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Determining the viscoelastic behavior of polyester fiberglass composite by continuous micro-indentation and friction properties

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ABSTRACT

The purpose of this study is to characterize the influence of specific micro-indentation test methods and frictional behavior on the viscoelastic properties of polyester fiberglass composite. Previous work shows that viscoelastic parameters for neat thermoset polymers can be successfully determined using a recently developed phenomenological model. In this study, similar depth sensing micro-indentation tests were performed on polyester fiberglass composite surface to determine the effect of fiberglass reinforcement on viscoelastic properties of the composite. Data obtained from micro-indentation tests was used to calculate the viscoelastic properties of the composite using the previously developed model, and compared to those of neat polyester. Results show that fiberglass significantly increased the both viscoelastic indentation modulus parameters, E_0^* and E_1^*, of the composite. Scratch tests were also performed on this composite, showing a higher coefficient of friction for a diamond stylus in contact with a polyester fiberglass composite than when in contact with a neat polyester. Moreover, the coefficient of friction decreased as the diamond stylus's sliding speed increased for the composite. A model is then applied to illustrate that the von Mises stress distribution in the material during a scratch test is dependent on scratch velocity.

1. Introduction

The fiberglass reinforced polyester composite used in this study is a type of polymer matrix composite (PMC) that uses continuous fiberglass fibers in a plain weave pattern for reinforcement. Polyester is a common thermosetting resin used as the polymer matrix for PMCs in various applications, ranging from automotive, aerospace, wind energy, to marine and sports equipment industry [1]. Fiberglass is the most common type of reinforcement used in PMCs due to its high strength to weight ratio. Fiberglass reinforcement could improve the tensile strength and modulus of the polymer matrix by as much as one order of magnitude [2]. The mechanical properties of the polyester fiberglass composite used in this study were previously reported by Ngo et al. in 2013 [3].

In another recently published study the viscoelastic properties of epoxy and polyester were determined by using the time-dependent contact model developed by Schwarzer [4]. Schwarzer assumed that the viscous material properties followed the three-parameter model as a mix of relaxation and retardation as shown in Eqs. (1) and (2):

$$\text{Relaxation } E(t) = E_0 + E_1 \text{Exp}[-t/\tau_R] \tag{1}$$

$$\text{Creep}: E(t) = \frac{E_0 E_1 (1 - \text{Exp}[-t/\tau_C])}{(E_0 + E_1(1 - \text{Exp}[-t/\tau_C]))} \tag{2}$$

where E, t, τ_R, τ_C, E_0 and E_1 are the time-dependent modulus of elasticity, time, relaxation time, creep time and two material constants, respectively. Since the Poisson's ratio, ν, was not determined, the results were reported in terms of indentation modulus parameters, namely:

$$E_0^* = E_0/(1-\nu^2) \text{ and } E_1^* = E_1/(1-\nu^2) \tag{3}$$

For reasons of simplicity only relaxation was considered and thus, only Eq. (1) was applied within our analysis. The reasons for this are mainly due the difficulties associated with the numerical solutions and are elaborated in more detail in the work of Schwarzer [5,6]. Two different micro-indentation test methods

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were used in this study. The first method, referred to as the “hold time method”, used the data obtained during hold time combined with unloading data. The second method, referred to as the “unloading method”, used only the data obtained during unloading. Both methods were used because the effective phenomenological material (viscous) information depends on the strain rate [4,7]. Depth sensing continuous micro-indentation tests were performed with a hold at maximum load period and then unloaded. The viscoelastic properties of polyester fiberglass composites were then determined using a new theoretical model based on hold time and unloading data [4]. Scratch tests were also performed to determine the friction coefficient for a diamond stylus sliding against the composite material. Fiberglass polyester composites are used in the boating and surfboard industry. In service, these devices are subject to many contacts with hard sharp objects such as stones and sand. Therefore it was decided to use the diamond indenter as the stylus. The purpose of this study is to characterize the influence of specific micro-indentation test methods and frictional behavior on the viscoelastic properties of polyester fiberglass composite.

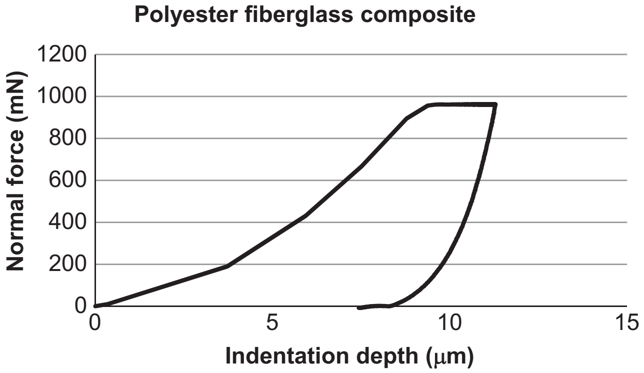

Fig. 1. Indentation load as a function of indentation depth for polyester fiberglass composite showing the hold at maximum load and unloading.

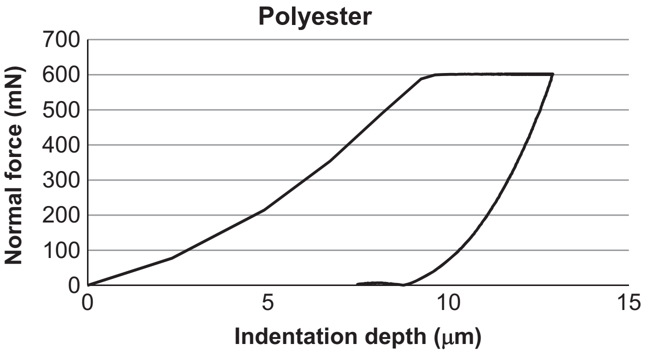

Fig. 2. Indentation load versus indentation depth for polyester showing the hold at maximum load and unloading (curve from Ref. [7], Fig. 2).

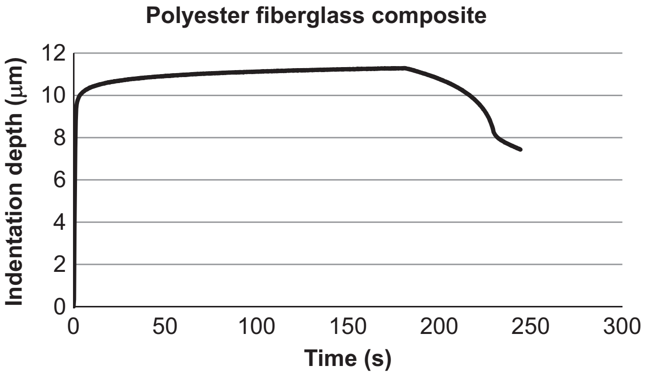

Fig. 3. Time-dependent behavior of indentation depth for polyester fiberglass composite during the test.

2. Experimental methods

A plain weave fiberglass fabric composed of 100% E-glass with a thickness of 0.300 mm and a surface weight of 279.6 g/m^2 was used in making the polyester-fiberglass test samples. The method of fabrication of the polyester fiberglass composite is described by Ngo et al. [3]. This method resulted in an average thickness of 0.428 ± 0.021 mm [3]. The mass fraction of fiber to polyester for this composite ranged from 35.9% to 46.7%.

Depth sensing continuous micro-indentation tests were performed using an Anton Paar Micro Indentation Tester (MHT). The stylus used was a calibrated diamond Vickers indenter. Five tests were performed on the sample. The initial loading was performed at a high loading rate (600 mN/s) in order to minimize the occurrence of creep during loading. The load was held at the maximum load for 180 s. The sample was then unloaded at a rate of 0.33 mN/s. A maximum indentation load of 960 mN was applied for the polyester fiberglass composite. This maximum load was used in order to compare the properties at approximately same indentation depth as the unreinforced polyester reported by Kohl et al. in 2015 [7]. See Figs. 1 and 2.

In order to determine the friction coefficient of a diamond stylus sliding against the polyester composite, scratch tests were performed using an Anton Paar Micro Scratch Tester (MST). The stylus used was a 20 μm radius diamond Rockwell indenter. Three repeated scratch tests were performed at each speed on the sample. The normal loading rate was 2000 mN/s with a nominal maximum load of 3500 mN. In order to investigate a rate dependence on the coefficient of friction, sliding speeds of 0.033 mm/s, 0.33 mm/s and 3.33 mm/s were used.

3. Results and discussion

Figs. 1 and 2 show the relationship between load and indentation depth for the continuous micro-indentation tests for polyester fiberglass composite and neat polyester [7]. The polyester fiberglass composite and the neat polyester exhibited similar creep behavior when held at the maximum load. Fig. 3 shows an increase in depth of penetration as the stylus continued to sink

Table 1
Values of parameters, E_0^*, E_1^* and τ_R for polyester fiberglass composite determined by using Schwarzer's model [4].

Material	Maximum load (mN)	Values obtained from hold time data			Values obtained from unloading data		
		E_0^* (GPa)	E_1^* (GPa)	τ_R (s)	E_0^* (GPa)	E_1^* (GPa)	τ_R (s)
Polyester fiberglass composite	960	4.049 ± 1.265	4.366 ± 2.138	12.028 ± 1.083	9.332 ± 2.670	2.806 ± 1.377	37.831 ± 9.531
Polyester resin (data taken from Kohl et al. [7])	600	1.643 ± 0.069	1.879 ± 0.267	16.840 ± 0.590	5.073 ± 0.375	0.511 ± 0.024	13.749 ± 3.887