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Determination of a critical stress and distance criterion for crack propagation in cutting models of cheese

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ABSTRACT

A critical stress at a critical distance crack propagation criterion is a good way to model the fracture in cheese. This physical criterion states that the crack-tip node debonds when the stress at a specified distance ahead of the crack tip on the assumed crack path reaches a critical value. Although this criterion is already used in other research domains, no consistent information exists on how the critical stress and distance should be determined.

A repeatable method for the determination of this criterion which combines experimental and numerical single edge notched bending tests was acquired. This criterion was validated with wire cutting experiments of cheese. The experimental and numerical results showed the same trend with a clear wire indentation and steady state cutting phase. The determination of a critical stress and distance criterion as proposed in this research is a good approach to model fracture and cutting of cheese.

1. Introduction

In recent years the replacement of physical experiments with numerical simulations is becoming increasingly popular in the food industry. A powerful framework to model the mechanical behaviour of food and other biomaterials is finite element modeling (FEM). In the domain of cheese research, finite elements have already been used to model the temperature evolution during cooling (Caro-Corrales et al., 2010; Cregan et al., 2013; Lezzi et al., 2011) and to model the salt diffusion during the brining process (Bona et al., 2007). Mechanical processing of cheese has been modelled by Goh et al. (2005) and by McCulloch (2008), who modelled wire cutting and ultrasonic cutting respectively. Research into the field of mechanical cheese processing is important, since sliced and shredded cheese represents a huge share of the cheese market (Gunasekaran and Ak, 2003).

The amount of literature available that uses finite elements to model the cutting process of cheese is limited. The usefulness of FEM to model mechanical processes that include fracture has been demonstrated in many other research fields which include the microcutting and milling of metals, cutting of wood, planar cutting of bone and many others (Alam et al., 2009; Chen et al., 2013; Le-Ngoc and McCallion, 2000; Salahshoor and Guo, 2014). Depending on the mechanical process and the material that is modelled, different techniques to model fracture and different fracture criteria were used.

It is a challenge to develop reliable FE models capable of accurate prediction of failure with a minimum number of easily determined material parameters. Gamonpilas et al. (2009) performed finite element simulations of wire cutting of starch gels. A failure criterion based on a critical fracture strain was used with a node-release technique. The crack was allowed to propagate in the gel when a maximum principal strain at a distance ahead of the wire attained a critical value. Specifically for cheese, Goh et al. (2005) simulated fracture in wire cutting using a cohesive zone model with a traction-separation law. In the FEM of McCulloch (2008) a critical stress at a critical distance crack propagation criterion was used to model fracture in cheese. This physical criterion states that the crack-tip node debonds when the stress at a specified distance

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ahead of the crack tip on the assumed crack path, represented by f, reaches a critical value, as shown in equation (1) (Li et al., 2002).

$$f = \sqrt{\left(\frac{\sigma_{xx}}{\sigma_f}\right)^2 + \left(\frac{\tau_{xy}}{\tau_f}\right)^2} \tag{1}$$

In this equation σ_{xx} is the stress component in the perpendicular direction to the crack path, τ_{xy} is the shear stress in the direction along the crack path and σ_f and τ_f are the failure normal and shear stresses of the material. The initially bonded nodes separate when $f = 1 \pm \Delta f$, where Δf is the given tolerance (Li et al., 2002).

Several researchers have used such a critical stress criterion when modeling the cutting process of other materials, such as metal, polyurethane foam and epoxy resin (Shet et al., 2003; Shet and Deng, 2003; Lucas et al., 2006). Although this criterion is regularly used, no consistent information exists on how the critical stress and distance should be determined. Martiny et al. (2013) studied mode I failure of metal-to-metal adhesive joints and identified the failure criteria by an inverse analysis, i.e. by choosing the critical stresses and distances in order to get the best possible agreement between the numerical predictions and the experimental data. Li et al. (2002), who studied the orthogonal metal cutting process, also stated that trial-and-error simulations were generally needed to determine this criterion. McCulloch (2008) proposed the use of single edge notched bending tests (SENB) to determine the critical stress and distance. In these SENB tests beam shaped samples with a notch cut in the lower edge are placed on two supporting pins. A probe is lowered on the middle of the sample until the inflicted bending causes material failure.

The method described by McCulloch (2008) was a good starting point, but had also some shortcomings. Firstly, the forces from the SENB models did not correspond with the experimental tests. The experimental forces produced in the SENB tests were considerably lower than the finite element predictions for the material models. After 1% strain the difference between the experimental and numerical forces already exceeded one order of magnitude. Secondly, the point of cheese fracture that was used as a boundary condition in the SENB models of McCulloch (2008) was arbitrarily set at 1 mm deformation for each cheese sample. However, research has shown that the deflection of the cheese samples needed to initiate fracture varies between different cheese samples. An individual determination of the fracture point allows a more accurate determination of the critical stress criterion. Thirdly, when using hyperelastic cheese models McCulloch took the stress at the initial crack tip as the critical stress. However, at this point the results are dependent on the mesh density and the radius of the keyhole used in the models. Mesh refinement or changes in the keyhole dimensions influence the stress results at the crack tip without leading to a convergence. It is necessary to use the critical stress at a distance from the crack tip. Lastly, McCulloch's method was not repeatable and standardized due to the fact that his samples and the initial cut were made manually with a scalpel blade.

In this research the method as first proposed by McCulloch is further developed. Then wire cutting models of cheese are constructed to examine the validity of the fracture propagation criterion.

2. Material and methods

The determination of the critical stress and distance criterion as described in this work is based on a combination between physical experiments and finite element models. Fig. 1 gives an overview of the general methodology.

Each of the main steps will be clarified separately in the following paragraphs.

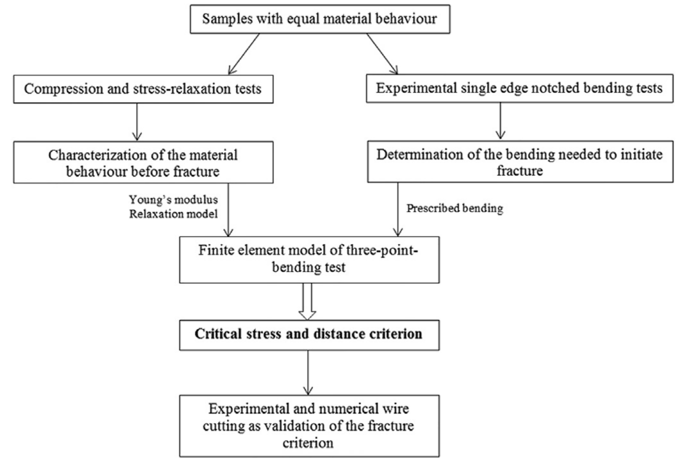

Fig. 1. Methodology to determine and validate the critical stress at a critical distance criterion.

2.1. Material behaviour

When only small deformations are applied, cheese behaves as a linear viscoelastic material (Gunasekaran and Ak, 2003). During processing of cheese, such as cutting, fracture will already occur after small deformations. Therefore the assumption was made that including the non-linear material behaviour of cheese in the models in order to mimick the behaviour of cheese during cutting was not necessary.

Linear viscoelastic behaviour is often modelled using the Generalized Maxwell model as described in Vandenberghe et al. (2014). This model consists of a Hookean spring defined by Young's modulus which is connected in parallel with a series of viscous Maxwell elements. The relaxation behaviour of these elements is then represented by a Prony series expansion (eq. (2)), where τ_i are time constants for $i = 1 \ldots n_G$, respectively. G_∞ is the residual Prony coefficient, representing the material behaviour at an infinite relaxation time. The dimensionless constants G_i and G_∞ are normalized so that they add up to 1 (eq. (3)).

$$G(t) = G_\infty + \sum_{i=1}^{n_G} G_i e^{(-t/\tau_i)} \tag{2}$$

$$G_\infty + \sum_{i=1}^{n_G} G_i = 1 \tag{3}$$

2.2. Selection of samples with equal material behaviour

This research was performed on 4 weeks old Gouda cheese. The cheese block had standard dimensions of $47 \times 30 \times 10$ cm^3.

Previous research showed the presence of spatial gradients of the fundamental material parameters in Gouda cheese (Vandenberghe et al., 2014). The design of the experiments takes this heterogeneity into account, as well as the previously detected symmetry in the length and width of a cheese block (Vandenberghe et al., 2014). .

The block of Gouda cheese was divided in a middle (M) and two side (S) sections. Both the middle as well as the side sections contain 4 slices in total and those slices were considered to be equal

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