A study of the fracture behavior of ballistic gelatin based on wire-cutting tests

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Abstract. The present study explores fracture properties of ballistic gelatin at different loading rates. Wire-cutting fracture tests were undertaken, and a new analysis method was proposed, in order to delineate the fracture force from the total cutting force. The new method was proved to be effective in obtaining the fracture toughness of ballistic gelatin at different cutting rates. It was found that the fracture toughness of 10% ballistic gelatin at 4°C increases almost linearly from 3.1 N/m at a cracking velocity of 10 mm/min to 19.4 N/m at 200 mm/min.

1. Introduction

Ballistic gelatin (BG) is made by mixing gelatin powder with water to form a homogeneous solution and then cooling the mixture in molds at different temperatures. The two most common gelatin formulations used are 10% at 4°C (Fackler gelatin) and 20% at 10°C (NATO gelatin), where the percentage refers to the amount of gelatin powder used in each formulation. The properties of BG can be modified easily to match various human organ tissues and it has become a popular modeling material or surrogate for many bioengineering or biomedical studies [1-3]. In these applications, it is required that the material be properly characterized in terms of mechanical stiffness and failure properties. There are several reports of the mechanical behavior of BG that were obtained from uniaxial compression or tension tests [4-7]. The results of these works, including the previous works of the present group [8,9], which showed that BG exhibits almost no plastic deformation and that it fractures as deformation reaches the elastic limit. Additionally, the stress-strain behavior and the failure properties of BG are sensitive to deformation rate and temperature. Cronin and Falzon [5] reported the dependence of the elastic limit of BG on temperature, strain rate and aging time from uniaxial compression tests. Moy et al [7] developed a tensile test method to obtain the tensile failure criteria for both 10wt% and 20wt% BG at two different loading rates and observed that the fracture properties of the gelatin were affected by the temperature and loading rate.

In the past, different test configurations, such as single edge bending, tearing, constrained tension and wire cutting have been adopted to evaluate the fracture toughness of biopolymers. Amongst these configurations, the wire cutting fracture test approach was studied by Czerner et al [10] and the test was proved to be effective in evaluating the fracture toughness of BG. The wire cutting test involves pushing wires of different diameters into the specimen to generate a steady state cutting process; the pushing load and the wire advance rate are recorded. The crack propagation rate is controlled directly by the wire advancing velocity, making the test very simple and straightforward to implement.

During the present investigation, the fracture properties of BGs were studied using wire cutting tests.
The main concerns were: i) consideration of the fundamental principle of wire cutting tests, and ii) the rate-dependency of the fracture toughness values obtained from tests on BG.

2. Materials and methods

2.1. Principle of the wire cutting test

The wire cutting process can be represented in Figure 1(a). The process involves not only fracture but also deformation and friction. The advancing load of the wire can be expressed as [10-13]:

\[ \frac{F}{l} = G_c + (1 + \mu) \sigma_c d_w \]  \hspace{1cm} (1)

where \( l \) is the crack length, \( G_c \) is fracture toughness of the sample, \( \sigma_c \) is a characteristic stress that is normal to the surface of the wire and is related to the limit of elastic deformation, and \( \mu \) is the kinetic friction coefficient between the wire and the sample. It is clear from equation (1) that the part of \((1 + \mu)\sigma_c\) must be separated in order to study \( G_c \). One widely used method is to change the diameter of the wire \( d_w \), so that \( F/l \) is proportional to \( d_w \) with an intercept of \( G_c \), which can be estimated by curve fitting. This method is referred to as “Method 1” in the present paper. The drawback of this method lies in two aspects: 1) a set of cutting wires with different diameters should be used, which results in an increase in the amount of test work; 2) as the wire diameter is increased, the cutting process become unstable due to the change of the fracture pattern from flat to rhombus-like [10,14], which tends to increase the experimental error.

![Figure 1](image)

**Figure 1.** Wire cutting of a specimen. (a) Wire cutting process and (b) Repeated cutting.

It was assumed during the present research that the part \((1 + \mu)\sigma_c\) in equation (1) can be estimated by repeating the cutting process following the original path of the first cutting, see Figure 1(b). The repeated cutting process involves only deformation and friction but without fracture, and therefore the load can be expressed as:

\[ \frac{F}{l} = (1 + \mu) \sigma_N d_w \]  \hspace{1cm} (2)

Here \( \sigma_N \) is used for the normal force, distinguished from \( \sigma_c \), as the deformation condition of repeated cutting is different to the initial cut. If the difference of \( \sigma_c \) and \( \sigma_N \) can be neglected, then the following approximation holds good:
\[ G_c = \frac{F - f}{l} \]  

(3)

This approximation (referred to as “Method 2” in the present paper) makes the test procedure much simpler. However, the condition of the approximation must be analyzed, and this is considered in the next sections.

2.2. Material and samples

The gelatin powder (Type-A), provided by QingHai Gelatin Factory (China), was used in the present study. The Bloom number is 250. Preparation of the gelatin solution (concentration of 10%) was described in [15]. In China, 10% BG at 4°C is the standard simulated target for ballistic tests [16-19]. Therefore, 10% BG at 4°C was specified for use in the present experiments. The solution was left in a thermostat at 40°C for hydration for 24 hours. Then, the solution was poured gently into cylindrical aluminum molds (40 mm in diameter and 40 mm in height) and cooled to form the gel. Gel samples were stored at 4°C for 24 hours before being used for the tests.

2.3. Wire cutting test

The wire cutting tests were conducted on a universal material testing machine with a purpose-designed clamp, see Figure 2. The selected cutting velocities were 10, 50, 100, and 200 mm/min. The wire diameters were 0.074, 0.106, 0.265, and 0.32 mm. The gel samples were cylinders with a diameter of 40 mm and a length of 40 mm. The test consisted of pressing steel wires of different diameters into the gel sample while the force (F) and the displacement (z) were registered continuously. After the initial cutting, the repeated cutting was conducted immediately. A video was used to film the whole cutting procedure. Each test was replicated at least three times.

![Figure 2. Gel sample of BG and the configuration of the wire cutting test.](image)

3. Results and discussions

3.1. Fracture toughness measurement with Method 1

A picture showing the cutting process, taken from a video camera, is presented in figure 3. It is clear that the wire can become curved, making the length of the crack, \( l \), not equivalent to the diameter of the sample. Therefore, in the following calculation, the length of the crack, \( l \), was calculated by measuring the length of the curve in the picture recorded by the video camera.
A typical force-displacement ($F$ vs. $z$) curves that were obtained from the wire cutting tests are shown in Figure 4 (the solid line). At the beginning of the test, the wire indents the gel and the load increases dramatically with increasing advancement of the wire. Once fracture of the sample is initiated, the load abruptly decreases and reaches the steady state cutting load, which is the effective phase of cutting. Breakdown of the cutting wire happens frequently during the indentation stage. Therefore, in the present tests, a notch was made using a razor blade to reduce the degree of indentation, and the force-displacement ($F$ vs. $z$) curve is shown as the dashed line in Figure 4. It is observed that the pre-made notch did not affect the cutting force during the steady-state cutting stage, while the peak value of the indentation force was decreased to make sure the wire did not break.

It was observed that the value of the cutting force $F$ increased with wire diameter. Figure 5 shows the $F/l$ values plotted against $dw$ for different cutting rates. The relationship exhibited good linearity and the values of the fracture toughness were $G_c = 11.0$ N/m and $G_c = 20.2$ N/m for cutting rates of 100 mm/min and 200 mm/min, respectively.
3.2. Fracture toughness measurement with method 2

A typical set of cutting force vs. advancing depth plots for a wire of \( d_w = 0.074 \) mm and cutting rate of 100 mm/min is shown in figure 6. The solid line is from the first cut, and the dashed line is from the repeated cutting, following the original path of the first cut. The value of \( G_c \) can be calculated using equation (3). The averaged value of \( G_c \) from three tests under the same conditions was \( G_c = 10.3 \) N/m, which is deviated from \( G_c = 11 \) N/m obtained from “Method 1” by only 7%. The averaged value of \( G_c \) for the cutting rate of 200 mm/min was \( G_c = 19.4 \) N/m, which deviated from \( G_c = 20.2 \) N/m obtained from “Method 1” by only 4%.

The same procedure was followed for cutting wires with diameters of 0.105 mm and 0.265 mm. It
was determined that the larger the diameter of the wire, the larger was the deviation value. Therefore, it was concluded that, in order to obtain the fracture toughness of BG, “Method 2”, which used a cutting wire with very small diameter, could be a more desirable alternative than “Method 1”, which used a set of cutting wires with different diameters. Furthermore, the cutting wire with \( d_w = 0.074 \) mm was suitable for use in “Method 2” to carry out wire cutting tests on BG.

3.3. Cutting velocity effect

The rate dependency of the fracture toughness of BG was studied using cutting test results for cutting velocities of 10, 50, 100, and 200 mm/min. The values of \( G_c \) were obtained using “Method 2”, with wire diameters of 0.074 mm, and the results are shown in Figure 7. There was a clear cutting velocity effect on \( G_c \). The latter increased almost linearly from 3.1 N/m at 10 mm/min to 19.4 N/m at 200 mm/min.

![Figure 7. Relationship between the fracture toughness and cutting velocity.](image)

4. Conclusions

In the present investigation, the fracture toughness of BG was studied using wire-cutting tests. The principle and test method of the wire-cutting procedure were discussed, and a new method was proposed. It involves a repeated cutting process that follows the original path of the first cut to separate deformation and friction effects from the fracture toughness value of the sample. The fracture toughness of 10% BG at 4°C was measured both by the new method via equation (2) and using the classic method via equation (1). Based on the findings, it was concluded that:

- The fracture toughness of 10% BG at 4°C could be obtained using the new method (\( d_w = 0.074 \) mm) for cutting velocities of 100 mm/min and 200 mm/min, which value is very close to that obtained using the classic method at the same cutting velocity.
- The proposed method made the test procedure much simpler and can be a lucrative alternative to the classic method.
- The diameter of the cutting wire should be as small as possible. For 10% BG at 4°C, \( d_w = 0.074 \) mm is satisfactory. Care should be taken to ensure that the cutting wire is not broken during the indentation stage of the cutting process, while a pre-made notch can decrease the indentation force dramatically.
- The fracture behavior of BG is sensitive to the cutting velocity. The fracture toughness of 10% BG at 4°C increases almost linearly from 3.1 N/m at 10 mm/min to 19.4 N/m at 200 mm/min.
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