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Fracture toughness and residual stress measurements in tempered glass by Hertzian indentation

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Abstract

Hertzian indentation was used to assess the fracture toughness (K_{Ic}) and the surface residual stresses of tempered soda lime glass. Although such measurements are usually performed on chemically strengthened glasses, where the thickness of the layer under compression is limited to several micrometres, our study considers the most useful case of thermally quenched glass, widely used in industry and where the compressed layer is several hundred micrometres thick. Measurements were performed on annealed and thermally quenched samples and residual stresses were calculated using two different models of the literature. Results were compared to stress measurements performed by a conventional photoelasticimetry technique. It is shown that Hertzian indentation gives qualitatively correct results which are comparable for each of the literature models used, provided that interfacial friction between the spherical indenter and substrate is correctly taken into account in the calculations. It is shown that a scratch tester used to perform sliding indentation onto the surface of the samples is a suitable tool for assessing the friction coefficient value.

Keywords: Hertzian indentation; Glass; Quenching; Toughness; Residual stresses

1. Introduction

In 1881, Hertz published his first studies on the behaviour of materials subjected to elastic contacts and gave the mathematical solutions of the stress field in a material loaded by a spherical indenter [1]. As the material is loaded by the indenter, the contact is initiated through a single point which gradually transforms into a disc shape. For a critical load value, a circular crack is generated from a pre-existing flaw at the surface of the material. If the load increases further, the ring crack quickly flares out into a typical Hertzian cone crack.

From optical measurements of the ring crack at the surface or measurements of the length of the cone, it is possible to determine, using different models, the critical stress intensity factor (toughness or K_{Ic}) of the tested material. Certain approaches do not require any optical measurements at all. From calculation of the stress field at the critical cracking load, the toughness can be estimated. The biggest advantage of this approach is that subjective optical crack length measurements can be avoided using acoustic emission (AE) devices. Indeed, because ring crack formation is a highly emissive mechanism, acoustic measurements allow the critical load to be determined with a good accuracy. The crack growth resistance can then be calculated using simple formulas reviewed by Warren [2].

More recently, Hertzian indentation was also proposed to determine the surface residual stresses in brittle materials. The underlying idea remains simple: as there is a critical load at which a ring crack is formed, the presence of surface stresses should shift this load. Hence, measurements of this shift could lead to determination of the level of residual stresses. Several theoretical models have been proposed for this purpose. One method, proposed by

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Roberts et al. [3], relies on measurement of the ‘apparent toughness’ variation induced by the residual stresses. To be applicable, the technique requires uniform stresses along the depth of the surface flaws. A second promising method for measuring stresses focuses on local strength variations [4]. This technique, developed by Bao et al. is based on the assumption that Hertzian crack initiation depends on the mean stresses within a surface thickness related to the material properties (the so-called ‘process zone’) rather than on the peak stress, as is usually considered. Since the mean stress for initiating a crack is a material constant, it can be defined as the local strength of the material at the contact point. Any variation of the local strength determined in this way can therefore be an indicator of the presence of residual stresses, be they compressive or tensile. Experiments have shown that residual stress measurements on strengthened glass using a polarizing device agree well with values deduced from local strength variations.

Determining residual stresses through Hertzian indentation is a user-friendly and no-time-consuming method, presenting many obvious advantages in comparison with the other usual techniques (X-ray or neutron diffraction for polycrystalline ceramics, birefringence methods for translucent materials, etc.). However, this method is not yet very popular in comparison with the other indentation techniques involving sharp indenters (Vickers, Knoop, etc.). The main obvious reason arises from the scattering of the results obtained so far, as noted by Bisrat et al. [5]. Nevertheless, in a recent paper, Geandier et al. [6] have shown that, in order to obtain better agreement between Hertzian indentation results and fracture toughness measured by standard means, the friction between the indenter and the sample has to be adequately taken into account. Following other work [7,8], these authors have shown that interfacial friction exerts a critical influence on the stress level reached during Hertzian indentation: not taking into account this aspect induces errors in the estimation of the fracture toughness. This statement appears to be fully confirmed by the results of the present work.

In this study, we choose to focus our investigations on soda lime glass. Glass was chosen for two reasons: first, there is an important demand in the industry for quantifying the residual stresses in complex shapes for which conventional techniques are often irrelevant. Hertzian indentation could be a satisfactory technique for addressing this issue. Secondly, since glass is a vitreous and translucent material, results are not influenced by microstructural effects and others artefacts as in the case of polycrystalline ceramics. In this way, the influence of friction on cracking can be more easily clarified.

In practice, fracture toughness measurements were performed on annealed and thermally quenched glass using different kinds of ball indenters (made with alumina or WC/Co). Samples with different levels of surface compressive stresses were produced to cover a wide range of surface compressive states. In order to determine the effect of interfacial friction between the indenters and the glass substrates, scratch test measurements were performed. Most of the literature studying the influence of interfacial friction just considers a rough approximation of this value. It is shown that scratch test measurements allow accurate determination of this value. A simple but effective way to introduce the contribution of friction into existing models of Hertzian cracking will be proposed. The influence of this correction on the residual stress assessment is discussed, and the benefits of the incorporation of friction are evaluated.

2. General formulations

2.1. Toughness measurements

According to Warren’s analysis, toughness (K_{Ic}) can be calculated through Hertzian indentation using the following relation [2]:

$$K_{Ic} = \left[\frac{E^* P_{min}}{C \cdot R}\right]^{1/2} \quad (1)$$

with

$$1/E^* = \left(1 - v_i^2\right)/E_i + \left(1 - v_m^2\right)/E_m \quad (2)$$

where v_i, v_m, E_i, E_m are Poisson’s coefficient and Young’s modulus of the indenter and the material, respectively.

In Eq. (1), P_{min} is the minimum load required to fracture the substrate, while R is the indenter radius, and C is a constant depending on the Poisson coefficients of both the indenter and the substrate. This constant is given in Table 1 for the case where the sample and indenter are elastically similar. If this is not the case, C can be calculated by considering the average Poisson’s ratio between indenter and substrate.

In practice, this method requires P_{min} to be determined by performing a series of Hertzian tests. Typically, 20–30 different tests are necessary to increase the probability of finding a surface flaw with a size close to the material critical flaw size. Toughness is then given by Eq. (1), calculated for the minimum critical load found.

Table 1
Constant C as a function of v_m (from Ref. [2])

v_m	C	c/a_{min}	v_m	C	c/a_{min}
0.1	789	0.0679	0.23	2490	0.0472
0.11	850	0.0664	0.24	2790	0.0456
0.12	917	0.0648	0.25	3131	0.0444
0.13	991	0.0632	0.26	3530	0.0423
0.14	1074	0.0616	0.27	4001	0.0407
0.15	1167	0.0600	0.28	4560	0.0391
0.16	1270	0.0584	0.29	5229	0.0374
0.17	1386	0.0568	0.3	6037	0.0357
0.18	1517	0.0553	0.31	7022	0.0341
0.19	1665	0.0537	0.32	8235	0.0324
0.2	1883	0.0521	0.33	9748	0.0307
0.21	2025	0.0504	0.34	11658	0.0290
0.22	2247	0.0488	0.35	14106	0.0273