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Experimental characterisation and numerical modelling of cutting processes in viscoelastic solids

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ABSTRACT

Rate dependency is an important phenomenon that can be observed during cutting of viscoelastic materials. This paper reports on results of both experimental and theoretical investigations that were obtained by using a polymeric food model system. Viscoelasticity was experimentally observed in relaxation experiments at small strains, and tensile tests were performed for large deformations at different tensile speeds. Finite viscoelasticity with Mooney-Rivlin elasticity valid for large displacements was applied for modelling the viscoelastic properties of the food model, and degradation and crack propagation were considered by cohesive fracture mechanisms. Model predictions were prepared by applying the finite element method using *Abaqus* and compared with experimental results. The good agreement between simulation and measurement especially for the maximum cutting force and the characteristic plateau validate the modelling strategy.

1. Introduction

Cutting is the most prominent technique used for separating food products into segments of defined size and geometry. During the cutting process, which can be performed at speeds that range from a few mm/s up to several m/s, the motion of the cutting tool through the material leads to a complex interplay of inelastic deformations and fracture including a certain amount of friction between the moving device and the substrate (Dowgiallo, 2005; Schneider et al., 2009). Fracture occurs when the deformation caused by the blade leads to local stresses that exceed the strength of the material.

Food products are generally complex materials with liquid, semi-solid or even hard and tough texture. In many cases, they exhibit a rate dependent inelastic, e.g. viscoelastic, material behaviour (Miri, 2011) which involves phenomena such as stress relaxation and creep. Therefore, the success of the cutting process depends on the cutting speed (Schuldt et al., 2016; van Vliet et al., 1993). If the kinetics of relaxation and creep processes in front of the cutting edge are faster than the chosen cutting speed, no cutting occurs. This results in extensive deformation and irreversible structural damage. To prevent these effects, the apparent stiffness of the material has to be increased by applying a higher cutting speed to limit the viscoelastic energy dissipation, or at lower material temperature to reduce structural mobility and flexibility (Steffe, 1996; Schneider et al., 2010).

Previously, Zhang (1999) studied the separation of the material in cutting processes using a vertical profile for different criteria, including geometrical considerations, an effective plastic strain criterion, a strain energy density criterion, and a nominal failure stress criterion. The geometrical separation criterion evaluates the distance between the cutting edge and the node at separation in the interface layer. Because one must use a finite distance to avoid numerical instability, whilst the actual desitance at separation is zero, Zhang determines the distance criterion as inappropriate. The effective plastic strain criterion was found to be not reliable in a practical application with a single threshold because effective plastic strain varies significantly even during stable cutting. The separation criterion based on the strain energy density is qualitatively similar to the effective plastic strain criterion. These criteria have also been discussed by Huang and Black (1996), Mamalis et al. (2001) and Movahhedy et al. (2000). Their findings are generally in line with the ones from Zhang. That the beginning of cutting cannot

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be simulated correctly by the geometrical criterion has been observed by Huang as well. Mamalis used the good agreement between predicted and experimental cutting forces as validation for their numerical model, as it will be done in this work too. Constitutive equations published in the study of Zhang (1999) were assumed to be either elastic-perfectly plastic or plastic with hardening. In case of perfect plastic material, the parameters for defining the onset of plastic deformation are constant while they change during the load history in case of plasticity with hardening. Further information on hardening and plasticity can be found e.g. in Lemaitre and Chaboche (1994), Simo and Hughes (2000), Haupt (2002) and Lubliner (2008). Both types of plastic theories are rate-independent. However, Zhang finally presumed that strain rate has a considerable effect on separation. McCarthy et al. (2010) studied the indentation of the blade into the workpiece. It was shown that a maximum stress criterion is a suitable measure for the strength of a polyurethane substrate in order to predict the onset of cutting. In this sense, the normal stress component perpendicular to the blade is found to be a good predictor for the onset of cut formation when it is equal to the failure stress as determined from the experimental uni-axial tensile tests. The simulation of the whole cutting process which requires the modelling of degradation and separation was not in the focus of McCarthy's investigation. Moreover, with the used hyperelastic constitutive model rate dependent effects could not play any role. Nevertheless, McCarthy finally expected that the viscoelastic material properties change the maximum stress considerably which makes the result strain-rate dependent.

Thus, the aim of the present study is to bring together experimental data and numerical approaches to predict the cutting behaviour at various cutting speeds. Different from the previous works, the rate effect is considered in this work using a viscoelastic material combined with a maximum stress criterion for separation. The numerical model is validated by the good agreement between numerically predicted and experimentally determined cutting forces. The modelling strategy calls for small and large deformation testing at various strain rates as a basis for subsequent finite element modelling. In this study a synthetic material with viscoelastic characteristics is used as a model system for food products which eliminates natural material variations, and sample preparation becomes more reproducible. Such model materials have been used by several authors to mimic biological or food systems (McCarthy et al., 2007; Jampen et al., 2001; Kohyama et al., 2004; Shergold et al., 2006). Here, a model system composed of the silicone elastomer Elastosil RT 745-S (Wacker Chemie AG, Munich, Germany) and icing sugar is used to represent a homogeneous matrix with a disperse phase. In addition to handling advantages, e.g. a widely adjustable specimen geometry, negligible aging effects, and temperature dependence, it is possible to adjust the mechanical and the cutting properties by a variation of the compounds of the model (Schuldt et al., 2016).

2. Material and methods

2.1. Model system and test specimen preparation

Elastosil RT 745-S (Wacker Chemie AG, Munich, Germany), a two component silicone elastomer with a curing agent, served as continuous phase of the model system. Its components A and B were mixed in a ratio of 1:1 (w/w), and commercial icing sugar was added as filler to obtain a disperse phase mass fraction of 35 % (w/w). The mass was then poured into PTFE molds, and finally polymerised at 103 °C for 2.5 h in a convection oven. The geometry of the molds ensured plane parallelism of all specimen geometries. Further information on sample preparation are given in our previous publication (Schuldt et al., 2016). Specimens of different geometry were prepared for the various characterisation and cutting experiments, i.e. cylindrical samples for relaxation tests, dogbone type specimens based on probe type 1BA of DIN EN ISO 527-2 (2012) for tensile tests, and cuboid samples for cutting tests, Fig. 1.

2.2. Experiments

2.2.1. Material characterisation

With the model system being a filled polymer, large inelastic deformations and rate dependent effects which also result in long-term relaxation and creep behaviour are anticipated. To characterise this behaviour experimentally, relaxation experiments and monotonic tensile tests at different tensile speeds were carried out. Irrespectively of the strain level reached in the experiment, the nominal strain

$$\varepsilon = \frac{u}{\ell_0} \tag{1}$$

and nominal stress

$$\sigma = \frac{F}{A_0} \tag{2}$$

are used to describe the deformation behaviour with ℓ_0 and A_0 the length and the cross section of the specimens in the reference configuration ($t = t_0 = 0$), respectively. The displacement of the crosshead along the longitudinal axis is given by u. The force F in the longitudinal direction of the specimen is defined positive for tension. All tests were performed using a 5564 universal testing machine (Instron Ltd., High Wycombe, UK) in displacement control.

Small deformation relaxation experiments were performed for compressive loadings. Cylindrical specimens were placed on the lower lubricated plate of a parallel plate device. In an ideal relaxation experiment, a constant strain level has to be reached at an infinite speed which cannot be realised in practice and has significant influence on the information available for parameter identification. Instead a steep displacement ramp with a speed $\dot{u}$ was used and the test was programmed so that 5 % of compressive strain is reached within 0.1 s and held constant subsequently. This corresponds to a crosshead displacement of $u = -0.565$ mm and a crosshead speed of $\dot{u} = -340$ mm/min. The latter represents a reasonable compromise of speed and inertia effects. Displacement- and force-time data were taken from the analogue output of the machine and digitized by a DAQPad-60210E A/D converter (National Instruments Germany GmbH, Munich, Germany) at 1000 data points/s.

It can be seen from the actual displacement-time curves, Fig. 2, that a displacement step $|\bar{u}| \approx 0.59$ mm is reached only after $\Delta t = 0.5$ s. Considering the geometry in the reference configuration $\ell_0 = 11.3$ mm and Eq. (1) the actual relaxation strain is $|\bar{\varepsilon}| \approx 5.2$ %. Monotonic tensile tests were carried out after attaching the dogbone specimens to the mechanical tensile test clamps between crosshead and force transducer of the testing machine. Tensile testing was performed in quadruplicate at three different crosshead speeds of $\dot{u} = \{1, 10, 100\}$ mm/min up to a maximum crosshead displacement of 200 mm. Force-displacement data were recorded with 60 data points/mm.

2.2.2. Cutting process

Cutting experiments were carried out using straight blades of dimensions 20 × 70 × 1 mm^3 with an edge angle of 20°. The blades were made of an alloy which is regularly used in slicing operations (WS 1.2379, X152CrMoV12, hardened to 63 HRC,