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Test Method

Evaluation of hybrid laser-cut and cast miniature fracture specimens

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ABSTRACT

This paper presents a new hybrid laser-cutting method for producing fracture test specimens from thermosetting materials. The hybrid approach combines casting of a sheet of material with subsequent laser-cutting of the test specimens. The new approach was compared to the traditional casting method using a fracture toughness test. For this study, a compact version of the tapered double cantilever beam (cTDCB) was used as a specimen geometry for both manufacturing methods. The cTDCB specimen is crack length independent, and crack length investigations were performed to ensure the crack length independence of the cTDCB specimens. The specimens that were made by the hybrid laser-cut method were found to be comparable to the specimens obtained by the traditional casting method. Moreover, the laser-cut method provides a fast and accurate method to make a significant number of samples in a reasonable time. These tests show that the hybrid laser-cut method could be a good alternative to the traditional casting method.

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1. Introduction

Samples that are consistent in size and material properties are critical for ensuring uniformity in polymer and composite testing. Sample fabrication should minimize the impact on the polymer structure, composite cure state, or processing conditions since variation in these can change material behavior. Several approaches for fabricating test specimens have been discussed in the literature including casting, waterjet cutting and laser cutting [1,5,6]. The current work investigates a new hybrid method which combines casting and laser cutting techniques to produce miniature fracture specimens rapidly and flexibly.

Casting is one of the oldest sample fabrication procedures and is considered the standard technique for many materials, including polymers and composites [2]. Manufacturing cast test specimen consists of pouring a liquid polymer into molds and allowing a complete cure. This approach produces specimens at or near the final shape. Several studies have addressed the construction and characterization of cast specimens [3,4]. The key advantage to this method is that complex shapes can be produced with a variety of materials. However, the accuracy of the cast samples depends on the precision and consistency of the molds. Consequently, any deviation in the molds can negatively affect the results.

While the casting approach is useful for a variety of materials, there are instances when high-precision samples can be difficult or impossible to achieve. For these cases, specimens are usually cut or machined. One popular approach is to use a waterjet cutting system. This tool can cut various solid materials by using a high-pressure jet that is a mixture of water and abrasive elements [7,8]. Moreover, this method is efficient for cutting hard materials such as metal or ceramics. However, waterjet can also be used without the addition of any abrasive components to cut soft materials, such as rubber or polymers. As such, several studies have discussed and characterized samples made using the waterjet method. Most of these studies have examined the impact of the edge finishing of the specimens [9–11]. While the waterjet cutting is flexible and precise, the systems are expensive and complex.

Another cutting approach is laser cutting. This technique can produce accurate samples inexpensively and quickly. Historically, the laser-cut approach is a more recent development than both casting and waterjet methods. During the last 50 years, the laser-cut process has grown, with investigations focusing on the use of CO_2 laser-cutting. Unlike waterjet systems, laser cutting systems are available at many price points, including systems that are very affordable. However, due to the optical nature and the thermal effects of the laser beam, this method has some limitations. Certain materials can require very high laser powers, and this limitation

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can make laser-cutting impractical for a broad range of materials. The laser-cut process is usually used to cut a relatively thin sheet of materials (less than 12 mm) such as acrylic and wood [12]. Laser cutters are typically used for cutting sheet plastics. While the approach is flexible and accurate, this cutting technique produces high temperatures, which results in a clean, polished edge, but can leave high thermal stress levels [13–15].

The new hybrid method presented in this work combines the casting and the laser-cut methods. This method requires the fabrication of only one simple mold for the casting of a uniform thickness plate. Epoxy Vinyl Ester (EVE) material was used in this study to produce the cast and the laser-cut specimens. A miniature tapered double cantilevered beam (TDCB) specimen configuration was used to investigate the fabrication process. The TDCB specimen was developed by Mostovoy, (1967) [25], and a version is shown in Fig. 1. This specimen provides a crack length independent measure of fracture toughness and has been widely accepted as a standard fracture specimen [16–18]. For fracture specimens to be independent of the crack length, the ratio of the change of the compliance to the change of the crack length (dC/da) must be constant. To develop miniature versions of the TDCB specimens that maintain the crack length independence, the relationship in Equation (1) must hold [19].

$$m = \frac{3a^2}{h^2} + \frac{1}{h} \tag{1}$$

where a is the crack length, h is the beam width, and m is constant. Equation (2) represents the relation between the dC/da value to the constant value m.

$$\frac{dC}{da} = \frac{8}{Eb_e} m \tag{2}$$

The required height profile determined from equation (1) can be quite complex. For large specimens, this curve can be adequately approximated by a linear taper. For miniature specimens, this approximation would occur in a region with the most severe curvature, potentially leading to problems with crack-length independence. Thus, accurately reproducing the complex taper curve in a miniature specimen is critical to ensure that the constant compliance region is as large as possible.

Despite the additional complications in fabricating specimens, the advantage of a crack length independent measure of fracture toughness is apparent for many applications. A common application is in the assessment of self-healing materials, where crack length determination can be challenging. In self-healing materials, the healing process creates uncertainty about the exact position of the crack tip within the specimen. By using a specimen that is crack-length-independent, the difficulties associated with locating the healed crack tip location are eliminated [20–25]. While these benefits are significant, the accepted dimensions of the TDCB are unfeasible when considering expensive materials such as biomaterials, dental composites or experimental polymers. Therefore, compact TDCB (cTDCB) specimens were designed specifically for the fracture characterization of these materials, as shown in Fig. 1 A. The advantage of using cTDCB specimens is reducing the cost of the fracture specimens. The new compact geometry uses only 5% volume of a traditional TDCB.

Fig. 1 C, shows the height profile given by Equation (1). The traditional TDCB design does not use this complex curve for the height taper, and instead uses a linear taper that approximates the complex curve.

Here we present a comparison of cTDCB samples fabricated using the casting method and the new hybrid laser-cut method. The thermal effects of the laser-cut process were also investigated. Epoxy Vinyl Ester is used as the material for this study because of the low cost and susceptibility to laser cutting.

2. Experimental

2.1. Materials

Epoxy Vinyl Ester (EVE) (DERAKANE 411-350) was used to make cTDCB specimens. EVE is a low viscosity resin (about 200 cps.) that is fast curing and has excellent mechanical properties [8]. A peroxide radical initiator in Methyl Ethyl Ketone is used to cure the EVE resin. The Vinyl Ester was mixed at room temperature in a ratio of 98:2 with catalyst.

2.2. Sample casting

After mixing, the resin was vacuum degassed to eliminate air bubbles. Next, the resin was poured into a molds and allowed a 24 h room temperature curing period. After curing, the sample was removed from the mold and a starter notch was created using a diamond saw (Buehler IsoMet 1000). A sharp crack was introduced with a razor blade just before testing.

2.3. Laser cut samples

Laser-cut specimens started with a cast 3.7 mm thick sheet of EVE. The EVE sheets were prepared using the same casting process above, but in an open square mold. After casting, the EVE sheet was cut into cTDCB samples using a commercial laser cutting system (Epilog Laser Fusion 50 Watt). The cutting process involved two phases. In the first step, the outer edges of the specimens were cut. This stage required a primary setting of the laser beam and adjusting the laser power, speed and the distance of the laser source to 75%, 2.5%, and 4.5 mm, respectively. The second phase was cutting the side grooves on both sides of the cTDCB specimens at the midline. During this step, the side grooves were aligned, and the sample position, power, and speed of the laser beam were carefully adjusted to get an accurate cut of 1 mm depth, which was achieved by adjusting the laser power to 50%, and speed to 80% of maximum. Unlike the casting method, the initial crack in the laser-cut process is created in the first cutting step. Finally, the laser-cut specimens were pre-cracked at the tip of the initial crack using a razor-blade.

2.4. Quasi-static fracture toughness testing

Quasi-static fracture tests were performed to assess the fracture toughness of all the specimens. Custom grips were made to hold the cTDCB specimen, which helped to ensure consistent specimen alignment. Specimens were tested in displacement control at a rate of 0.05 mm/s using a custom load frame. Crack length investigations were performed to ensure that the cTDCB specimen was crack length independent. A series of quasi-static tests were used to develop the dC/da curve using laser cut specimens. Each set consisted of ten specimens per crack length, which ranged from 6 mm to 14 mm.

2.5. Residual thermal stress study

During laser cutting of specimens, the laser beam generates localized high temperature. This thermal impact could change the physical and mechanical properties of the laser-cut specimens. To investigate the thermal effect during the laser cutting, a series of EVE specimens were post-cured in a closed oven at 90 °C for 8 h.

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