of the hole drilling process had to be improved to account for the viscoelastic nature of polymer materials and their high thermal expansion coefficients. It was crucial to take the latter factor into account to guarantee reproducible and accurate results.

In the present work, residual stress measurements were realized in polycarbonate samples based on recommendations of [1,2], i.e. thermal and viscoelastic time dependent effects were taken into consideration. Samples were drilled manually with a low rotation speed of about 30 rpm. Strains were measured by strain gauges at a nominal feeding voltage of 0.5 V. A known loading stress state was applied by subsequent bending of post-annealed polycarbonate samples, which was then measured by the hole drilling method. This way, the reliability of

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https://doi.org/10.1016/j.polymertesting.2018.09.024
Received 31 July 2018; Accepted 19 September 2018

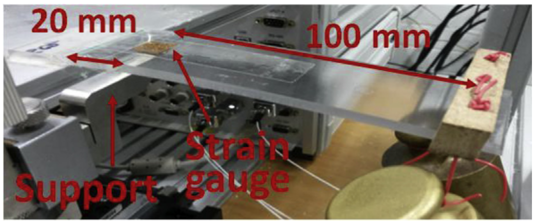

Fig. 1. Bent polycarbonate sample loaded with a total weight of 1 kg. A bending length of 100 mm is realized at the strain gauge position. A support structure is mounted close to the bottom surface of the sample to limit bending during the drilling process.

the method was evaluated. Lastly, different heat treatments were conducted to induce specific residual stress states in the polycarbonate materials. Subsequently, it is demonstrated that these residual stresses improve the resistance of the material to environmental stress cracking.

2. Stress analysis of bent polycarbonate samples

To evaluate the accuracy of residual stress measurements with the hole drilling method, polycarbonate samples were subjected to a well-defined bending stress. Samples were produced by injection moulding using an Engel E-Motion 100 injection moulding machine with an injection rate of 100 mm/s, a melt temperature of 290 °C, a mold temperature of 80 °C and a packing pressure of 50 MPa. Samples of dimensions of 160 mm × 60 mm x 4 mm were processed and were further milled to the final dimension of 160 mm × 40 mm x 4 mm. The samples were fixed at one side and bent by mounting a weight of 1 kg and a bending length of 100 mm was realized at the measuring position (Fig. 1). As a strain gauge was present at this position for the hole drilling test, it was first used as a load stress sensor (before drilling). In Fig. 1, the strain gauge rosette measured a deformation ε_x of 2771 μm/m, ε_y of -644 μm/m and ε_{135° of 1276 μm/m (see Fig. 5 for the coordinate system). As this strain gauge rosette was still not drilled, the Hooke's law was applicable, giving a load stress $\sigma_x$of about 7.2 MPa in the bending direction and σ_y of about 1.2 MPa in the transverse direction. Note that the stress σ_y in the transverse direction is not negligible. Indeed, part of the transverse shrinkage of the sample is restricted by the fixing of the sample and induced stress in the transverse direction (Fig. 1). The load stresses σ_x and σ_y were the values induced directly at the surface and the resulting in-depth theoretical bending stress profiles were then deduced assuming linear elastic beam theory. Concerning the measurement with the hole drilling method, in order to avoid any superimposed effect of initial residual stresses in the material, the polycarbonate samples were previously stress relieved by annealing of 4 h at 115 °C followed by slow cooling in an oven. To measure the relieved strain after drilling, two kinds of strain gauge rosettes were glued onto the sample surfaces: models EA-031RE and EA-062RE (Vishay Micro-measurement). These strain gauge rosettes were drilled with a 1 mm diameter hole and a 2 mm diameter hole, respectively. Using a bigger strain gauge rosette enables determining information in increased depth in the material, however, the accuracy of measurements is reduced as the measured strains become smaller for the same drilled hole depth. During a measurement, strains were measured after each drilled increment and converted to stresses using calibration coefficients adapted to the sample geometry. The finite element analysis conducted to obtain the calibration coefficients is explained in detail in Ref. [7]. Calibration coefficients provided in the standard [8] were not used as they are about 10% erroneous for material with a Poisson's ratio of about 0.4 [9]. The polycarbonate material was considered linear elastic isotropic with a Young's Modulus of 2400 MPa and a Poisson's ratio of 0.4.

Results of a first series of preliminary tests are shown in Fig. 2. In each graph, the expected bending stress profile from the beam theory is highlighted by the red dotted line. The calculated loading stress is about 7 MPa directly at the surface in the longitudinal direction X and decreases linearly at larger surface distances within the material. In the transverse direction Y, only small stress values were expected due to the restricted shrinkage of the sample. In Fig. 2a, the small strain gauge rosette EA-031RE was used and it can be seen that the measured stresses in the longitudinal direction X are different by a factor of about two near the surface, i.e. a loading stress of 14 MPa was measured instead of the expected theoretical value of 7 MPa. In Fig. 2b, a second measurement was realized under the same measuring conditions, but in this case with a bigger strain gauge EA-062RE. Results show the expected tendency of the stress profile with an accuracy of about 2 MPa. During both measurements, high strain relaxations were noticed after drilling only the foil of the strain gauge rosette and not yet the underlying sample material (strain relaxation not shown). The different steps to drill the carrier foil of the strain gauge are represented in Fig. 3. The carrier foil of the strain gauge is about 70 μm thick and need to be drilled before drilling the underlying polycarbonate sample. For simplification, a blue dot was drawn on the sample (not on real experiment sample), it is visible in the middle of the strain gauge. Each time, after drilling the strain gauge with drilling steps of about 5 μm, the presence of this blue point was confirmed. When the point is no more visible, it means the drill removed material of the sample. That way, it was possible to define when the drill comes into contact with the sample. When drilling the carrier foil of the strain gauge, no high strains were expected, however this relieved strain was about 280 μm/m for the small strain gauge rosette EA-031RE and 110 μm/m for the larger one. These values are uncommon and are usually in the order of about 20–60 μm/m for applications on polymeric materials and thought to be induced by residual stresses in the strain gauge itself and the bonding between the strain gauge and the sample. Note that the relieved strain is nearly zero when these strain gauges are applied on metallic materials as metals are stiff enough to resist deformation induced by the strain gauge. Thus, this uncommonly high strain relaxation during drilling of the strain gauge foil is a consequence of the fact that the stiffness of the strain gauge and the underlying polycarbonate is in the same order of magnitude. In the case of the two preliminary tests shown in Fig. 2 (graphs a and b), the relieved high strains indicate that the bending stresses were induced, not only in the material, but also in the strain gauge. In fact, at the surface, both the polycarbonate sample and the strain gauge were stretched to the same extent by the applied load. Furthermore, as strain gauges are even stiffer than the investigated polycarbonate samples, the bending stresses in the strain gauges are even higher than those in the samples. Consequently, measurements became inaccurate near the surface of the sample, especially for the smaller strain gauge rosette EA-031RE (Fig. 2a). In Ref. [7], it is explained why the released strain was higher for the smaller strain gauge. Considering the formalism and the calibration coefficients of the hole drilling method for evaluation of the results, two strain gauges can be equivalent, resulting in the same measured strain during an experiment [8]. In this study, this holds true if the drilled hole diameter, the increment size and the strain gauge dimensions are all proportionally reduced or increased. In Fig. 4, this is illustrated with the model a and b. The model (a) corresponds to a strain gauge type EA-062RE and the model (b) is an idealized equivalent strain gauge geometry with half the size of (a). The model (c) corresponds to the smaller strain gauge EA-031RE. The conditions for model equivalence are almost fulfilled between the real strain gauges EA-062RE (model a) and EA-031RE (model c) as the dimensions of strain gauge EA-031RE are two times smaller than those of the model EA-062RE. However, the thickness of both gauge foil is the same. In other words, the increment size when drilling the foil of the small strain gauge is not reduced. As a consequence, the residual stresses locked in the foil influenced in a greater way the measurement in the case of small strain gauges.

This relieved strain is expected to influence the overall results. In fact, after drilling only the foil of the strain gauge, a deformation