Oral processing – a rheologist's perspective

Linking solid food behaviour in-mouth to microstructure design – an on-going challenge

Dr Pretima Titoria and Professor Kathy Groves

A Leatherhead Food Research white paper

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The design of healthy products that deliver from a sensory perspective can prove challenging for many product developers. This is especially true for those who manufacture dry products such as crisps, snacks and biscuits. In order to preserve desired sensory qualities, manufacturers need to understand how ingredients create microstructures, and get to grips with how these structures break down in the mouth, creating eating experiences that consumers have become accustomed to. This is where the sciences behind oral processing and product development combine to form a powerful tool. In this White Paper, Dr Pretima Titoria and Professor Kathy Groves attempt to exploit the tools of rheology and microscopy to bring us closer to linking solid food breakdown to microstructure design.

While oral processing is a relatively new area of research, the numerous benefits of the scientific methods are often discussed. Having been around for the past 20 years, the science has gained enormous recognition in the past decade and was recognised with its first dedicated international conference at the University of Leeds in July 2010[1].

The science of oral processing revolves around the understanding of how foods and beverages break down in-mouth, and the deconstruction process in the oral cavity. This process results in the delivery of specific texture, mouthfeel, and flavour release profiles, all of which contribute significantly towards sensory enjoyment. An overview of oral processing science and the instrumentations was provided by Dr Pretima Titoria in a previous white paper edition[2], available online to Members.

The benefits of using oral processing science in conjunction with product development are extensive. This marriage can accelerate renovation and innovation projects, including those associated with sugar, fat and salt reduction strategies, and proves especially useful when reduced versions do not deliver the exact same sensory profiles as the mainstream ones. In addition, this combination can also provide a strategic route towards the development of enhanced products catering to weight-conscious people (weight management/satiety) and the elderly (swallowing issues/ dysphagia), as well as for

[1] Rsc.org. (2010). International Conference on Food Oral Processing - Physics, Physiology and Psychology of Eating. [online] Available at: http://www.rsc.org/events/detail/4345/international-conference-on-food-oral-processing-physics-physiology-and-psychology-of-eating

[2] Titoria, P. (2017). From first bite to swallow: the science of oral processing. Leatherhead Food Research. [online] Available at: https://www.leatherheadfood.com/files/2017/12/White-paper-58-Oral-processing.pdf

those who demand exciting and novel sensory experiences.

Scientific progress

Several peer-reviewed scientific papers have been published which focus on the use of instrumental techniques such as tribology and rheology, and on the correlation of instrumental data with sensory data from trained panels and consumers. A thesis by Liu[3] looked at the rheological, tribological and sensory assessment of particle-filled gels. The findings revealed that use of the right types of fats, solid fat contents and emulsifiers results in desired product break down in the mouth. The right combination will initiate coalescence of fat droplets which then provide a lubricating effect, therefore influencing the perception of creaminess. Another example is Cargill[4] which confidently announced that it has used tribology to identify texturising agents that influence the lubricant property of zero or low-calorie carbonated drinks. By using this technique, Cargill is able to compensate for the sensory loss brought about by the removal of sugar.

Using the principles of oral processing in solid products

It should be noted that whilst several publications discuss homogeneous fluid-based products (e.g. beverages) and soft homogeneous semi-solid products (e.g. cheese spreads), there remains the challenge of understanding the breakdown of dry solid and particulated foods, and crucially, how to use instrumental data in a beneficial way with respect to product design.

Leatherhead believes that rheology, paired with microscopy, plays an important role in understanding the oral processing behaviour of dry solid foods, and when combined with a unique sensory profiling tool called Temporal Dominance of Sensation (TDS), offers a powerful package for product developers. This white paper focuses solely on the utilisation of rheology and microscopy to map and understand the deconstruction process of dry solid products in-mouth.

Leatherhead selected a number of commercial, low-moisture snacks with different textural properties for investigation (Table 1). Samples varied from aerated, light products to compacted, dense products and were subjected to specific large-deformation and small-deformation rheological measurements (see sidebar on "A Beginner's Guide to Rheology").

Product	Description
Product 1	Lightly aerated and crunchy
Product 2	More aerated (than Product 1) and crunchy
Product 3	Compact and particulated
Product 4	Compact and crunchy
Product 5	Aerated and crunchy (like Product 1), but softer & more delicate
Product 6	Dense, hard, brittle and crunchy

Table I: Brief descriptions of selected low-moisture & dry snacks

[3] Liu, K. (2016). Lubrication and perception of foods - Tribological, rheological and sensory properties of particle-filled food systems. [ebook] Available at: http://edepot.wur.nl/377888
[4] Asia Pacific Food Industry (APFI) (2017). Promising Mouthfeel With Tribology - apfoodonline. [online]. Available at: http://apfoodonline.com/industry/promising-mouthfeel-with-tribology/

Role of texture analysis

Bulk quantities of masticated samples, spat out halfway through eating (six chews) and just before swallowing, were subjected to texture analysis. Large-deformation analysis took place in order to effectively measure bolus firmness. Figure 1 compares bolus firmness of the three products at 'six chews' (halfway) and at the point of swallowing (PoS). Whilst no direct correlation could be found to explain the relationship between ingredient functionality, texture and product type, it is very interesting to note that firmness of the boluses at PoS was very similar. This indicates that regardless of the product type and microstructure (including particle size), a specific firmness range would trigger the swallowing process.

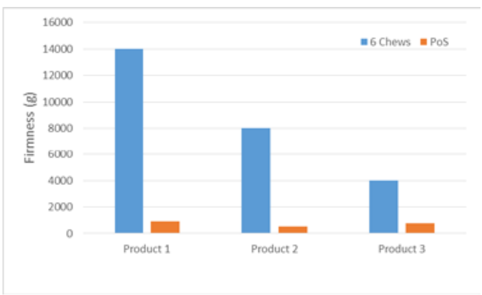

Figure 1 Texture analysis conducted on boluses at six chews (halfway) and at point of swallowing

Role of oscillatory rheology

Small quantities of the masticated samples (spat out before swallowing) were subject to oscillation rheology. The samples, formed into 1 or 2mm films for the rheometer, were then probed, mimicking the space between the tongue and palate as closely as possible.

Two different oscillatory rheological measurement types were conducted. The first is an amplitude sweep, whereby increasing strain is applied to the sample, representing the process by which the tongue shears in one continuous motion across the bolus in the mouth as closely as possible.

Figure 2 shows the results from two products, where data is presented in the form of elastic (G') and viscous (G'') moduli. The following conclusions were drawn:

- Product 4, with its higher G' value, produced the firmest bolus, whereas Product 5 produced the softer bolus
- Product 4 changed from solid-like behaviour to a liquid-like behaviour later (i.e. G'' becoming dominant (higher than G')) very smoothly, whereas Product 5 transitioned to a liquid-like behaviour following some resistance as denoted by a "hump" in the G'' parameter

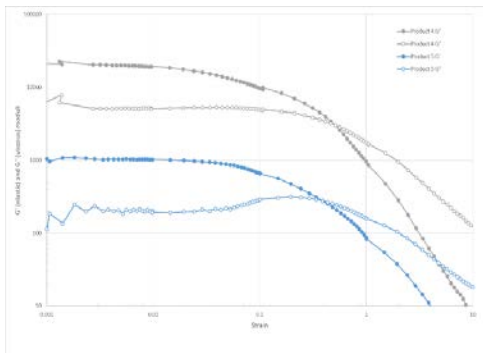

Figure 2 Examples of bolus behaviour (Products 4 & 5) at Point of Swallowing in response to increasing strain application

The power of microscopy comes in here to explain the differences in the rheological behaviours of Products 4 and 5. As shown in Plate I, Product 4 exhibited a biphasic starch-

A beginner's guide to rheology

Rheology is a study of flow and deformation when a certain amount of force is applied to a sample. There are two analytical branches of rheological measurement, which are small-deformation and large-deformation. Small-deformation rheology involves measuring the samples without destroying the samples, and can be measured on rheometers. Low amounts of oscillatory forces are applied to the samples, which result in a gentle and non-destructive probing of the microstructures. Such non-destructive measurements can be carried out as a function of time or temperature, which are called "time sweeps" and "temperature sweeps" respectively. There is also "amplitude sweeps"; however this involves applying gradually increasing amounts of strain to the samples, going from the non-destructive stage to a destructive stage.

Data from the rheometers would be presented in the form of elastic (G') and viscous (G'') moduli. In simple terms, G' would represent the solid-like behaviour of the product, whereas G'' would represent the liquid-like behaviour of the same product. Taking this further, the ratio of G'' to G' (G''/G') is called Tan δ; Tan δ values of less than unity indicate elastic-dominant (i.e. solid-like) behaviour and values greater than unity indicate viscous-dominant (i.e. liquid-like) behaviour . Therefore theoretically in simple terms, the higher the Tan δ values, the more paste-like or liquid-like, the product would be, and the lower the Tan δ values, the more solid-like the product would be.

Large-deformation rheology involves samples that are destroyed during measurements, such as on the universally well-known texture analyser. Key attributes, such as hardness, elasticity, crunchiness, stickiness and brittleness, are measured on the texture analyser, and these bulk samples are actually compressed or penetrated. Another example of large-deformation rheology is viscosity measurement, where the fluids are forced to flow upon application of increasing force, resulting in destruction of the original structures within the fluids; viscosity is often measured on viscometers or rheometers.

protein continuous matrix with ungelled discontinuous phase; the starch (stained dark-blue) and protein (stained green) particles were loosely aggregated. The microstructure was therefore able to flow easily upon application of force.

In contrast, Product 5 was a very different networked structure which contained large potato cells, with purple-stained starch gel phases, both of which were thought to contribute to the "hump" of resistance before flowing, upon application of force.

These microscopy observations, together with the rheological characterisations, explain how microstructures are determined by ingredients, and how these break down in-mouth in terms of bolus deformability and stretchability. Both influence how the flavour release and mouthfeel behaviour are manifested within the consumer oral cavity.

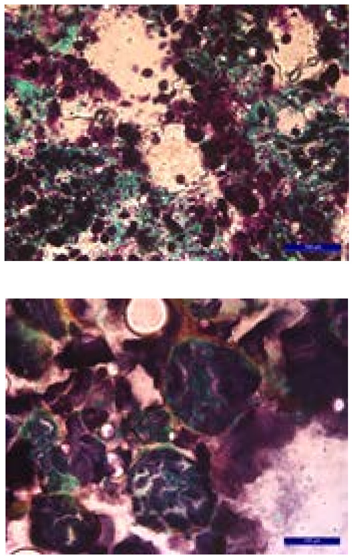

Plate I Microstructures of Product 4 (top) and Product 5 (bottom), stained with toluidene blue and viewed under the light microscope (starch granules stained dark-blue, whereas proteins stained green)

As previously mentioned, two different rheological methods were carried out. During the second, Leatherhead went one step further with small-deformation rheological characterisation of the boluses. This involved measuring the G' and G'' values as a function of applying a low strain and a high strain in three cycles, one by one. The aim was to measure the rheological changes as a function of mastication (chewing) three times. However, in this case, the ratio of G'' and G' was quantified and used to minimise the number of graphs, which may have been confusing and unclear for interpretation purposes. This ratio of G'' to G' is called Tan δ, and is explained further in the 'beginner's guide' box.

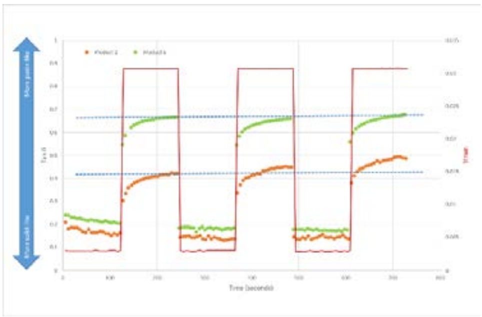

Figure 3 Examples of snack behaviour (Products 2 and 6) during the on-off strain application to mimic the mastication process

Figure 3 demonstrates the effect of 3-step, on-off oscillatory strain on the material properties of boluses that were spat out just before swallowing. Tan δ values were calculated from the measurements of G' and G'', which provide information on the bolus behaviour.

Figure 3 indicated the following findings:

- Product 2 was marginally more solid-like than Product 6 at the start of the process
- Upon application of the on-off strain, Product 2 became progressively more paste-like (as indicated by the blue dotted line from 1st cycle to 3rd cycle).
- Product 6 exhibited the same behaviour, but was significantly more paste-like than Product 2 (i.e. higher Tan δ values), meaning that Product 6 deformed more dramatically than Product 2 from solid-like state to paste-like state
- Furthermore, Product 6 did not show any indication of softening within the 3 cycles studied, indicating that the product microstructure was rigid against the applied on-off strain application, and would require further masticatory forces to shear it further into paste-like consistency in readiness for swallowing

Whilst the rheological properties have been characterised in this example, the roles of other critical attributes should not be overlooked. In particular, particle size distribution, particle hardness and stickiness, and human physiology, should not be forgotten.

So what, and what next?

The most important thing to remember is that rheology, used in conjunction with microscopy, is key to picking up key differences in microstructural properties when we consider the dry products studied above. This seedling of knowledge can be amplified, expanded upon and consolidated through effective utilisation of advanced analytical and characterisation equipment. These methods include rheometers with shear and vertical (axial) movements (to mimic more closely the oral 3-dimensional movement) as well as rheo-optic/rheo-microscopy equipment (to measure and visualise at the same time).

There have also been announcements about artificial mouths, such as one by Ecole Nationale Vétérinaire, Agroalimentaire et de L'Alimentation[5]. The new artificial mouth prototype, called AMADEUS, stands for "Automated Mastication for Artificial Destructuration and Extensive Understanding of Stimuli". This approach, as with the others mentioned above, allows for a systematic characterisation of products without the interference of human physiology, specifically the saliva production and the amylase enzyme (which is naturally present in saliva).

In order to correlate the instrumental findings to real-life scenarios, appropriate sensory techniques are required. Temporal Dominance of Sensation (TDS) is a relatively new dynamic sensory methodology that can record several sensory attributes simultaneously over time, and could potentially be exploited to supplement the instrumental data.

Several questions and enormous prospects arise from these exciting preliminary findings, and one of these is whether the rate of solid-like to paste-like structures have a significant effect on satiation & satiety, as well as flavour release profiles.

Conclusion

Rheology and microscopy are powerful analytical tools that provide scientific insight into the mechanisms behind food breakdown in the mouth. More importantly, they can offer illumination on the functional roles of the ingredients in terms of construction (i.e. before mastication) and deconstruction (during and after mastication), therefore allowing product developers to tweak or adjust recipes to generate products with better texture, mouthfeel and flavour release profiles. Such information can be enhanced or consolidated by employing other areas of research, such as colloidal science (to evaluate emulsions' and colloids' behaviour in-mouth) and polymer science (to evaluate hydrocolloids' behaviour in-mouth), as well as flavour chemistry.

[5] Guilloux, M. & Tarancon-Serrano, P. & Cataneo, C. & Vigneau, E. & Le-Bail, A. & Lethuaut, L. & Prost, C. (2014). Efficiency of a New Artificial Mouth Prototype to Mimic Salt Release During food Oral Processing In Order To Explain Dynamic Saltiness Perception of Pizza Varying in Salt Content. [online] Available at: https://www.researchgate.net/publication/306066650_Efficiency_of_a_New_Artificial_Mouth_Prototype_to_Mimic_Salt_Release_During_food_Oral_Processing_In_Order_To_Explain_Dynamic_Saltiness_Perception_of_Pizza_Varying_in_Salt_Content

How Leatherhead can help?

Leatherhead has many years of experience and expertise in application, interpretation and correlation of rheology and microscopy. We are able to use complementary techniques to map the deconstruction of food & beverage products in-mouth and work backwards to ingredient selection and product design. Balancing the instrumental analysis, Leatherhead has dedicated trained panels to provide sensory feedback on critical attributes, therefore offering a comprehensive and science-focused approach to the use of oral processing science in development of products with desirable texture and mouthfeel characteristics.

About the author

Dr Pretima Titoria

Pretima graduated with a B.Sc. (Hons) in Food Technology at the University of Reading and obtained her Ph.D. in the area of rheological characterisation of food biopolymers/hydrocolloids at Cranfield University. She continued to develop her skills in this area over several years while working at the Institute of Food Research, Norwich and at Dupont Cereal Innovation Centre, Cambridge, before joining Leatherhead Food Research in 2001. Pretima is now a Senior Consultant within the Science & Innovation department, and project-manages several Confidential Contract Research projects. Pretima has many years' experience in physico-chemical characterisation of ingredients, interim products and final products, focusing on the textural and microstructural properties and their effect on product quality and stability, as well as their role in oral processing. Pretima is a Fellow at the Institute of Food Science and Technology (FIFST).

Professor Kathy Groves

Kathy has over 35 years' experience in food microscopy and product development where she has pioneered the use of microscopy for food structure analysis and quality assessment. She has applied her expertise across multiple categories including snacks, confectionery and beverages, and numerous research areas including protein functionality, starch and fat interactions, meat quality and emulsions.

Kathy has a degree in Biochemistry, is a Fellow of the Royal Microscopical Society and a member of IFST. She is also Visiting Professor at the University of Chester and has presented on nanotechnology and food to the Government's House of Lords Select Science Committee.

About Leatherhead Food Research

Leatherhead Food Research provides expertise and support to the global food and drinks sector with practical solutions that cover all stages of a product's life cycle from consumer insight, ingredient innovation and sensory testing to food safety consultancy and global regulatory advice. Leatherhead operates a membership programme which represents a who's who of the global food and drinks industry. Supporting all members and clients, large or small, Leatherhead provides consultancy and advice, as well as training, market news, published reports and bespoke projects. Alongside member support and project work, our world-renowned experts deliver cutting-edge research in areas that drive long-term commercial benefit for the food and drinks industry. Leatherhead Food Research is a trading name of Leatherhead Research Ltd, a Science Group (AIM:SAG) company.

help@leatherheadfood.com T. +44 1372 376761 www.leatherheadfood.com

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Originally founded by Professor Gordon Edge as Scientific Generics in 1986, Science Group was one of the founding companies to form the globally recognised Cambridge, UK high technology and engineering cluster. Today Science Group continues to have its headquarters in Cambridge, UK with additional offices in London, Epsom, Boston, Houston, San Mateo and Dubai.

info@sciencegroup.com

www.sciencegroup.com

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