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On the mechanics of wire cutting of cheese

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Abstract

The wire cutting process is used in the food industry during the manufacture and testing of products. The cutting process involves fracture as well as large strain deformation and surface friction. This paper investigates the mechanics of the wire cutting process of cheese through a combination of experiments, theory and finite element simulations. The experiments revealed that there was secondary damage on the cut surface, thus a higher fracture energy would be consumed than the common assumption of a single crack propagation. The numerical simulations showed that there was a six-fold change in the strain rate when wire diameters of 0.25 to 2 mm are used. This strain rate effect was modelled through a modification of a previous theoretical analysis of the wire cutting process. The numerical models were also used to predict the cutting forces using two failure criteria: critical strain, which was applied to the initiation of cracking, and a cohesive zone model to simulate crack propagation. Both criteria showed reasonable success in predicting the cutting forces, particularly for cuts made with small wire diameters.

Keywords: Food texture; Wire cutting; Viscoelastic; Fracture toughness

1. Introduction

Many food processes, such as shredding and cutting, involve breaking the food into smaller components. Fracture of food also occurs during mastication when the structure of the food is broken down and the flavour and aroma are released. The concern of food technologists is in designing foods that break down in the optimal way. For example, during a separation process, the food must not crumble to reduce wastage. When eaten, the food must fracture in a way which provides the optimal sensorial experience.

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Few studies in the literature have investigated in detail the fracture behaviour of foods. The three-point-bend test has been utilised in studies of cheese at low temperatures [1–3]. However, at room temperature when cheese exhibits a high degree of non-linearity, viscoelastic effects and low stiffness, conventional fracture tests that are widely used to determine the fracture properties of engineering materials can be difficult to apply. Therefore, the wire cutting test has been proposed as a simpler alternative to measure the fracture toughness, G_c [2,4,5].

The wire cutting test involves pushing wires of known diameters through specimens from an initial indentation to a steady-state cutting stage. The force–displacement relationship depends on a combination of fracture, plastic/viscous deformation and surface friction effects, but the exact details of the mechanics of cutting is still not understood. The objective of this study was to evaluate the possibility of separating the various energy dissipation mechanisms in order to make use of the wire cutting test for determining G_c.

2. Experiments

The experimental data presented in a previous paper [6] are used here. Two cheeses, mild Cheddar and Gruyere, were tested at 21 °C. The material calibration tests involved monotonic uniaxial compression tests performed at true strain rates, $\dot{\varepsilon}$, of 0.25, 2.5 and 25/min, and relaxation tests performed at a true strain rate of 2.5/min up to a strain of 0.04. The true stress, σ, and true strain, ε, were calculated based on the assumption that the material was incompressible [7–9].

Wire cutting tests were performed using steel wires of diameters, d, of 0.25, 0.5 and 0.89 mm, as well as dowel pins of diameter 1.6 and 2 mm. The specimens for the wire cutting tests were rectangular blocks of length 25 mm, height 20 mm and width 15 mm for the three smaller diameters. Blocks of length 30 mm, height 30 mm, and widths 20 and 30 mm were used for the 1.6 and 2 mm diameters respectively. Three cutting speeds, v, of 5, 50 and 500 mm/min were used. For each case of d and v, three cuts were made on a new specimen each time. The steady-state cutting energy was obtained by dividing the cutting force, F, by the specimen width, b.

3. Constitutive models and numerical methods

3.1. Constitutive models

The cheese samples were assumed to be incompressible and homogeneous. A non-linear viscoelastic model consisting of separable strain and time dependent functions was chosen to model the constitutive behaviour of the cheese. The selection of the model for the cheeses was based on previous observations from the uniaxial compression tests [9] that (i) the measured stress showed a non-linear dependence on the strain; (ii) the stresses were strain rate dependent; (iii) the strain dependent behaviour was separable from the time dependent behaviour; and (iv) a large proportion (~90%) of the total imposed deformation (up to strains of ~0.5) was recovered after a recovery period of ten minutes.

The viscoelastic model is defined as follows. During a step strain relaxation test, the model characterises the relaxation stress as the product of separable strain ($\sigma_0(\varepsilon)$) and time ($g(t)$) dependent functions, i.e.,

$$\sigma(\varepsilon, t) = \sigma_0(\varepsilon)g(t) \tag{1}$$

where σ is the stress at true strain ε and time t. The strain dependent function has dimensions of stress and the time dependent function is dimensionless.

The strain dependent behaviour was modelled using the Van der Waals hyperelastic potential [10,11]. For this potential, the stress during the uniaxial deformation state is expressed as,