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A finite element model for ultrasonic cutting

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Abstract

Using a single-blade ultrasonic cutting device, a study of ultrasonic cutting of three very different materials is conducted using specimens of cheese, polyurethane foam and epoxy resin. Initial finite element models are created, based on the assumption that the ultrasonic blade causes a crack to propagate in a controlled mode 1 opening, and these are validated against experimental data from three point bend fracture tests and ultrasonic cutting experiments on the materials. Subsequently, the finite element model is developed to represent ultrasonic cutting of a multi-layered material. Materials are chosen whose properties allow a model to be developed that could represent a multi-layer food product or biological structure, to enable ultrasonic cutting systems to be designed for applications both in the field of food processing and surgical procedures. The model incorporates an estimation of the friction condition between the cutting blade and the material to be cut and allows adjustment of the frequency, cutting amplitude and cutting speed.

Keywords: Ultrasonic cutting; Multi-layer cutting; Finite element modelling; Material properties; Friction

1. Introduction

Ultrasonic cutting devices which use a tuned blade (or blades) resonant in a longitudinal mode, have been used to cut a range of materials from confectionery, baked products and frozen foods, to wood, cortical bone, some foams and composite materials [1,2]. Although ultrasonic cutting is an established technology, computational representations of cutting are limited [3,4]. The performance of cutting operations has been shown to be dependant on cutting parameters and the geometrical design of the blades [5]. The blade design process typically uses finite element (FE) models validated by experimental modal analysis (EMA) to develop blades that are tuned to a specific mode of vibration [6]. The optimal cutting conditions for the material to be cut are usually determined from experimental testing. This tends to be an iterative process which could be reduced or eliminated if cutting parameters such as the blade tip amplitude and cutting speed could be predicted prior to blade design and manufacture. High power ultrasonic cutting is gaining interest for medical applications, offering significant advantages to patients and surgeons from reduced operation times and improved accuracy. Ultrasonic cutting has also become established in the food processing industry as the technology produces cuts of high quality and accuracy and reduces system downtime due to cleaning of the blades.

In this study, an FE model of ultrasonic cutting of a multi-layer product is developed. Three different materials were chosen for the study; two elastic–plastic biomechanical test materials (epoxy and polyurethane foam), and a widely available viscoelastic material, mild cheddar cheese. The materials were selected to provide distinct challenges for modelling multi-layer products, but were also readily available to allow mechanical test data to be incorporated in the model and to allow experimental validation. The resulting modelled layered product of epoxy, polyurethane foam and cheese was generally considered to be representative of the variations in material properties typically encountered both in food products and biological architectures.

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This paper investigates a method of representing ultrasonic cutting as a 2D FE model by addressing the cutting mechanism as a fracture mechanics problem. Ultrasonic cutting is modelled using a fracture approach in mode I opening whereby a crack propagates due to a normal stress at a predetermined distance ahead of the crack tip. Biomechanical test blocks of E-glass filled epoxy resin and polyurethane foam, materials which replicate the mechanical properties of bone, are used as test materials along with mild cheddar cheese and are tested for their material and fracture properties for inclusion in the models. The contact condition at the interface between the vibrating blade and the material being cut is also incorporated in the model using a Coulomb friction condition [7]. Single-layer and multi-layer cutting models are assessed and their implications for the design of ultrasonic cutting systems are discussed.

2. Material validation and test methods

E-Glass filled epoxy resin and polyurethane foam mechanically mimic the mechanical properties of human bone and, when layered, represent the transition through cortical to trabecular bone. Mild cheddar cheese has been chosen due to its soft viscoelastic nature, availability and widely documented material studies [8,9]. The three materials allow the development of the FE model to be applicable both to cutting of layered food products and biological materials for surgical applications. The materials are tested in tension to extract values for Young's modulus and stress–strain data used in the FE models. Single edge notch bend (SENB) studies were performed experimentally to benchmark this material data for computational SENB models used to determine the critical stress and its location ahead of the crack tip in mode I opening conditions.

2.1. Materials testing

The materials were tested in uniaxial tension and compression using a Lloyds testing machine. A cross-head velocity of 5 mm/min was used in all tests. The test specimens were cut from the same batch and tests were performed at room temperature.

2.1.1. Tension tests

Tension specimens of cheese were manufactured by slicing a block to the required thickness using a wire cutter. Final dog-bone specimens were produced by cutting around an aluminium template using a scalpel. Small cracks and tears, which were found to form on the sides of the specimen, were minimised by cutting in one continuous movement. Correct gripping of the cheese specimens was difficult due to the soft, temperature dependant nature of the material, and grip tightening needed to ensure good contact whilst avoiding specimen damage. Uniaxial tension is not commonly used for testing cheese as a result of these difficulties [9] and the mechanical properties in tension are commonly assumed to be the same as in compression. However, the failure of the material can be more accurately observed in tension than in compression.

Epoxy and foam specimens were milled using a diamond-tipped cutter to minimise the production of small hairline fractures in the material. Although all of the specimens were manufactured from the same batch, small inaccuracies may occur due to specimen development, handling and test preparation. Food products such as cheese, as with many other materials, also vary within batches making reproducible mechanical properties data difficult to obtain. The variation can clearly be seen in the stress–strain tensile test results for cheese shown in Fig. 1(a). The stress–strain results for epoxy and foam, providing

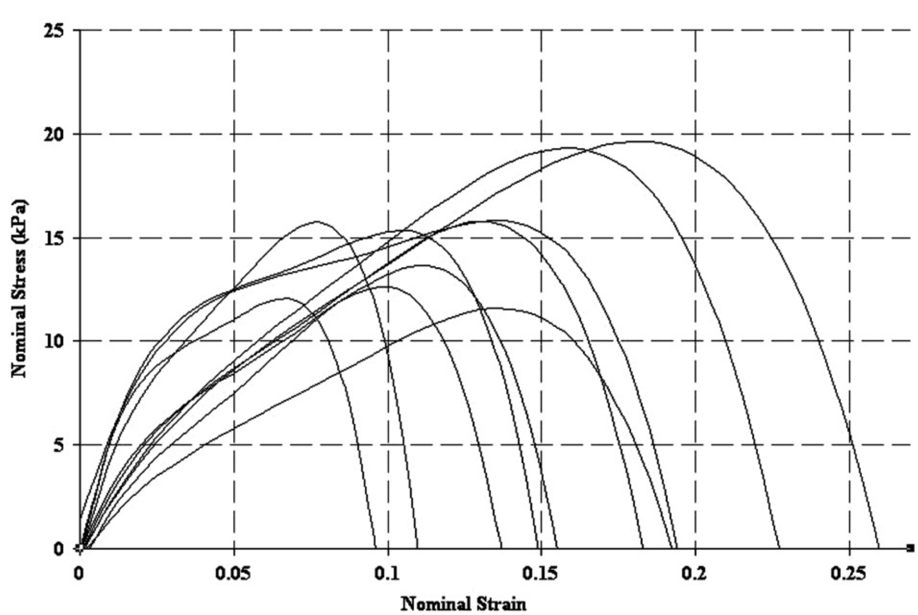

Fig. 1(a). Nominal stress–nominal strain experimental data for tension tests of 10 mild cheddar cheese specimens cut from a single block.