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High-speed cutting of foods: Development of a special testing device

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ABSTRACT

Because of the viscoelastic and therefore time-dependent properties of many foods, cutting at high velocity is a complicated process that may lead to undesired fracture and deformation and, thereby, reduce cutting quality. In addition, the analysis of the process is difficult because of the limited availability of commercial equipment for high-speed testing. This work reports on the development of a test station for high-speed cutting that enables a cutting velocity of up to 10 m/s; process analysis is realized by force and video data capturing. Using a bubble gum matrix as example, the increase in cutting velocity (from 10^{-4}–10^{1} m/s) as well as the decrease of sample temperature resulted in a decrease of the viscous contribution of the material and an increase of elastic effects that was reflected by reduced material deformation and brittle fracture during cutting. The holistic description of these effects was realized by interpreting cutting forces, video data, and results of dynamic mechanical analysis. The described test station with high-speed process analysis represents a prominent tool for demonstrating the sensitivity of viscoelastic foods towards temperature and mechanical stresses caused during cutting.

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1. Introduction

The cutting process is in general determined by the complex interplay of product properties (mechanical properties, composition, geometry, …) (Schneider et al., 2002; Schuldt et al., 2016a), and technical parameters covering characteristics of the applied movement (cutting velocity, excitation, slice-to-push-ratio) (Arnold et al., 2011; Atkins et al., 2004; Zahn et al., 2006) and of the cutting tool (knife and blade edge geometry, blade surface) (Marsot et al., 2007; Schuldt et al., 2016a). When cutting into a soft material with a straight edge blade, a deformation zone is formed in front of the cutting tool where tensile stresses dominate (Fig. 1). If fracture tension of the material is exceeded, a crack is initiated that, in case of stable crack growth, further grows with ongoing blade displacement. This means that the material in front of the blade edge is deformed to a certain amount until fracture occurs (McCarthy et al., 2007; Schuldt et al., 2016a, b). For isotropic materials and with constant boundary conditions, the deformation and crack initiation zone in front of the edge will be shifted by the amount the blade penetrates into the material (Boisly et al., 2016; McCarthy et al., 2007). Additionally, friction that arises from the relative motion between the blade and the newly formed cutting surfaces results in shear stresses and lateral deformation. As a consequence, the cutting behavior of a particular product is strongly linked to its rheological properties.

In the food industry, a large variety of products is cut at high cutting velocity. This is true for e.g. fruits, vegetables and meat, and for cut-and-wrap products such as cheese, sausages and sweets (bubble/chewing gums, soft and hard caramels). Because all these foods are viscoelastic, the energy introduced by the cutting tool that leads to elastic and plastic deformation and fracture in the product, and to friction between blade and product depends on material characteristics and cutting velocity (Lorenz et al., 2013; Schuldt et al., 2016b; van Vliet et al., 1993).

At low deformation rate or at low cutting velocity viscoelastic materials dissipate energy, causing for example stress relaxation. With increasing cutting velocity, less time is available for this process, and the elastic response to deformation (including fracture) becomes more and more dominating (Boisly et al., 2016; Loncin and Merson, 1979; van Vliet et al., 1993). When a velocity of approximately 1 m/s is exceeded, dimensional and placement accuracy of the product becomes challenging; a further increase in

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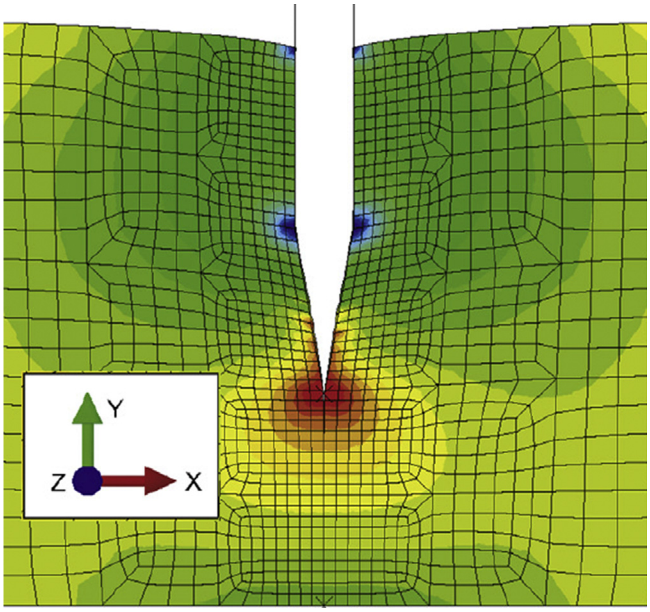

Fig. 1. Stress distribution and deformation in orthogonal cutting with a straight edge blade. (from Boisly et al., Experimental characterization and numerical modelling of cutting processes in viscoelastic solids, Journal of Food Engineering 191 (2016) 1–9. With permission from Elsevier).

cutting velocity may lead to uncontrolled fracture phenomena such as product splintering, and undesired deformation effects such as irregular cutting surfaces; product deformation and insufficient cut accuracy are the consequence. This is, in line with production interferences, a major factor that limits the throughput of industrial cutting machines. Since cause and effects are often unknown, the optimization of such machines is frequently based on an empirical adaptation of technical parameters, whereas an analytical correlation of product characteristics with damage events is frequently lacking.

A main reason for that is that it is difficult to evaluate high-speed processes on the basis of material characteristics of foods at high deformation rate, or velocity. This is because commercially available equipment for quasi-static compression or tension tests generally operates at velocities in the dimension of mm/min or a few cm/min (Chen and Opara, 2013). There is, to the best of our knowledge, no standard testing machine available on the market that allows material characterization of solid foods and the corresponding process analysis at a testing velocity > 1 m/s. Equipment to apply testing velocities > 1 m/s includes, for example, linear actuators, rotational systems, and Charpy impact pendulum or drop weight testers (Field et al., 2004; Meyers, 1994; Olwig, 2006) which, in theory, provide the possibility of high-speed testing. High acquisition costs, little flexibility in the applicable testing velocity, and the combination of difficult force data capturing and high engineering costs by designing tailor-made test stations are limiting factors. Dowgiallo (2005, 2015) designed a special test station by combining a servo-mechanical device with the force acquisition system of a universal testing machine to cut fibrous food materials with a velocity up to 4 m/s. We are, to the best of our knowledge, not aware of any other publication that deals with cutting of foods combined with a sufficient force data recording at a velocity of 1 m/s and more.

This study reports on the design of a high-speed test station, allowing to cutting foods with a velocity of up to 10 m/s. For quantitative process analysis, force-displacement data are collected, and high-speed video information is captured. A viscoelastic model bubble gum, a typical cut-and-wrap product, is exemplary used as target material to analyze the cutting behavior over a cutting velocity range of 6 magnitudes. We additionally analyze the effect of sample temperature to illustrate presumable disturbing events during industrial processing, and to demonstrate the capabilities of the test station. Finally, it is investigated whether the deformation behavior in dynamic mechanical analysis can be used to predict cutting behavior.

Supplementary video related to this article can be found at http://dx.doi.org/10.1016/j.jfoodeng.2017.08.001.

2. Materials and methods

2.1. Test station for high-speed cutting

The basic operation principle of the high-speed test station (HSTS) is the combination of rotational and linear motion (Fig. 2). The sample is placed in an appropriate recess of a sample support skid mounted on a linear ball screw actuator. The sample skid is driven towards the cutting blade which is mounted on a rotor, and which moves along the perimeter of the rotor with the given circumferential velocity. By synchronizing the movement of the linear actuator and the rotor system, the sample is perpendicularly cut (almost no blade inclination) with a pre-set cutting velocity. During cutting, the blade separates the sample by moving through a gap in the skid (width, approximately 5 mm). To capture force as a function of time, the blade is mounted on a piezo-electric force transducer (Type 9027C, Kistler Holding AG, Winterthur, Switzerland) with appropriate data processing (data collection rate, up to 60 kHz). Visual documentation of the cutting process is achieved by a CR3000 $\times$ 2 high-speed camera system (Optronis GmbH, Kehl, Germany). A sketch of the mechanical part of the entire test station is shown in Fig. S1.

2.2. Test station for low and intermediate cutting velocities

A 5564 universal testing machine (UTM; Instron Ltd., High Wycombe, UK) was used to cut the samples with a velocity up to 10^{-2} m/s. A sample support rig (also with a 5 mm gap) was mounted on a 100 N strain gauge force transducer attached to the bottom frame of the UTM, and the cutting blade (same as used in the HSTS, provided by ASTOR Schneidwerkzeuge GmbH, Storkow, Germany; see Fig. 2) was mounted on the crosshead of the instrument. After placing the samples in the rig the blade was lowered until contact with the sample was achieved, and the displacement reading of the instrument was set to zero. The cross-

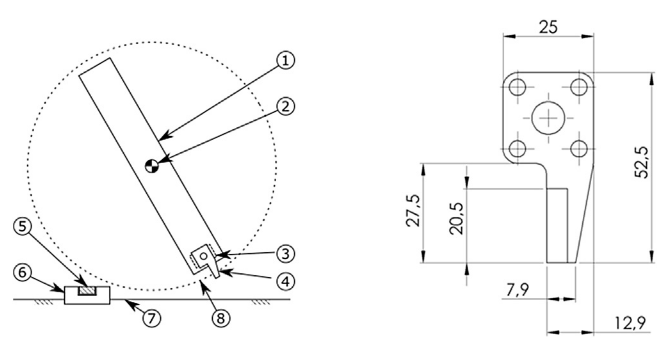

Fig. 2. Operating principle of the high-speed test station (left) with a rotor (1), the rotational axis (2), a blade (4) mounted on the force transducer (3), the sample (5) in the sample support skid (6), the linear axle (7) and the rotational lane with a radius of 0.5 m (8). Geometry of the blade, 1 mm thick, 20.5 mm of cutting edge, and 10° cutting wedge angle (dimensions in mm) (right).

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