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High-speed cutting of foods: Cutting behavior and initial cutting forces

Stefan Schuldt, Yvonne Schneider, Harald Rohm*

Chair of Food Engineering, Technische Universität Dresden, 01062 Dresden, Germany

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ABSTRACT

The viscoelastic properties of foods determine deformation, fracture and friction during industrial cutting applications and substantially affect the cutting behavior, especially at high cutting velocity. Using a custom-built high-speed test station the cutting behavior of representative foods (either based on a protein network, plant tissues and sugar based confectionary) and food models on elastomer basis was investigated at a cutting velocity ranging from 10^{-4} m/s up to 10 m/s. On the basis of cutting force data and dynamic mechanical analysis performed between 1 rad/s and 10^{0} rad/s, the cutting behavior of the systems was investigated. In general, the cutting force profiles depended on cutting velocity and could be related to deformation characteristics that were measured in dynamic mechanical analysis (except for plant tissue whose inherent composite structures seem to contribute to brittle behavior at each cutting velocity). Sugar based confectionary showed a strong rate dependence with brittle fracture and splintering in the high-speed region. For all systems except plant tissues a velocity dependent deformation cutting parameter, derived from the initial cutting forces, coincides with the power law frequency dependence of the complex modulus. This relation was used to build a model approach with which the pre-crack cutting forces at high-speed cutting velocity can be predicted with commercially available standard testing machines.

1. Introduction

Cutting with a blade is the most prominent method in food processing to separate products into pieces with defined macroscopic dimensions. According to Schneider et al. (2002), four phases can be distinguished in a cutting process: (1) a start-up phase in which full contact between cutting edge and product is achieved, (2) a deformation phase in which the cutting force F_C increases linearly, and (3) the separation phase where the resistance of the product, and friction between blade and product determine the cutting force. In the detaching phase (4) the material is completely separated, and F_C drops to zero. As a consequence, the contributions to F_C come only from deformation in phase (1) and (2) and from deformation, fracture and friction in phase (3) (Dowgiallo, 2005; Schuldt et al., 2016a, b). From these considerations it is obvious that the quality of the cutting process is a function of the mechanical properties of the product, and of the properties of the blade (Marsot et al., 2007; Schuldt et al., 2016b).

Another important factor is the cutting velocity. In industrial production, most foods are cut at a velocity of up to several m/s. Because the majority of foods are viscoelastic their deformation, fracture and friction properties depend on time scale and hence loading velocity (Lorenz et al., 2012; Schuldt et al., 2016a; Vliet et al., 1993). Especially at high cutting velocity v, deformation and fracture effects can therefore lead to undesired product deformation and splintering, and to insufficient cutting quality. Despite the demand for high-speed process analysis, only limited experimental data are available. As there is a lack of standard machines for testing at $v > 1$ m/s, the investigation of cutting behavior at elevated cutting velocity is challenging, and the barriers for designing tailor-made testing devices are responsible for the resulting research gap. By using a pendulum-type device that allowed cutting velocities between 1 and 7 m/s, Guts et al. (2010) determined the work necessary to transect selected foods. Dowgiallo (2005) cut fibrous foods at a cutting velocity of up to 4 m/s which was, to the best of our knowledge, the only high-speed food cutting study that continuously recorded cutting force-displacement data until Schuldt et al. (2018) came up with the combination of a

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* Corresponding author.
E-mail addresses: stefan.schuldt@tu-dresden.de (S. Schuldt), harald.rohm@tu-dresden.de (H. Rohm).

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commercially available universal testing machine and a special custom-built test station for the analysis of cutting forces from low cutting velocity up to the high-speed region of 10 m/s. Using bubble gum as example, they showed increasing cutting forces, and an increase of elastic effects up to brittle fracture with increasing cutting velocity, which was basically in accordance with results of dynamic mechanical analysis (DMA). Using additional high-speed video sequences, it was demonstrated that the test station allows the holistic analysis of high-speed cutting.

For a basic understanding of the cutting process as well as for modeling approaches it is important to link physical product characteristics to phenomena observed during cutting, e.g. deformation and fracture. Schuldt et al. (2016a) analyzed the cutting behavior of different viscoelastic food models at slow and intermediate cutting velocity ($\leq 1.7 \times 10^{-2}$ m/s), especially with respect to cutting phase (2), and showed that there is a positive correlation between the 1st F_C derivative (cutting stiffness) and the complex modulus measured by DMA. It was further shown that the velocity (or time) dependence of these two parameters follows power law, and it was therefore suggested that it could be "*reasonable to predict pre-crack cutting forces at high cutting velocity from DMA results and/or cutting forces obtained at moderate cutting velocity … if no fundamental change in the mechanical properties takes place at very high cutting velocity*".

The aim of this work was to cut viscoelastic food models and real foods over a broad cutting velocity range to get more information on the velocity dependent cutting behavior. With the use of DMA results, the cutting behavior of the systems will comprehensively be described and explained. The influence of viscoelasticity on cutting velocity dependence of the materials will also be discussed. Special emphasis is placed on the deformation phase (2) of cutting, so that the correlation between deformational pre-crack cutting parameters and DMA frequency dependence (see Schuldt et al., 2016a) will be verified for high cutting velocity. Based on that approach, a model will be presented to predict initial high-speed cutting forces.

2. Materials and methods

2.1. Materials

In previous studies Boisly et al. (2016) and Schuldt et al. (2016a) established and demonstrated the suitability of elastomer-based viscoelastic systems for being used as models for foods. These tailor-made elastomers were made using a two-component elastomer with a curing agent (Elastosil RT745-S, Wacker Chemie AG, Munich, Germany; for details of sample preparation, see Schuldt et al., 2016a). To vary material properties, corn starch and AK1000 silicone oil (Wacker Chemie AG, Munich) were added as filler or softener, respectively: sample f31 contains 31 % (w/w) filler, f40 contains 40 % (w/w) filler, and f35s20 contains 35 % (w/w) filler and 20 % (w/w) softener. All model systems were analyzed at room temperature.

As representatives of foods that are cut in industrial scale, the following items were selected: (a) foods consisting of a polymeric protein matrix with different disperse fillers: Bergkäse, a hard cheese variety with a casein matrix with dispersed milk fat globules; Leberkäse, a semi-solid aqueous actin/myosin matrix with emulsified animal fat; and Salami, an air-dried sausage from grounded fat, muscle tissue, and spices. (b) plant tissues, with potato being presented in this work. Additionally, the cutting behavior of carrots and asparagus was analyzed but will not be presented in this paper as it principally showed the same effects as potato. (c) Toffee, representing soft candy with a continuous phase of a supersaturated sugar solution and a disperse phase, consisting of sugar crystals and oil droplets. All foods were obtained in local retail stores except toffee which was manufactured in the Candy Lab of Chocotech GmbH (Wernigerode, Germany). All food samples were adjusted to 15 °C or 30 °C (only toffee) in an IPP55 environmental chamber (Memmert GmbH + Co. KG, Schwabach, Germany).

2.2. Cutting experiments

Orthogonal cutting experiments were performed with a 5564 universal testing machine (Instron Ltd., High Wycombe, UK) at a cutting velocity v of 10^{-4} m/s (this velocity not for the model systems), 10^{-3} m/s, or 10^{-2} m/s, and with a high speed test station at 10^{-1} m/s, 10^{0} m/s, or 10^{1} m/s. In both instruments a blade with 1 mm thickness, 10° wedge angle, 20.5 mm cutting edge length and a width of 10 mm was used. Further information on the operating mode of the testing machines, the cutting procedure and the blade geometry is given in Schuldt et al. (2018).

The samples used in the cutting experiments had a rectangular cross-section that was $10 \cdot 20\,\text{mm}^2$ (cutting width $w = 10$ mm; length of the cut $u = 20$ mm) for the model systems, and $15 \cdot 20\,\text{mm}^2$ ($w = 15$ mm; $u = 20$ mm) for all foods except toffee ($15 \cdot 15\,\text{mm}^2$; $w = u = 15$ mm) (see Fig. 1). F_C (N) was recorded versus blade displacement l (mm) in five individual replicate experiments with new samples. To obtain additional information on the cutting behavior of the systems, video capturing of the cutting experiments was done using a CR3000x2 high-speed camera system (Optronis GmbH, Kehl, Germany).

2.3. Analysis of force data

To eliminate effects of sample dimension, F_C was normalized to a cut width of 10 mm. For the sake of clarity, this normalized cutting force F_N is further expressed in force units. The force/displacement curves were then analyzed to obtain the deformational pre-crack cutting parameter s_0 (N/mm), which corresponds to the slope of F_N *vs.* l in the deformation phase, and which was determined by linear regression of the initial linear part of the normalized cutting force. These F_N *vs.* l slopes were then fitted against v using power-law by

$$s_0 = a \cdot v^b \tag{1}$$

where a refers to s_0 at 1 m/s, and b reflects the velocity dependence of s_0.

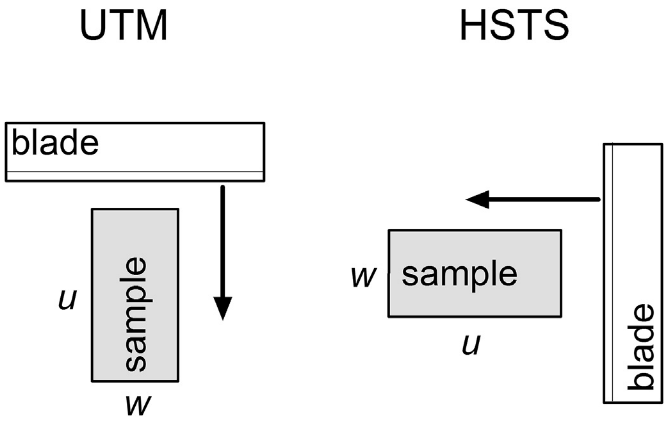

Fig. 1. Geometrical cutting conditions for the universal testing machine (UTM) and the high-speed testing machine (HSTM) with the cutting width w and the length of the cut u. The arrows indicate the moving direction of the blade.