Alongside appearance, odour and taste, the texture, especially the crispness and crunchiness, play a key role in consumer acceptance of foods. The food industry endeavours to offer products with a defined, uniformly high quality on the market. Alongside sensory tests of products by trained tester panels, instrumental measuring methods are used in preparation or as flanking measures. Their results correlate to a high degree with the sensory assessment of foods and they frequently require lower time and human resources inputs. This expert knowledge paper on sensory testing is the second part of the series on “Instrumental Sensory Analysis”. It provides an overview of the state of the art in the area of “Mechanical texture analysis of foods”.

1. History

Mechanical-technological testing is the oldest discipline in the field of materials testing. Already in the 15th and 16th century, Leonardo da Vinci and Galileo Galilei expressed their thoughts about the bending stress and elastic behaviour of materials. Further findings were added in the course of time. In the 18th century the first test machines were then developed in France. Since the mid-19th century, various companies in Germany have become engaged successively in developing and building equipment, machinery and systems for mechanical-technological testing of materials. Over the years, a comprehensive programme of manually operated hardness testing equipment right up to complex test systems for in-process applications have been developed.

2. Terms in mechanical texture analysis

2.1 Texture

Texture testing is a sub-area of “rheology”, i.e. the science that deals with the flow and deformation behaviour of solid and fluid bodies under the influence of mechanical forces. It is a physical discipline. According to ISO (International Standards Organization), texture is defined as the totality of all rheological and structural (geometric and surface-related) properties of a food that can be measured by mechanical, tactile (feeling), visual (sight) and auditive (hearing) receptors.

Consequently both hands and fingers, as well as lips, palate and tongue and also ears (hearing) are involved in sensing the texture. Alongside this tactile sensory perception (surface sensibility, e.g. the feel to the touch perceived through fingertips), the kinaesthetic perception (sense of movement, e.g. the feeling perceived during chewing, snapping/breaking the product), is one of the elements of texture. Texture is thus designated as a multi-dimensional quality parameter, the complex structure of a food. Examples of texture properties are the crunchiness of Vienna-type sausages, the creaminess of desserts or the crispness of wafers. The brittleness, firmness/hardness, cohesion (internal product cohesion), resilience, stickiness and elasticity as well as the rubberiness and chewability alongside a number of other texture properties are included too. The size, form and cell structures of the food also have a crucial influence on the texture properties.

2.2 Viscosity

The term “viscosity”, also a texture property, is used to describe the flow behaviour of fluid products. If two fluid layers are pressed against each other, a resistance develops (toughness, inner friction), which is termed flow resistance. If the flow resistance is low, the food is thin. As the flow resistance increases, the viscosity of a food increases too. The viscosity is temperature-dependent. Viscosity measurements are conducted, for example, in order to optimize a pasty substance as regards its consistency, or to adjust it optimally for the production line (e.g. pumpability, filtering capability). In the food industry yoghurt (with and without fruit pieces), sauces, mustard, tomato purée and oils are products that are frequently tested.

2.3 Mouth-feel

The mouth-feel describes how a food behaves in the mouth. It covers on the one hand texture properties that are perceived by tactile perceptions as a result of pressure and contact in the mouth space (e.g. creamy, fatty, oily, fluid, viscous, sticky, powdery, sandy, grainy). On the other hand, kinaesthetic perceptions during biting (e.g. crunchy, firm to the bite, brittle), during chewing (e.g. crispy, resilient, crumbly) and during swallowing are also included. Furthermore, geometric properties of a food (e.g. size, form, broken pieces) and properties connected with the water content of a food (juicy, dry) that can be perceived by scanning with tongue and palate are involved too. Constituents of the mouth-feel, properties that are based on temperature perceptions (hot, cooling) and those based on irritating/painful perceptions that materialize through irritation of free nerve endings in the mouth space (e.g. spicy, tingling, burning) are also included here. In addition, strictly speaking the mouth-feel also covers taste and retronasal odour (aroma perception).
2.4 Haptics

Haptics in the narrower sense describes all product properties that can be perceived by touching such as size, form and consistency. These parameters can be perceived both by feeling with hands and fingers and via lips, tongue and pharyngeal space, with areas of overlap with the term “mouth-feel”.

In a more comprehensive sense, human haptic perception includes:

- tactile perception (components of the surface sensibility),
- proprioception (depth sensibility),
- temperature perception (thermal reception) and
- pain perception (nociception).

2.5 Acoustics

Acoustics is the study of sound and its propagation. It comprises all aspects connected with this, starting from the origin and generation, the propagation, influencing and analysis of sound. Furthermore, sound perception through hearing and its effect on the environment are examined.

Sound results when a sound source stimulates the gas molecules in the air to vibrate so that they spread in sinusoidal waves and bring the ear-drum in the human ear to vibrate as a result of pressure fluctuations. In the middle ear, these movements are amplified and passed on to the sensory cells which convert them into bioelectric impulses. The information makes its way to the brain via the hearing nerve. A healthy ear can perceive a sound pressure starting from 2·10⁻⁵ Pa (hearing threshold). With some foods, acoustic perceptions connected with their specific texture play an important role for consumers. Examples here are the crispy noise heard when consuming potato crisps or sponge fingers, or the crunching of biscuits, Vienna-type sausages or (above all dark) chocolate, when pieces are bitten off. Some companies invest considerable amounts in creating textures that supply the perfect sound.

3. Instrumental texture analysis - possibilities and opportunities

3.1 Human sensory texture testing

One possible way of analyzing the texture of foods is to subject the food products to human sensory texture testing within the context of product tastings. Here the texture properties are described on the basis of terms used for mouth-feel or finger-feel, and depending on the sensory method their intensity is analyzed, compared with other product properties, or evaluated with reference to a standard. The sensory descriptors focusing on texture are summarized by way of example in Figure 1. Depending on the food produced, the expressions vary. Properties of a jam are expressed in different terms than properties of cornflakes. Standardized and thus unified product designations are rare, so that the language development/fixing of the descriptive terms is the responsibility of the respective panel.

<table>
<thead>
<tr>
<th>Texture property</th>
<th>Sensory designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>soft, firm, hard</td>
</tr>
<tr>
<td>Cohesion</td>
<td>crumbly, crunchy, brittle</td>
</tr>
<tr>
<td>Deformation behaviour</td>
<td>plastic, elastic</td>
</tr>
<tr>
<td>Stickiness</td>
<td>adhesive, sticky, viscous-sticky</td>
</tr>
<tr>
<td>Viscosity</td>
<td>thin, thick</td>
</tr>
</tbody>
</table>

3.2 Instrumental texture analysis - equipment and methods for mechanical texture measurement

As a supplement to human sensory texture testing, instrumental measuring methods that can be carried out quickly and easily are increasingly being used in the food industry, not least due to the associated savings in time. Instrumental tests in the form of mechanical texture analyses imitate sensory tests of foods. Various physiological processes such as e.g. biting and chewing are imitated by mechanical operations, or the flow behaviour of foods in the mouth is recreated. In a number of differing tests/experiments and using different instruments, forces, paths/distances and energy values etc. are captured, linked and allocated to sensory properties.

In a standardized experimental structure, instrumental texture analysis excludes any subjective influences on the test. For this, measuring methods that are introduced internationally, but only seldom standardized, are used. The challenge for texture analysis is that food texture properties generally represent a very broad scatter. In order to obtain reproducible test results, careful sample treatment and test preparation are vital. Where this is done, in some cases amazingly high correlations with human sensory testing are achieved. Slight fluctuations in the product quality can frequently be elicited much more clearly with instrumental texture analysis.
3.2.1 Preparation for testing

As a consequence of the non-homogeneity of the products, which is one of the main difficulties in instrumental texture analysis, proper test preparation is crucial for success – as indeed it is with directions for human sensory analyses. Uniform samples provide one basis and the proper composition of the mechanical measuring equipment, i.e. the interplay of testing tools and sample, provide another. As regards the sample size, it should be ensured that this is sufficient and maps the structures to be examined. Frequently it can happen that instead of small test samples the entire product is more suitable for proper analysis.

The place and direction of sample removal and the sample cut and form should always be identical. As regards the relevant test tools, it is crucial that in the case of pressure tests uniform sample stresses are applied, so that shear forces do not falsify the result (see Figure 2). In penetration tests, e.g. in a yoghurt beaker, it should always be ensured that the tests/experiments are carried out in the same containers. Different container geometries lead to different measuring results. Furthermore, the preparations and pre-settings (calibration etc.) specific for the respective equipment and methods must be taken into account.

3.2.2 Technical equipment and analysis methods

3.2.2.1 Texture analyser

Texture analyzers are electronically controlled universal testing machines that use a force sensor to record the force necessary in order to travel a defined path in a given time at a given speed, or to penetrate into a sample with a defined force. Texture analyzers or penetrometers serve to examine critical properties of various foods by measuring the necessary forces via a measuring element pressed into the sample. Depending on the composition and structure of the molecules in the products, specific textures result that mean different physical properties. Textures determine the fragility, hardness, elasticity, adhesiveness, stretchability or chewability of foods.

To examine these physical quantities, the “multi-function devices” of the texture analyzers can be equipped with a large number of technical devices and measuring probes that imitate in principle the bite into a product or the chewing process in the mouth. For example there are penetration dies with a wide range of geometries, bending, pulling or cutting devices, or different blades. They record the force resulting on deformation and breaking of the product to be tested in a given impression time and impression depth. The result is measured in kilogram (kg), Newton (N), pounds (Lb) or US ounces (oz). Depending on the area of the penetration tip (spike) used, a value in kg per cm² results for the pressure at which the area or layer tested yields. Data interfaces join the texture analyzers with computers and via data transfer this ensures integration into various software programs, both for standardized definition of test parameters in advance and for determining the results and processing them graphically.

Bite behaviour and bite firmness tests

Equipment that simulates the bite into foods and thus provides information about the bite behaviour as well as the crispiness and firmness include the Kramer shear cell, the Warner-Bratzler shear cell and the OTMS cell (Ottawa Texture Measuring System). While the Kramer shear cell and the Warner-Bratzler shear device use one or more blades that move through the sample material at constant speed, compressing, shearing and extruding it, the OTMS cell uses compression and extrusion to ascertain the firmness. By measuring the shear behaviour, using different knife forms too, it is possible to supply information about the tenderness/toughness of meat and fish products, the crunchiness of Vienna-type sausages or the bite behaviour of bakery products. For example, simple knife blades are used to test bite firmness of sausage slices, or blunt blades are used to simulate the bite with back teeth. The OTMS cell is ideally suitable for products with good extrudability such as vegetables, fresh cheese and meat patés or for extrudates and cereals. Here too, different extrusion plates and specific supple-
mentary devices ensure optimal technical adaptation of the equipment to the products to be examined (see Figure 3).

Pressure tests with different pressure dies are comparable with this. They are used to record the breakage tendency, freshness and firmness of sweets, coffee beans or fruit. By converting the experiment, it is also possible to use the method for measuring elastic products such as cakes, cheese, fish and marshmallows. The compression and relief behaviour reveals the firmness, stickiness, degree of ripeness and visco-elastic properties.

Butter cutters are also used to determine firmness. Following the specifications of ISO 16305, a stainless steel wire cuts through a defined piece of butter, cheese, egg, vegetable or fruit and measures the forces that occur. To check the degree of ripeness of fruit and vegetables, a penetration test is conducted using a penetrometer and insertion needle in order to determine the peel and the consistency of the fruit flesh.

**Stretchability and bending capability measurements (elasticity)**

With a special dough extensibility rig, developed by Dr. Rolf Kieffer, it is possible to record processing properties, stretchability, elasticity and stickiness of doughs and gluten, as well as of chewing gum. Thus different formulations and processing technologies in the bakery product sector can be compared with each other and adapted to each other as regards the desired product result. A 3-point bending device in which the sample is placed on bending supports and subjected to a centric load is included in this category. This is particularly suitable for examining variations in bending and breaking strength, breaking inclination and brittleness depending on the recipe, for instance in pasta, wafers, biscuits and chocolate bars. A special cheese extensibility measuring device serves to examine the stretchability of hot pizza cheese (Mozzarella).

**Hardness and firmness measurements**

The multiple puncture probe or also various penetration dies are used for hardness measuring. Fat structures in butter or margarine are broken up via various cyclically running processes, using extrusion disks. The residual hardness provides information about the result. A similar mode of operation is applied for ice cream, fresh cheese and cooked pasta. The various penetration dies for hardness tests are comparable with this. Alongside cylindrical dies that produce pressure tension via their area and shear tension via the edges, spherical dies work via vertical and horizontal forces. For fish, meat and cooked sausage, compression dies with a large surface area are frequently used. Cylindrical measuring dies are mainly used for penetration tests to examine the firmness of yoghurt, puddings and desserts.

Special dies for standard tests are available for measuring the firmness of bread (AACC, gel firmness/bloom hardness). In the AACC test, a cylindrical die is applied at constant speed to defined slices of bread and compresses them by up to 40%.

**Chewing process and resilience**

The Texture Profile Analyser (TPA) is used to simulate the chewing process. Generally, a sample is subjected to stress twice, cyclically, with the compression die secured to the texture analyser for the specific product or test. The chewability can then be recorded in measuring terms as a force-time diagram and the parameters firmness, elasticity and chewability can be calculated via the ratios of the surfaces to each other (see Figure 4).

**Crumbliness and gratability**

The gratability of cheese can also be measured under modified test conditions with the texture analyser. For this, the device is placed in a horizontal position so that uniform force can be exerted on the sample.

Generally, temperature-control and climate-control chambers support the temperature control of the products, as regards atmospheric humidity too, thus ensuring that the conditions needed to test chilled products such as pizza cheese or frozen products such as ice cream can be maintained.
3.2.2.2 Viscosimeter

A viscosimeter is a measuring device used to determine viscosities or the “thickness” of fluids. There are different types of viscosimeters for the various viscosity ranges.

In capillary viscosimeters, the fundamental measuring principle is the flow of the liquid to be measured through a thin tube. A fixed liquid volume runs at constant pressure through a tube of defined length and radius and the time required for this is measured. In the rotational viscosimeter, however, a motor is used to rotate a body in a liquid. The torque and the geometry of the rotating body and the vessel as well as the speed of rotation determine the viscosity. By contrast with rheometers, viscosimeters can only measure newtonian fluids (mineral water, beverages, oil and liquids that retain their viscous strength even under pressure) correctly.

3.2.2.3 Rheometers

Many substances unite properties of a solid body (elasticity) and of a liquid (viscosity). Depending on the external conditions, they change their viscosity. Such “fluids” are called non-newtonian fluids. Rheometers, in other words measuring devices that measure these specific viscosities, are used for instance as farinographs, extensographs or amylographs, or as mixolabs and alveographs, to monitor grain and flour quality. The resistance of a dough to constant mechanical stress is measured and recorded. These stresses may be kneading, extending or gelatinization tests (with rising temperature).

4. Potential applications for instrumental texture analyses

The potential applications for instrumental texture analyses are diverse. For example, it can be examined already during product development what influence process parameters or recipes will have on the texture quality. The product to be developed can be defined and produced as regards the desired texture properties, e.g. hardness, elasticity, stickiness, with the aid of measurable parameters. After a product is brought onto the market, the above criteria are the critical quality parameters that need to be permanently monitored. Through standardized analytical texture measurements, it is possible to record even the tiniest deviations and express them in figures, so that they are transparent for the different production establishments. Mechanical properties of foods are generated in the production process. Here the intermediate products play a role, especially where they influence and steer the texture properties of the end product. Furthermore, defective products can also be used to identify deviating process conditions, and the process-relevant properties such as suitability for machine operations or form stability can be optimized.

Further examples of applications are

- **product development, including**
  - assessment of the quality and processing properties of food raw materials;
  - generation of foods with a required texture by continuous examination of different recipes in the production process;
  - benchmarking for product optimizing or in the case of use of alternative ingredients and contents;

- **quality testing, including**
  - checking of goods on receipt, examination of defined tolerance values in supplied products;
  - production process: determining structural modifications of the product as a function of the process parameters, e.g. temperature, moisture and cooking/baking time;
  - transport/storage: determining stackability, firmness, shelf life and stability.

**Case example: bakery products**

Mechanical texture measuring methods make it possible to examine the bread crumb rheological properties with regard to maintaining freshness. It is possible to provide information about the firmness, softness, elasticity, stickiness, resilience and chewability of the bread crumb. The texture quality of biscuits, which in addition to the water content depends essentially on the production conditions, can be measured by regular tests along the production line so that observance of the optimal production conditions is maintained.

**Case example: dairy sector**

Within the context of an extensibility test of pizza cheese (Mozzarella), a test fork is placed in a bowl of melted cheese and drawn out using the texture analyser. The force profile provides information about the extensibility of the cheese at a defined temperature (see Figure 5).

**Case example: fruit/vegetable processing**

Fruits that are subjected to industrial processing must satisfy high mechanical requirements. The skin operates as a natural packaging and protects the fruit against collapse. The resistance force of the fruit skin is thus an important parameter that also influences the quality of the end products made from it. The mechanical property of the fruit skin can be assessed via the force application necessary to penetrate it with a needle probe. Its toughness and resistance can be measured in
this way. If the needle penetrates into the fruit flesh, the force necessary for this provides information about the degree of ripeness of the fruit (see Figure 6).

5. Overview of technology suppliers (selection)

Various suppliers of instruments and services for mechanical texture analysis currently on the market are compiled in the following Table 1.

Table 1: Overview of technology providers (selection)

<table>
<thead>
<tr>
<th>Company</th>
<th>Products/ Application areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>WINOPAL Forschungsbedarf GmbH</td>
<td>• Texture Analyser/material testing - TA.XTplus - TA.HDplus - TA.XTExpress - all common tools for examining texture</td>
</tr>
<tr>
<td><a href="http://www.winopal.com/">www.winopal.com/</a></td>
<td>• Powder properties • VolScan Profiler (laser-based volume determination) • Dough rheology</td>
</tr>
<tr>
<td>Zwick Roell</td>
<td>• zwicki-Line • Space-saving, single-column testing machine for test forces up to 0.5 / 1 / 2.5 / 5 kN • All common tools for texture examination</td>
</tr>
<tr>
<td><a href="http://www.zwick.de">www.zwick.de</a></td>
<td></td>
</tr>
<tr>
<td>Lloyd Materials Testing</td>
<td>• Food Firmness Instruments:</td>
</tr>
<tr>
<td><a href="http://tectra.hu/pdf-docs/Lloyd-PSG-TA.pdf">http://tectra.hu/pdf-docs/Lloyd-PSG-TA.pdf</a></td>
<td></td>
</tr>
<tr>
<td>Stable Micro Systems</td>
<td>• Powder Flow Analyser • D/R Dough Inflation System • Automated Linear Indexing System • Temperatures Control • Material Tester • Volscan Profiler • Probes and Fixtures</td>
</tr>
<tr>
<td><a href="http://www.stablemicrosystems.com/">www.stablemicrosystems.com/</a></td>
<td></td>
</tr>
<tr>
<td>Texture Technologies</td>
<td>• Texture Analyzer: - TA.XTPlus - TA.HDPlus - TA.XTExpress</td>
</tr>
<tr>
<td><a href="http://www.texturtechnologies.com/">www.texturtechnologies.com/</a> food-texture-analysis.php</td>
<td></td>
</tr>
<tr>
<td>FTC Food Technology Corporation</td>
<td>• TMS-PRO - Texture Analyzer • TMS-Touch - Texture Analyzer • TU-12 - Texture Analyzer • TMS-2000 - Texture Analyzer • TM-2 - Texture Analyzer • TU - Texture Analyzer</td>
</tr>
<tr>
<td><a href="http://www.foodtechcorp.com">www.foodtechcorp.com</a></td>
<td>• and many other systems for tests of breaking, bending, shearing, distribution, penetration, puncturing, compression, extrusion, bulk analysis and tension.</td>
</tr>
<tr>
<td>Anton Paar Germany GmbH</td>
<td>• Polarimeters • Viscosimeters • CO2-sensors • Equipment for measuring surface tension • and many others</td>
</tr>
</tbody>
</table>
6. Summary and prospects

In the food sector, texture is understood to cover the properties resulting from the macrostructure and microstructure of the food. We touch foods with our hands, feel and compress them between lips, palate and tongue, and crush them with our teeth. The human senses assess not only the mechanical properties of foods, but at the same time chemical, geometric and structural properties. With some foods, even sounds are caused by chewing. We perceive the texture quality holistically during consumption and decide whether we like this or not.

Even if humans alone are able to perceive food in its complexity in sensory terms due to the interaction between human senses and the linking of sensory perceptions in the brain, instrumental sensory analyses provide valuable support in certain sub-sectors. Supplementing human sensory methods, texture analyzers are now used in various areas and provide excellent opportunities for analyzing texture and securing/validating human sensory testing results. For instance, the mechanical instruments in the field of texture analysis make it possible to imitate biting and chewing processes or bending behaviour and allow conclusions to be drawn regarding bite behaviour, elasticity and firmness, as well as concerning the viscosity of foods.

In future it will be an interesting challenge to find further customized technical solutions that make it possible to examine newly developing textures reliably and furthermore permit measuring and consideration of the acoustics developing during chewing and biting as attributes for crispness or crunchiness.

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