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A Finite Element Model for Ultrasonic Cutting of Toffee

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Abstract. The performance of an ultrasonic cutting device critically relies on the interaction of the cutting tool and the material to be cut. A finite element (FE) model of ultrasonic cutting is developed to enable the design of the cutting blade to be influenced by the requirements of the tool-material interaction and to allow cutting parameters to be estimated as an integral part of designing the cutting blade. In this paper, an application in food processing is considered and FE models of cutting are demonstrated for toffee; a food product which is typically sticky, highly temperature dependent, and difficult to cut.

Two different 2D coupled thermal stress FE models are considered, to simulate ultrasonic cutting. The first model utilises the debond option in ABAQUS standard and the second uses the element erosion model in ABAQUS explicit. Both models represent a single blade ultrasonic cutting device tuned to a longitudinal mode of vibration cutting a specimen of toffee. The model allows blade tip geometry, ultrasonic amplitude, cutting speed, frequency and cutting force to be adjusted, in particular to assess the effects of different cutting blade profiles.

The validity of the model is highly dependent on the accuracy of the material data input and on the accuracy of the friction and temperature boundary condition at the blade-material interface. Uniaxial tensile tests are conducted on specimens of toffee for a range of temperatures. This provides temperature dependent stress-strain data, which characterises the material behaviour, to be included in the FE models. Due to the difficulty in gripping the tensile specimens in the test machine, special grips were manufactured to allow the material to be pulled without initiating cracks or causing the specimen to break at the grips. A Coulomb friction condition at the blade-material interface is estimated from experiments, which study the change in the friction coefficient due to ultrasonic excitation of a surface, made from the same material as the blade, in contact with a specimen of toffee. A model of heat generation at the blade-toffee interface is also included to characterise contact during ultrasonic cutting. The failure criterion for the debond model assumes crack propagation will occur when the stress normal to the crack surface reaches the tensile failure stress of toffee and the element erosion model uses a shear failure criterion to initiate element removal. The validity of the models is discussed, providing some insights into the estimation of contact conditions and it is shown how these models can improve design of ultrasonic cutting devices.

Introduction

Ultrasonic cutting devices, which use a tuned blade or multiple tuned blades resonant in a longitudinal mode of vibration typically at a low ultrasonic frequency in the 20-100 kHz range, are used in some food industries to achieve a reliable and accurate cut in food products which are sticky and difficult to cut using more traditional technologies. Such food products include confectionary, frozen foods and baked products [1, 2]. Advantages of ultrasonic cutting in the food industry include reduced cutting force, high precision cutting, reduced cutting time and reduced downtime of machinery due to cleaning of blades [3].

Currently the design of an ultrasonic cutting device is based on achieving a blade profile that meets the requirements of tuning, the depth of cut for the product, the blade ultrasonic cutting amplitude and the stress limits. The design therefore focuses on the geometry and material considerations of the blade. Subsequently a blade design will be adapted to cut a specific product by modifying existing designs. This means that ultrasonic cutting devices are not optimised for the particular food product they cut even though the interaction between the blade cutting edge and the food product largely determines the optimal cutting parameters, including frequency, cutting edge vibration amplitude, cutting edge profile, power requirements and feed rate. These parameters are food material dependent and currently are largely estimated from cutting trials and experimental cutting tests. Therefore a significant improvement in the design process could be made if the effect of the food material on the cutting parameters could be evaluated as part of the design process. The development of a computational simulation of ultrasonic cutting, using finite element models, is described in this paper, with the aim of providing a means of assessing the effects of the food material in the design of the cutting device.

In some previous studies, ultrasonic cutting has been modelled as a linear elastic fracture mechanics problem. However, it is known that the influence of temperature in ultrasonic cutting is significant [4,5]. Therefore, this study represents ultrasonic cutting as a coupled thermal-mechanical finite element model. Two approaches have been considered; one using the debond model and the other using the element erosion model in the finite element package ABAQUS.

Toffee has been selected as the food material for this study because it is sticky, highly temperature dependent and often difficult to cut. Since the finite element models rely critically on the description of the material properties and the contact condition between the cutting blade and the material, this study also highlights the difficulties of extracting accurate and consistent data from experiments using food products.

Material Testing

Toffee is a typical food material that is highly temperature dependent, brittle, hard and difficult to cut using conventional cutting techniques. For most food products, including toffee, conducting standard mechanical tests in order to extract materials properties data is very difficult. There are often problems creating specimens and then creating consistent specimens and then there are difficulties holding food specimens in test machines. In tension tests, which are vital for extracting data for cutting models, gripping of specimens is highly problematic and the result is that in most studies food products are only tested in compression [6]. However, the tensile and compressive behaviours are very different and therefore this approach is not sufficient for cutting models.

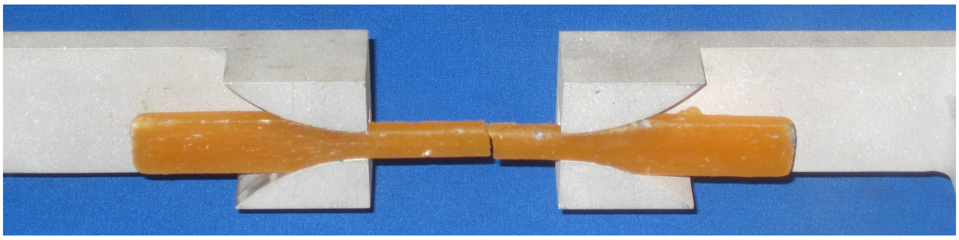
Specimen Preparation. To provide consistent tensile test specimens from a single batch, the toffee was prepared in the lab from the basic ingredients of syrup, water, sugar, butter and vinegar. The mixture was prepared, slightly cooled and then poured into moulds and allowed to set for an hour. The dog-bone specimen moulds were specially designed and were pre-greased to permit easy removal of specimens.

Test Procedure. For this study uniaxial tension tests were conducted on toffee specimens using a Lloyds test machine at a strain rate of 5 mm/min and at temperatures of 20, 25, 30 and 35°C. From this data, corresponding temperature-dependent stress-strain curves were derived for toffee, and from these the values for Young's modulus, yield stress, plastic strain and ultimate tensile strength were determined, and are presented in Table 1. Other thermal properties in Table 1 were estimated from published data on a range of food products [7].

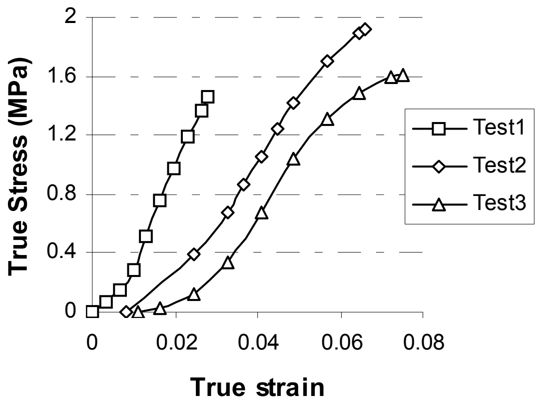
In conducting tensile tests on food specimens, breakages will occur at the grips due to the development of fine cracks in the material. To overcome this problem, and allow dog-bone specimens to be pulled in tension, specially designed grips were used that pull from both sides of the specimen on the curved surfaces at either end of the gauge length of the dog-bone shape. The thickness and width of the specimen was measured using a micrometer and then the specimen was mounted in the grips and tested in an environmental temperature controlled chamber on the Lloyds test machine at a constant rate of 5 mm/min. A duplicate toffee specimen with an embedded thermocouple was mounted in the chamber on a duplicate set of grips that were held on a clamp stand. The thermocouple signal was monitored until the required test temperature was reached and then the temperature was held constant for 30 minutes to allow the specimen to completely equilibrate at the test temperature. Subsequently, the specimen was pre-tensioned and then tested to failure.

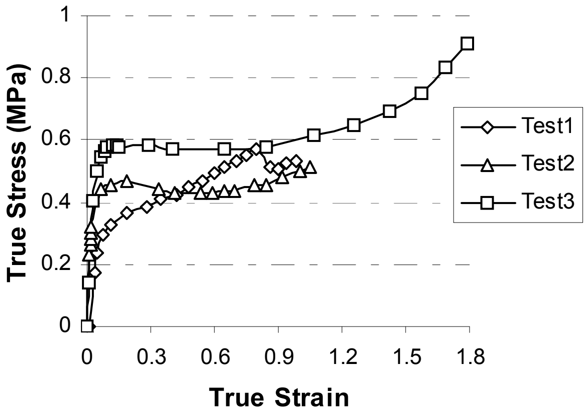
Results. The gripping arrangement has been very successful and has allowed stress-strain data to be obtained for toffee at temperatures of 20, 25, 30 and 35 °C. The grips and specimen configuration, and results for tension tests on toffee at 25 and 30 °C are shown in Fig. 1. The figure shows clearly the level of variation, which results from testing food materials, even when specimens have been very carefully and consistently prepared and tested from the same batch. Such variations can be attributed in part to the presence of tiny air bubbles within the material, which are removed as far as possible in the preparation stage, and to inconsistencies in the distribution of ingredients in the mould as it sets. However, temperature control also has a significant effect.

Figure 1 illustrates the temperature dependence of the material. Toffee is a material that is sensitive to very slight changes in temperature near room temperature, due to its low glass transition, which is approximately 40 °C. Even 1°C difference in temperature in the range of 20 - 40 °C has a significant effect on the mechanical properties of the material during testing. This high sensitivity to the test temperature results in variations between the stress-strain data derived from different tests. It can be seen clearly from Fig. 1(b) that at 25 °C the material is very brittle but from Fig. 1(c) that at 30 °C the toffee behaves in a ductile manner with high plasticity.



(a)





(b) (c)

Fig.1: (a) Tensile test grips for toffee specimens and (b) measured tensile test data for toffee at 25°C and (c) measured tensile test data for toffee at 30 °C

Estimating the Friction Boundary Condition

Previously, authors have studied the effect of friction at the interface between an ultrasonically excited surface and a contact surface in extrusion and cutting processes [1,8], demonstrating that ultrasonic excitation alters the coefficient of friction. For the development of the finite element models of ultrasonic cutting, it is assumed that at a contact surface between the ultrasonic blade and the food material, a friction boundary condition exists that can be modelled as a Coulombic friction condition. In this study, the friction coefficient was determined by experiment. A specimen of toffee was pulled at constant speed across a half-wavelength titanium ultrasonic block horn, which was designed by FE analysis and tuned to its first longitudinal mode frequency. A weights and pulley system, as shown in the schematic in Fig. 2, allowed the coefficient of friction to be calculated from Eq. 1. The coefficients of static and dynamic friction, μ_s and μ_d, were calculated, where, F_P is the weight attached to the pulley, F_S is the dead weight on top of the specimen, and m is the mass of the specimen. Tests were conducted with and without ultrasonic excitation of the block horn. The experiment was repeated several times and an average value for the coefficient of friction was recorded. Without ultrasonic excitation of the bock horn, the coefficients of static and dynamic friction were found to be 0.240 and 0.116 respectively. With ultrasonic excitation the coefficient of dynamic friction was found to be 0.032. Similar values of μ_d were estimated for a range of ultrasonic vibration amplitudes tested. The coefficient of dynamic friction under ultrasonic excitation of the test surface, of 0.032, was used in the FE model of ultrasonic cutting to simulate the interface boundary condition.

$$\mu_{s,d} = \frac{F_P}{F_S + mg} \tag{1}$$

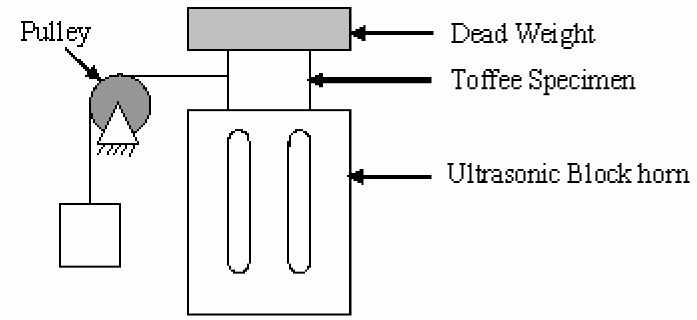


Fig. 2: Schematic of friction experiment

FEA Ultrasonic Cutting Model

Material Model. Toffee was modelled as a temperature dependent elastic-plastic material by including four stress-strain curves at temperatures of 20, 25, 30 and 35°C. Due to the spread of results from the tensile tests conducted at each temperature, one representative stress-strain curve for each temperature was selected to simulate the mechanical behaviour of toffee. From each curve, values for the Young's modulus and yield stress were determined and then a power law curve was used to smooth the plastic region of each curve.

To allow the material data to be accepted by ABAQUS, certain criteria have to be met to allow the program to interpolate between each of the temperature dependent curves. All plastic regions must have the same number of data points and be spread over approximately the same range of plastic strain [9]. This posed a problem, because toffee at 20 and 25°C exhibits brittle behaviour with almost no plasticity whereas toffee at 30 and 35°C exhibits high plasticity. This caused the plastic strain to range from 0 to approximately 1.4, which is a very large range for ABAQUS to interpolate over. To overcome this problem, two dummy plastic curves were generated for toffee at

20 and 25°C using a power law curve fit to a plastic strain of 1. These curves, along with the other two for toffee at 30 and 35°C were then included in the FE models. Both dummy plastic regions were included only to allow the material data to be accepted in the FE program and were ignored in the analysis. This was achieved by setting the critical stress for temperatures of 20 and 25°C to be equal to the yield stress in the debond model, and by setting the shear failure in the element erosion model to an infinitely small value close to 0. For both models this represents where the break load occurs in the experimental tensile test. The curve fitted data included in both FE models is shown for each temperature in Fig. 3.

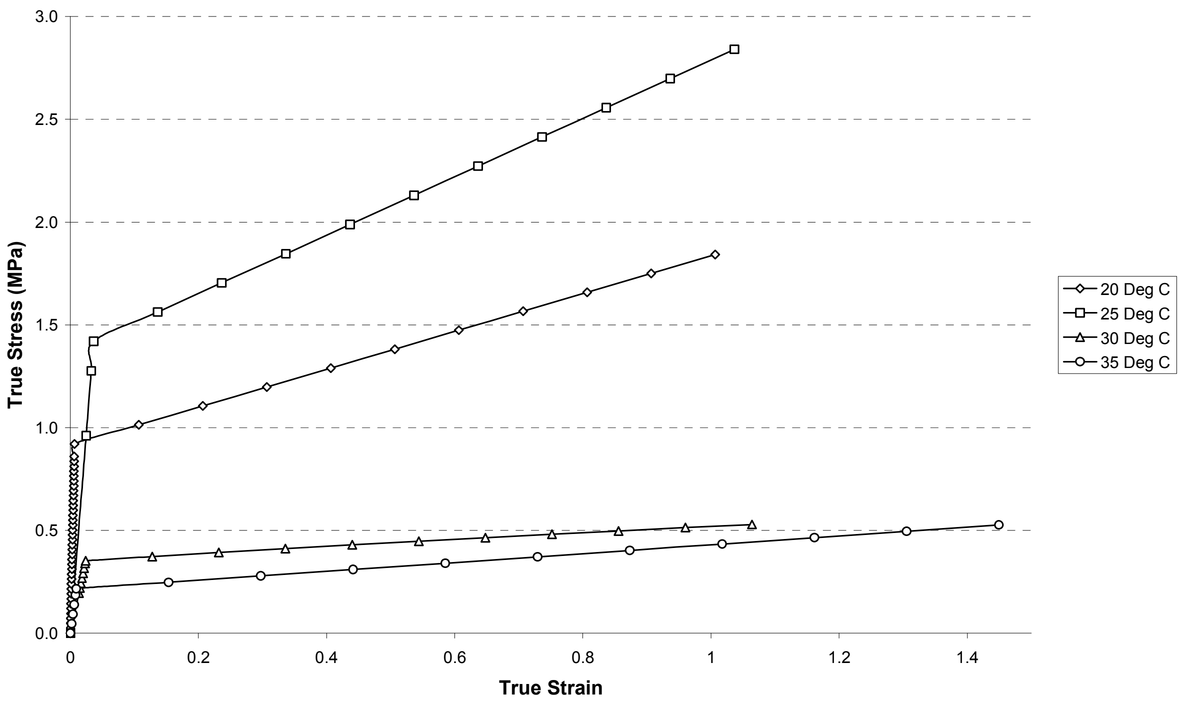


Fig. 3: FE tension test data for toffee at 20, 25, 30 and 35°C.

Table 1: Mechanical properties of toffee included in FE models

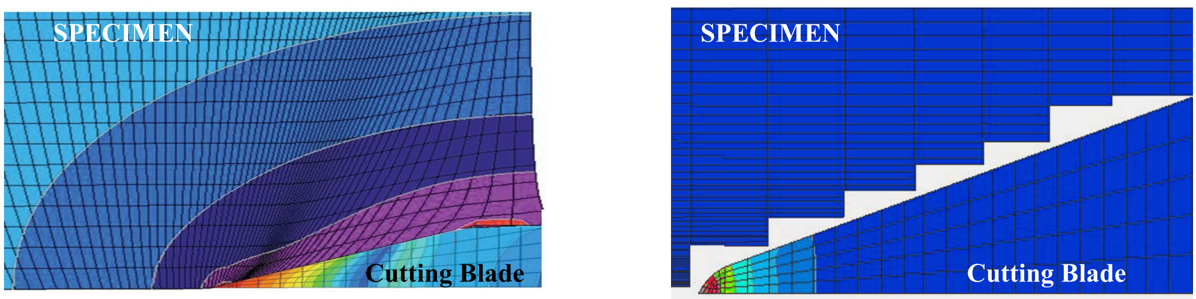
Mechanical Properties of Toffee					
Temperature [°C]	T	20	25	30	35
Density [kg/m^3]	ρ	1411.06	1411.06	1411.06	1411.06
Young's Modulus [MPa]	E	138	33.4	14.7	0.216
Yield Stress [MPa]	σ_Y	0.921	1.89	0.352	0.216
Ultimate tensile strength [MPa]	σ_{UTS}	0.921	1.89	0.529	0.527
Poisson's Ratio	υ	0.490	0.490	0.490	0.490
Specific Heat [J/Kg°C]	c	1200	1200	1200	1200
Thermal Expansion [µm/m°C]	α	1.00E-05	1.50E-05	2.00E-05	2.00E-05
Thermal Conductivity [W/mK]	k	0.9	0.9	0.9	0.9
Shear Failure	τ_F	0.0001	0.0001	1	1

Coupled Thermal-Stress Models. A fully coupled thermal-stress analysis using the implicit and explicit solver in the finite element package ABAQUS was performed which allowed the influence of temperature generated by friction at the blade-material interface to be accounted for in the modelling procedure. Two 2D FE models were developed to represent ultrasonic cutting. Both models utilised the symmetry condition about the cutting plane to enable cutting to be represented as a half model for computational efficiency.

The titanium blade was modelled as an elastic deformable body with the following material properties: Young's Modulus 114 GPa, density 4425 kg/m^3, poisson's ratio 0.31, specific heat 586 J/Kg°C, coefficient of thermal expansion 9.0E-06 μm/m°C, and thermal conductivity 6.6 W/mK. Toffee was modelled as a temperature dependent elastic-plastic material. The initial temperature of the blade and the specimen in the model was 20°C. The specific heat, coefficient of thermal expansion and thermal conductance of toffee is included to fully define the thermo-mechanical properties of the material and are given in Table 1. A coefficient of friction of 0.032 is included from the experimental tests to define the contact condition at the interface. The frictional heat generation option is also used which converts all energy produced by the frictional contact into heat and distributes the heat generated due to friction at the interface equally into the blade and toffee due to conductance. A film condition is included on the blade and specimen surface representative of a heat sink to allow heat to be removed from the surfaces due to convection during cutting.

Data is presented from the model for ultrasonic cutting parameters that are typical of current cutting devices. The ultrasonic blade frequency was 35 kHz and the blade tip amplitude was 50 μm. The toffee was moved into the blade at a constant velocity to a constant depth in the material.

Coupled Thermal-Stress Debond Model. The debond model simulates ultrasonic cutting as a fracture mechanics problem in mode I where a crack propagates when a critical normal stress is reached at a pre-specified distance ahead of the crack tip. A 2D half model with a defined crack tip and propagation direction was created, where the nodes defining the theoretical crack were tied to an analytical rigid reference surface using contact conditions. When the blade moves into the material, and the critical stress ahead of the theoretical crack tip is reached, the nodes debond and the crack propagates, simulating cutting. The mesh for this 2D model, during cutting, is shown in Fig. 4(a).



(a) (b)

Fig. 4: Mesh and contour plot of temperature for (a) debond model, (b) element erosion model, during ultrasonic cutting

Coupled Thermal-Stress Element Erosion Model. An alternative 2D half model of ultrasonic cutting was developed in ABAQUS using the element erosion option to define failure within the material. The model used a shear failure criterion at each temperature, which corresponds to the break point at each temperature on the stress-strain curves to define the material failure condition. Due to the high deformation of the elements within the model at the blade-toffee interface, the adaptive mesh option is used which automatically adjusts the nodal coordinates of highly deformed elements ensuring they remain within convergence limits until the failure criterion is met and the element is eroded from the solution. The mesh for this 2D model, during cutting, is shown in Fig. 4(b).

Discussion. Temperature at the cut site is difficult to measure as sensors are easily damaged by the blades during cutting. Previous experiments conducted by the authors have measured temperature at various locations in a specimen and as close as 1 mm from the cut site. It is hoped that, by validating the FE model against the temperature measurement data, the model could be used to predict temperature at the actual cut site. These findings are important for customising blade designs to specific food materials, because temperature effects can be significant in the cutting process.

Figure 5 plots temperature-time curves predicted from the debond FE model at a location in the toffee specimen, at a depth of 1 mm from the line of cut. The FE model allows an evaluation of the effects of varying the ultrasonic cutting parameters on the temperature during cutting. For example, Fig. 5 shows the relationship between cutting speed and temperature in a toffee specimen. The model is run for four different feed rates with a constant depth of cut. To achieve a solution within manageable computational time, the cutting speeds are set unrealistically high in the current FE models, however the model predicts that the cutting temperature can be reduced by increasing the cutting speed, which is consistent with results from previous experimental studies of ultrasonic cutting in a variety of different materials [10].

Similar results are achievable for the debond and element erosion models. However, the element erosion model removes the need to pre-notch the specimen and allows better opportunities for convergence through adaptive meshing. The element erosion model also accommodates dynamic effects rather than adopting a quasi-static approach and removes the need to assume perfect cleavage, which is a limiting assumption of the debond model. However, the debond model is significantly less computationally intensive and, for many parameter adjustments, can provide well-correlated estimates of temperature and stress. Both models can allow cutting parameters to be changed easily, such as blade tip vibration amplitude, frequency, cutting speed, cutting depth, blade geometry, blade material and specimen material, and can accommodate multi-layered material models.

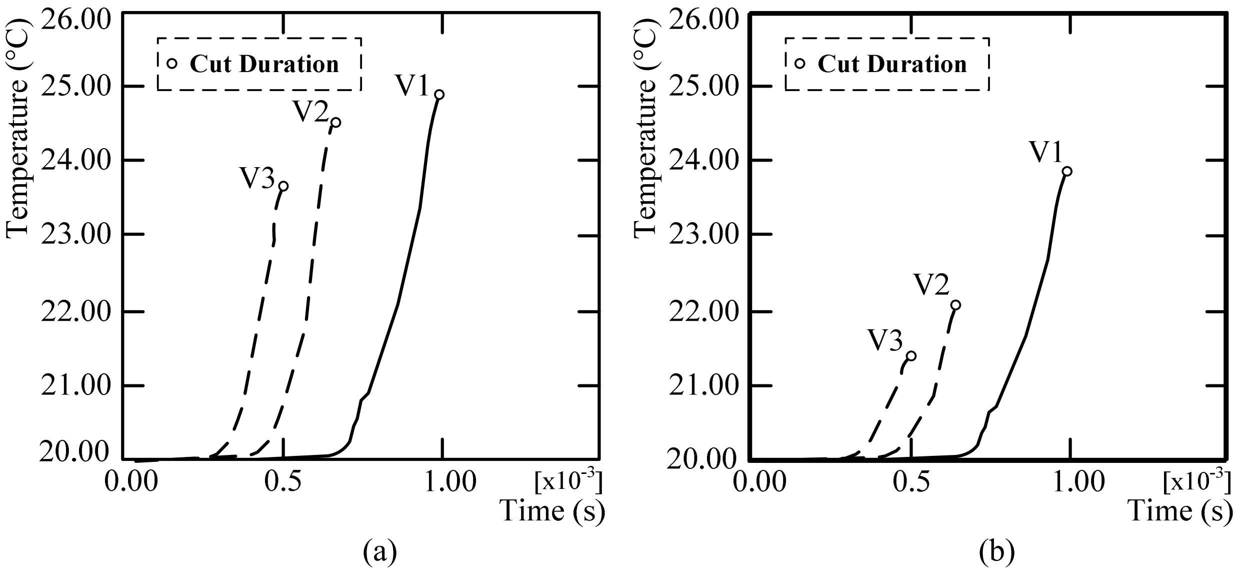


Fig. 5: Effect of cutting speed on temperature 1mm from cut site as predicted from (a) the element erosion FE model and (b) the debond FE model.

Conclusions

Two different approaches to represent ultrasonic cutting as a 2D finite element model have been presented. One using the debond option in ABAQUS standard which represents cutting as a fracture mechanics model and one which uses the element erosion option in ABAQUS explicit, where elements are removed from the solution when a shear failure criterion is reached. Both models account for thermal issues that are present during ultrasonic cutting due to friction at the blade-toffee interface. Temperature dependent material data for toffee were derived and included in the FE model. On application of ultrasonic excitation to a block horn, a significant reduction in the coefficient of friction at the interface between the block horn and toffee specimen was recorded and this reduced friction coefficient was included in both FE models to characterise the contact condition at the interface between the blade and specimen.

FE models have been used to predict the effect of velocity on the temperature distribution at a distance 1mm from the cut site in material specimens of toffee. These preliminary results correlate with previous experimental investigations, which found that ultrasonic cutting temperature reduces with increased cutting velocity.

Further work will consider ultrasonic cutting as a 3D thermal-mechanical model where blade orientation at the cut site and different blade geometries can be accommodated. In this case, only the element erosion model can be used.

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