Accounting for porosity, time and temperature dependency in fracture mechanics concepts on polyvinylidene fluoride material

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ABSTRACT

The polyvinylidene fluoride (PVDF) under study is a semi-crystalline polymer that exhibits sensitivity of mechanical properties to both strain rate and temperature. Furthermore, this material is subjected to a significant cavitation during deformation. A comprehensive experimental database was built in order to analyze the fracture behaviour in the ductile to brittle transition domain. Tensile tests were carried out on smooth and notched specimens at temperatures ranging from −50 °C to 20 °C. The results were used to determine temperature-dependent material parameters by using the mechanics of porous media. The obtained set of parameters was validated on two kinds of pre-cracked specimens, by using the local approach of fracture mechanics. With the help of a finite element code, both global and local approaches of fracture mechanics were shown to complement one another: whereas classical formulae of J-integral fail to characterize crack initiation for this PVDF, the present methodology allowed the plot of J_{1C} values with respect to temperature.

1. Introduction

Increasing use of plastic materials in structural applications is more and more evidenced nowadays. This development has to be accompanied by efficient scientific investigations such as polymer engineering, structural mechanics and failure assessment. Among the solutions proposed by each domain of research, sometimes compromise is required. For instance, for structural analysis, technical polymers have to be as rigid as possible. This can be obtained either by raising the Young's modulus of the material (chemistry solution) or by over-sizing the structures (engineering solution). Use of glassy polymers (high Young's modulus) was then frequently recommended. However, it is known that the higher the Young's modulus (high stiffness), the more brittle the failure of the material. The failure assessment concepts recommend the use of any material in its domain of high toughness. One of current solutions is incorporating rubber particles into these glassy polymers in order to increase their toughness (see for instance [1]).

Fig. 1 schematically summarizes these aspects. The dashed line shows the evolution of the Young's modulus of the PVDF material under study with respect to temperature. The second y-axis (solid line) represents the "fracture toughness" of the material. The glass transition temperature T_g separates the domains of high (resp. low) Young's modulus. Similarly, the ductile to brittle transition temperature (DBTT) is the temperature below which brittle failure of the material is expected to occur. T_g is a current data for polymeric materials nowadays. DBTT is much less accessible. Actually, it depends on the definition of toughness. For years, investigations on instrumented impact testing apparatus have been used in order to determine the impact strength of polymers. This latter was taken as the measure of toughness. Since polymeric materials

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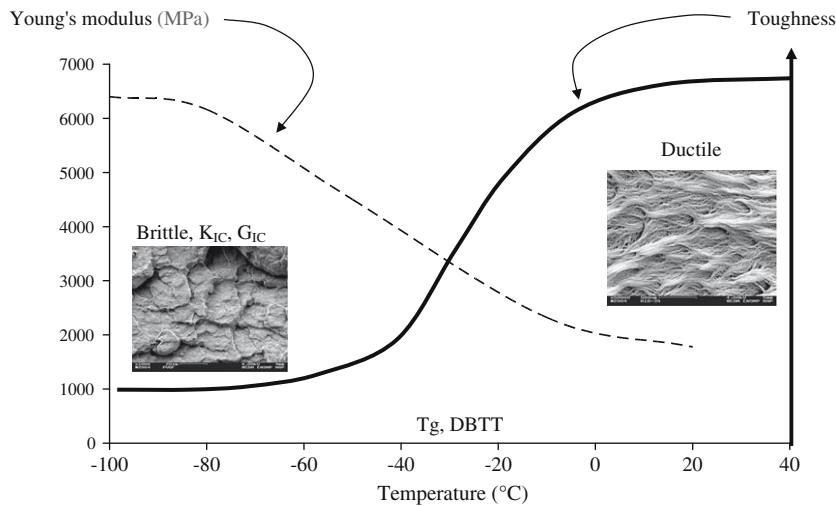 E-mail address: lucien.laiarinandrasana@ensmp.fr (L. Laiarinandrasana).

Fig. 1. Trends of the Young's modulus and toughness with respect to temperature.

are extremely sensitive to temperature and strain rate effects, the dynamic aspect of impact loading also allows the use of semi-crystalline polymers in their domain of high Young's modulus, even at temperatures greater than T_g. Some recent publications [2–4] report research on rubber toughened semi-crystalline polymers. The aim was to improve their fracture behaviour under impact loading. However, the impact strength parameter only operates in the brittle failure domain.

Application of the fracture mechanics concepts is now accepted as a useful tool to investigate the temperature dependent fracture behaviour of a given material [3]. Namely, the so-called global approach of fracture mechanics takes benefit of load parameters such as stress intensity factor K, energy release rate G, J-integral or Essential Work of Fracture (EWF). They have been extensively used for years, especially on metallic materials. Applying these concepts for polymeric materials is not straightforward and much care has to be taken. Indeed, the choice of the loading parameter whose critical value represents the toughness is not so obvious. This is the first objective of the present paper.

In the present study, the PVDF material of interest exhibits a significant amount (10%) of initial porosity. It is to be noted that with such an amount of initial porosity, the present PVDF is not a commercial grade. This latter generally exhibits less than 1% of initial porosity. In contrast, the PVDF of interest here is a model material with high porosity level aiming at checking the feasibility for a given model to handle such an amount of void volume fraction. Experimental results evidenced that this PVDF can be considered as a temperature dependent viscous material.

First, an attempt was made to determine the J-integral on pre-cracked specimens by using an analytical formula [5]. This approach requires elastic–plastic material coefficients such as Ramberg–Osgood hardening parameters. Since neither the viscous deformation nor the porosity of the material can be taken into account in this simple elastic–plastic model, the use of mechanics of porous media is proposed. To this end, the use of finite element (FE) method is required.

Experimental data obtained at various temperatures were utilized to identify material coefficients dealing with the mechanics of porous media. FE computations of cracked specimens at selected temperatures were then performed in order to check the ability of the model to simulate crack initiation and growth. In order to complete the experimental database at every investigated temperature and with two kinds of cracked specimen geometries, some numerical results taking advantage of the local approach of fracture mechanics were also produced. This database was then utilized to come back to the global approach of fracture mechanics. The aim was to compute J-integral evolution of each test by means of FE analysis. This gives access to J_{IC} and allows the plot of J_{IC} values against the test temperature.

2. Experimental procedure

The material of interest is the same PVDF as in Challier et al. [6], provided by ARKEMA. The specificity of this PVDF is that it was extruded with a significant level of porosity in order to investigate highly porous media. Hence, this model material differs from the standard industrial grades, which exhibit less than 1% of porosity. Nevertheless, the deformation and damaging mechanisms of this model material are supposed to be representative of standard PVDF materials. Challier et al. [6] reported that the void volume fraction is equal to 10%, consisting of two populations of voids that differ in their respective diameters of 1 μm and 0.1 μm. To obtain this value, some samples of the material were broken in liquid nitrogen. The fracture surfaces were then examined with the help of a scanning electron microscope (SEM). The porosity was calculated as the area fraction of cavities. The glass transition temperature T_g was estimated by the DSC technique at −42 °C and the melting point T_m is about 170 °C. The PVDF material is a semi-crystalline polymer whose degree of crystallinity is approximately 50%. This material whitens under deformation, presumably due to the growth of the significant initial porosity.