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Pre-crack cutting properties of viscoelastic food models

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ABSTRACT

The cutting of foods and its result, namely cutting quality, is determined through a complex interaction of simultaneously acting and interrelated cutting energy contributions, and strongly depends on the mechanical properties of the viscoelastic food itself. Pre-crack deformation and cut initiation play a key role in the initial phase of the cutting process. Silicone rubbers with different types and amounts of dispersed materials were used to model food systems with customized viscoelastic properties that were characterized by dynamic mechanical analysis and cutting experiments. The cutting stiffness derived from the force measured during cutting was identified as a useful parameter to conclude on the material properties of the systems. The rate dependence measured in small deformation frequency sweeps was highly related to the viscoelastic profile of the model systems, and could be directly related to the cutting stiffness measured at different cutting velocity. The results contribute to a suitable selection of cutting modeling parameters, and are helpful to deepen the understanding of material behavior at high-speed cutting applications.

1. Introduction

In food processing, cutting is the most important technique for separating viscoelastic solids into segments with predefined size and geometry. Segment size and shape accuracy, accurate product deposition before packaging, and clean manufacturing demand high precision in processing and cutting quality. These factors depend on technical parameters such as cutting velocity, blade geometry and blade sharpness, and on the material properties of the food (e.g., viscoelasticity, homogeneity, thermo-physical state). The most important material characteristics that determine cutting quality are mechanical properties. Therefore it is essential to identify and to describe these properties in context of the relevant cutting process parameters. For example, cutting velocity is a technical key parameter for increasing product flow in industrial manufacture. There is, however, empirical evidence of general limitations and undesired effects at high cutting speed, because the mechanical behavior of viscoelastic solids is highly rate dependent (Booij and Thoone, 1982; Rohm and Lederer, 1992; van Vliet et al., 1993).

When cutting with a knife, which is the case in almost all industrial high-speed applications, a blade penetrates the target material with a defined velocity and creates a fracture area, forming two new surfaces at both blade sides. Because the target material is nearly all the time in contact with the blade, the cutting energy W_C acting on the blade

$$W_C = W_E + W_{D,v} + W_{D,f} + W_{fract} + W_F \quad (1)$$

refers to the sum of elastic deformation energy W_E, the dissipative energy originating from viscous flow $W_{D,v}$ and initial friction $W_{D,f}$, the fracture energy W_{fract}, and the frictional energy W_F between cutting material and blade (Dowgiallo, 2005; Schneider et al., 2001; van Vliet, 1996). W_{fract} is zero when the blade is already in contact with the product but a crack in front of the cutting edge has not yet been initiated, and is mainly derived from W_E (van Vliet, 1996). W_F originates from the relative motion between blade and cut surface, and becomes significant after crack initiation or when surfaces are attached after extreme deformation.

Depending on fracture properties such as fracture strain, and on the magnitude of W_F and W_{fract}, the cutting energies W_E and W_D may be responsible for the better part of W_C. W_E and W_D, related to pre-crack deformation induced by the blade, strongly depend on the mechanical properties of the cutting material that can be analyzed by, e.g., uniaxial compression or tension, or dynamic mechanical analysis in compression or shear once boundary conditions are defined (Barden et al., 2015; Luyten and van Vliet, 1995;

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Rohm and Lederer, 1992). Because these characterization methods are commonly used for material or texture modeling (McCarthy et al., 2010; Chen and Opara, 2013; Kästner et al., 2012), it is essential to identify suitable material properties. It is, however, difficult to relate the respective results to cutting because of the complex integration of different loads. Another way to characterize cutting properties is to analyze cutting forces. Schuldt et al. (2013) used parameters from cutting experiments (cut initiation, cutting stiffness) with defined elastomers to identify knife sharpness properties. When dealing with defined knife properties, it is on the other hand possible to characterize unknown or undefined cutting materials.

Many sliceable foods such as cheese or sausages comprise a biopolymeric network structure containing solid, semi-solid and liquid fillers (Barden et al., 2015; Bruno and Moresi, 2004; Jaros et al., 2001). Several attempts have been made to make use of elastomers for the simulation of various biobased materials. For the instrumental quantification of chewing forces, Kohyama et al. (2004) used silicone rubber as food model to overcome issues of poor reproducibility that was observed with real foods. Other authors used silicone rubber to simulate cutting properties of biological tissues such as skin (McCarthy et al., 2007), or to simulate the rate dependent development of shear moduli of soft solids in medical applications (Shergold et al., 2006). Apart from advantages concerning geometry and handling (e.g., negligible temperature dependency), the main advantage of using such model systems is that specific mechanical properties can be targeted by a proper compound selection.

The aim of this work is to identify objective material characteristics to directly describe cutting force parameters before crack initiation. Special focus is set on cutting velocity dependence as integral technical cutting parameter. The characteristics of the model systems may further be used in the stepwise numerical material simulation of the complex cutting process, and allow to draw conclusions on real food systems and their behavior in industrial cutting.

2. Materials and methods

2.1. Cutting materials

Model systems were made from Elastosil® RT 745-S (Wacker Chemie AG, Munich, Germany), a two component silicone elastomer with a curing agent. Components A and B were mixed 1:1 (w/w). By adding fillers or softeners it is possible to adjust the modulus or viscoelasticity. AK1000 silicone oil (Wacker Chemie AG, Munich) was used as softener (Gundermann and Odenbach, 2014), and corn starch, purchased in a local super market, as filler (Table 1). The base elastomer samples were prepared by vigorously mixing components A and B with a spatula for 5 min. After adding fillers or softeners to the mixture, they were mixed with (A + B) in the same way. After mixing was completed, the sample was degassed in a vacuum chamber at 10^4 Pa for 5 min. Finally, the mixture was filled into PTFE molds. Cylindrical samples (d, 12 mm; h, 10 mm) were made for dynamic mechanical analysis, and cuboid samples (base area, 20 mm × 20 mm; h, 10 mm) were made for cutting tests. The elastomer was finally polymerized at 103 °C for 2.5 h in a convection oven.

Table 1
Sample codes and composition of the model materials.

Sample	Fraction [% w/w]		
	Base elastomer	Filler	Softener
Reference	100	–	–
f20	80	20	–
f35	65	35	–
f45	55	45	–
f20s20	60	20	20
f35s20	45	35	20

2.2. Cutting experiments

Cutting blades made of a martensitic steel alloy (WS 1.2379, X152CrMoV12; compliant with AISI D2 and EN ISO 4957; hardened to 63 HRC, polished), a material that is regularly used in high-speed slicers, were obtained from ASTOR Schneidwerkzeuge GmbH (Storkow, Germany). For cutting experiments, a straight blade ($20 \times 70 \times 1$ mm^3; edge angle 20°) was fixed in a clamp mounted on the crosshead of a 5564 universal testing machine (Instron Ltd., High Wycombe, UK). An aluminum sample support rig was attached to a 100 N force transducer that was fixed at the bottom frame of the instrument.

Cutting was performed vertically without blade inclination. The samples were placed on the sample support rig. The crosshead with the attached blade was lowered until contact with the samples was achieved, and displacement on the instrument was set to zero. The cutting procedure was started by raising the cross-head for 20 mm, and then the samples were cut at 10 mm/min or 1000 mm/min until a cutting depth of 8 mm was achieved. Cutting force F [N] was continuously recorded as a function of displacement l [mm] (100 data points/mm). Cutting stiffness d [N/mm] that was used for further evaluation refers to the first F/l derivative:

$$d = \frac{\partial F}{\partial l} \tag{2}$$

All cutting experiments were performed in four replicates.

2.3. Dynamic mechanical analysis (DMA)

An RSA3 Solids Analyzer (Rheometric Scientific Inc., Piscataway, N.J., U.S.A.) was used to perform dynamic mechanical experiments in compression. The cylindrical samples were placed on the lower plate of the parallel plate device. After application of a sufficient static force, frequency sweeps were performed from $\omega = 1$–100 rad/s at a strain of 0.5% (linear viscoelastic region). Complex modulus E^*, storage modulus E' and loss modulus E'' were recorded as a function of ω, as was the loss factor $tan\ \delta = E''/E'$. All tests were performed in fourfold.

3. Results and discussion

3.1. Mechanical properties of the model systems

The complex modulus and loss factor of the unsubstituted reference polymer at 10 rad/s was 0.3 MPa and 0.24, respectively, which is similar to that of sliceable foods such as cheese or sausages (Bruno and Moresi, 2004; Rohm and Lederer, 1992). The addition of corn starch as filler led to a successive and significant increase of E^* up to 2.7 MPa for the sample with 45% (w/w) filler (f45), and also to a significant increase of the loss factor $tan\ \delta$ (Table 2). The increase of E^* is the result of the inclusion of a considerable amount of rigid particles in the gel network matrix (Bokobza, 2009; Jampen et al., 2001). The reference and the filled polymers exhibited a loss factor <1, which corresponds to predominantly elastic properties. An increase of $tan\ \delta$ means that viscous contributions become more important in the system. The fact that the incorporation of the filler resulted in an increase of $tan\ \delta$ points on an alteration of the network because of poor interactions between the filler and the