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Application of indentation fracture mechanics approach for determination of fracture toughness of brittle polymer systems

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Abstract

The analysis of cracks formed close to hardness impressions is a part of the current trend which deals with the development of simplified approaches for determination of fracture mechanics parameters of brittle polymer materials. However, up to now only very limited experimental knowledge exists of how to calculate the fracture toughness of these materials based on indentation fracture mechanics. Within the scope of this work, fracture toughness values for polymethyl methacrylate (PMMA) and polystyrene (PS) determined on the basis of a method proposed by Laugier have been found to be in good agreement with conventionally determined values. Furthermore, the fracture toughness of a number of other materials such as PMMA/SiO_2 nanocomposites and syndiotactic PS has been determined using this Laugier approach.

Keywords: Indentation fracture mechanics; Fracture toughness; Polymethyl methacrylate; Polystyrene

1. Introduction

The new trend in materials research, process optimisation and components engineering using polymers results in the application of increasingly thin layers, miniaturisation and nanostructuring as well as the necessity to analyse small sample quantities. However, this is not effectively reflected in the advancement of new testing procedures or the adaptation of the existing methods to evaluate the fracture safety and the lifetime of polymer materials, structures and components. Furthermore, new material concepts such as molecular or nanoparticle reinforced polymer–ceramic hybrids, which combine the properties of polymer and ceramic materials, are at present under intensive consideration. One possible starting point for the solution of many resultant problems concerning the fracture behaviour and the related component safety can be the implementation of indentation fracture mechanics approaches.

As shown in a large number of investigations dealing with inorganic non-metallic materials such as glasses and ceramics, cracks often formed close to hardness impressions—especially for materials having small resistance against crack initiation—can be analysed within the scope of indentation fracture mechanics and used to determine the fracture toughness of these materials [1,2]. In comparison to inorganic glasses and ceramics, indentation

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fracture mechanics investigations have been rarely reported for polymers as bulk materials [3–11] and polymer layers deposited on a hard substrate [12–14], in spite of the advantages of low-cost and time-saving determination of fracture toughness using only small amounts of materials.

2. Indentation fracture mechanics approaches

In principle, cracks or crack-like structures nearby Hertz impressions generated by blunt indenters, such as ball-like indenters, should be distinguished from those formed by sharp indenters, such as Vickers indenters. The following relationship has been theoretically found for the stress intensity factor K_I for cracks near a Vickers impression [2]:

$$K_I \sim HV\sqrt{a}\left(\frac{E}{HV}\right)^{1/2}\left(\frac{c}{a}\right)^{-3/2}, \quad (1)$$

with E is the modulus of elasticity, HV the Vickers hardness, a the half length of the impression diagonal and c the radial crack length.

For calculation of K_I values according to Eq. (1), a factor of proportionality (geometrical factor) has to be introduced depending on the shape of the cracks. The cracks, which are in line with the diagonals of the hardness impression and define the level of fracture toughness, are typically semi-circular shaped (Fig. 1a). Besides these radial cracks, lateral cracks often occur on unloading. The initiation and propagation of cracks in epoxy resin and PMMA, which were generated by spherical and cone-like indenters, have already been observed using a high-speed camera [6]. For most polymers like PMMA, (see [3] for example), so-called Palmqvist cracks [15] were formed under sharp indenters (Fig. 1b). Here, the individual cracks, which start to grow from the corners of the impression diagonals, are separated by the plastic zone beneath the hardness impression, at least at small loading conditions, and tend to coalesce under higher loading. Characteristic proportions of the crack or plastic zone make it possible to estimate without difficulty if semi-circular or Palmqvist cracks are produced [3,16]. According to this, when the ratio of the corresponding radial crack size after indentation c to the hardness impression a (c/a) or to the scale of the plastic zone (c/r_p) is less than 3.5 [16] or 0.7 [3], respectively, Palmqvist cracks appear.

Numerous approaches have been developed to characterise quantitatively the fracture toughness in terms of Vickers impressions. Altogether, 19 equations have been reviewed by Ponton and Rawlings [17,18], which are applicable either for semi-elliptical ("half-penny") or Palmqvist cracks or for both under specific conditions. The adaptation of

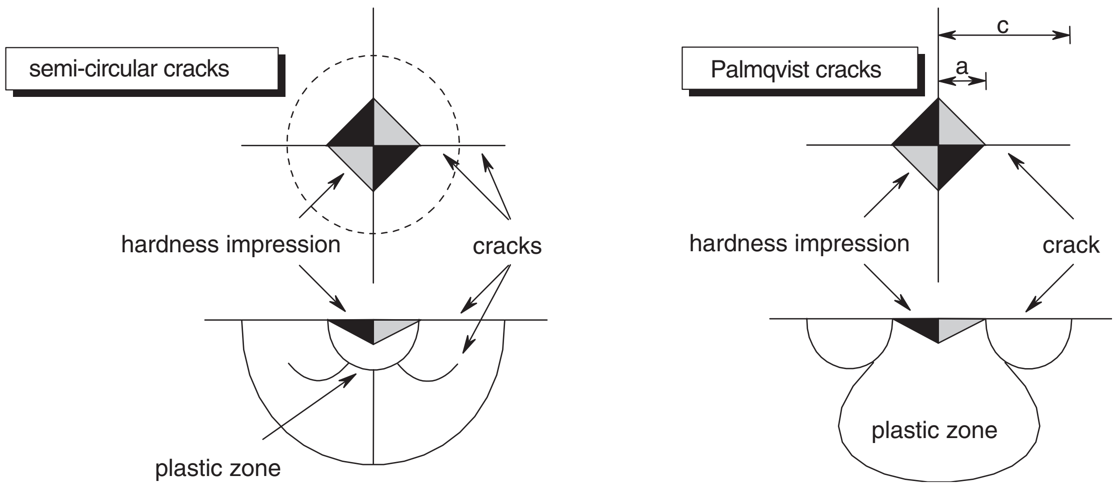

Fig. 1. Scheme of hardness impressions having cracks, (a) semi-circularly shaped crack system, (b) Palmqvist crack system.