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Why food microstructure?

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Abstract

Food technology is a controlled attempt to preserve, transform, create or destroy a structure that has been imparted by nature or processing. Nowadays food scientists and food engineers have many microscopy and imaging techniques available to probe into the structure of food and rationally design processes that enhance the quality of products. Image analysis and image processing provides the needed quantitative data for the analysis and design of food microstructure. This article discusses how food structure is related to nutrition, chemical and microbiological stability, texture and physical properties, transport properties and product engineering.

Keywords: Foods; Microstructure; Diffusion; Image analysis; Nutrition; Texture; Stability

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1. Introduction

Food technology may be defined as a controlled attempt to preserve, transform, create or destroy a *structure* that has been imparted by nature or processing (Aguilera & Stanley, 1999). The last century saw the birth and development of an extremely successful food industry that processed at large scale the many products now available in the supermarket. Food engineers and food technologists succeeded at producing safe, diversified, convenient and good quality foods in large quantities to feed the consumers of affluent societies. It can be said that major advances in food engineering during the 20th century came from transfer and adaptation of knowledge from related fields such as chemical and mechanical engineering. The impact was largely at the *processing or macroscopic level* through the adaptation of unit operations and design of process equipment to transform and preserve foods, something never done in the past. In fact, food process engineers by transforming and stabilizing materials of biological nature, were the first bioengineers.

Further improvements on the quality of existing foods and the creation of new products to satisfy expanding consumer's demands during this century will be based largely on interventions at the *microscopic level*. This is so because the majority of elements that critically participate in transport properties, physical and rheological behavior, textural and sensorial traits of foods are below the 100 μm range. Some of these structural elements contributing to food identity and quality are: plant cells and cell walls, meat fibers, small particulate material in powders, starch granules, protein assemblies, food polymer networks, crystals of many types, oil droplets, gas bubbles, and particles of colloidal nature, among others (Fig. 1). Another reason that favors the change in scale of intervention is that we now have the tools and basic knowledge of materials science, biology, genomics and computer science. The shift in focus from processes to products has been forecasted for the food and chemical industry as well (Aguilera, 2000; Cussler & Wei, 2003). At an industry/university conference held a few years ago, it was recognized that the functionality and customer appeal of products from a major multinational company in the food and consumer's

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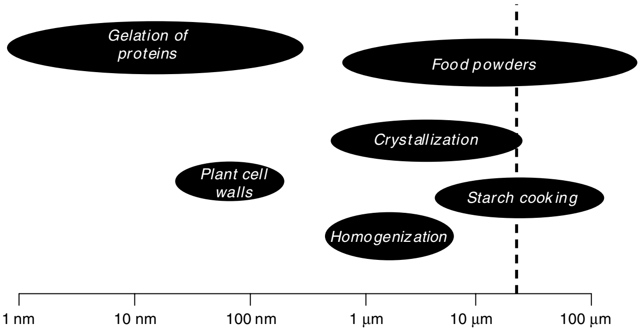

Fig. 1. Scale of food processes and elements in the microstructure.

chemicals business depended mainly on the microstructure of products in the 0.1–100 μm range (Villadsen, 1997). Lately, researchers from a major food multinational even announced the birth of *nanotechnology* in food research, meaning scales up from one nanometer to the micron range, such as those found in self-assembly colloidal structures and interfaces (Leser, Michel, & Watzke, 2003).

Food engineers in the past missed a unique opportunity to make a major contribution to the engineering sciences by neglecting the effect that microstructure has in the properties of foods. In part this was because the concept of structure, fundamental in other engineering disciplines and in materials science, was not firmly established in chemical engineering and by extension, not transferred to food engineering. In fact, food engineering and chemical engineering textbooks are extremely similar in approach, except for the examples and a couple of unit operations. Another reason is that foods are complex multicomponent systems and microstructural elements are difficult to observe in their natural or transformed states. Thanks to advances in biology and materials science we count now with powerful microscopes to probe into foods, from the atomic level to the micron range, in many cases, non-intrusively and in real time (video microscopy). Examples are the laser confocal scanning microscope (CLSM) and the recently developed environmental scanning electron microscope (ESEM). Nowadays, major food companies have groups devoted to the study of food microstructure and its impact on processing and product properties. In spite of the recognized significance of microstructure in food technology (validated by the extensive use of microscopy in research to support other instrumental data) its full adoption in academia has been slow. Reasons for this gradual adoption may be the high cost of the instrumentation, the need of a multidisciplinary approach (microscopists, food scientists, engineers) and the idea that images only provide subjective information.

Engineers are used to plan experiments, observe phenomena, quantify key data, and propose a physical and mathematical model that attempts to explain their findings. In foods this means being able to see and derive quantitative data at dimensions that are beyond those detected by the human eye. In what has become a classic experiment in engineering sciences, Osborne Reynolds (1883) devised a transparent-sided tank containing a glass tube with "a trumpet mouth of varnished wood" to follow changes in the pattern (structure) of a water stream from laminar to turbulent flow. The result is the Reynolds number, a non-dimensional parameter amply used to correlate transport data in transport phenomena. Thus, observation and the creation of images whether in our brain or as recorded data (e.g., pictures), are determinant in experimental work and modeling. Unfortunately, in foods and other biological materials, many key phenomena occur at the microstructural level (e.g., below 100 μm). At such scale, few structural elements in foods are recognized by the naked eye while most are discernible only with the aid of microscopes and other physical methods (e.g., MRI, light diffraction).

A search in the *FSTA database* (done on 11.20.03) produced 209 matches of publications titles having the words microstruct* for the period 1997–2003, and 37 matches for 2003 alone. The objective of this paper is to present examples that reflect the importance that microstructure has in food process engineering and product design. We hope to turn the interest of food engineers to the microscale in an effort to unveil basic mechanisms and opportunities for product development.

2. Chemistry, nutrition and stability

2.1. Composition and structure

In general, composition gives only limited information regarding the physical state, structure or engineering properties of foods. Extreme examples are fruits, vegetables and meat in their natural and disintegrated states. Fruit juices, vegetable purees and ground meats have a chemical composition similar to their sources yet very different physical properties, rheological behavior and sensorial attributes. Similar analogies may be derived for aerated structures or foams in egg, dairy and cereal products, among others, as air does not show up in the composition. The composition of most foods may be represented by a point inside a pyramid whose triangular base is a ternary diagram having as vertex lipids, protein and sugars + polysaccharides content and water is the apex (Aguilera & Stanley, 1999). Foods that we know behave very differently may overlap within such 3-D composition diagram. Moreover, proximate composition ignores that a small concentration of key components—such as emulsifiers in emulsions and foams—can have a profound effect on structure.

2.2. Microstructure and nutrition

Contrary to popular belief, a fruit or vegetable as created by nature is not necessarily more nutritious than in its processed form. It has become recently evident that the presence of cell walls can be a controlling factor in the bioaccessibility or the proportion of ingested nutrients available for absorption in the gut and later traced in the blood plasma. One specific case is the bioavailability of carotenoids from plant tissue subjected to different treatments causing cell disruption (Fig. 2). Mashing carrot tissue into juice as well as grating or cutting it breaks open the cell structure and releases the cell content making micronutrients more available for absorption. On the contrary, cooking favors cell separation during mastication and retention of intact cell walls, thus effectively protecting the cell contents during passage through the gut (Tydeman et al., 2003). Another example is availability of lycopene, an effective antioxidant, from tomato products. Processing of tomato into tomato paste involves extensive cell disruption and release of lycopene from the cellular compartments by heat treatment. Researchers found that the lycopene response in plasma was 22–380% greater after consumption of the same amount of lycopene from tomato paste than from fresh tomato (van het Hof, West, Weststrate, & Hautvast, 2000). Another case is starch digestibility in the small intestine, under study by scientists at IFR in Norwich. Enzyme activity in the gut is restricted by the porosity and permeability of the microporous, crystalline matrix of processed starch. Controlling matrix properties may reduce starch digestibility thus maintaining low blood sugar levels important to control diabetes. The corollary of these findings is that work still needs to be done on how the structure of processed foods affects the actual availability of nutrients for consumers increasingly concerned about health and well being.

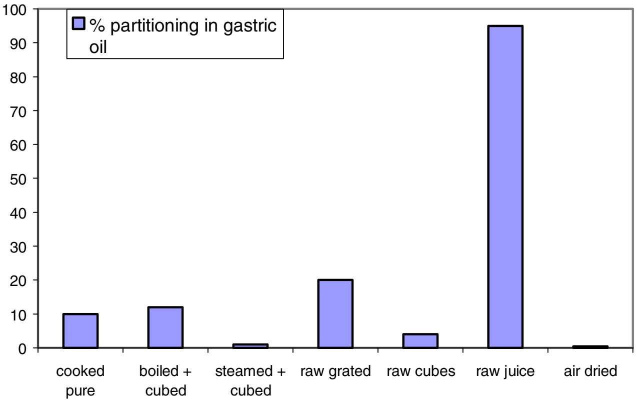

Fig. 2. Partitioning of carotene into gastric oil phase from carrot preparations (Tydeman et al., 2003).

2.3. Chemical and microbiological stability

Stability against unwanted reactions is achieved in nature mainly by three means: Complexing key reactants into passive forms, restricting the mobility of reactants and, compartmentalizing. For example, control of biochemical activity within a cell is often achieved by physically separating the reactants in microstructural locations (Haard & Chism, 1996). Disruption of cell microstructure influences formation of flavors, off-flavors and browning reactions. A well known example is *Allium* species where flavor precursors are converted to flavor compounds when cells are disrupted by chewing or other means of mechanical injury. Changes in structure mediated by freezing and drying can activate enzymes in unheated plant tissues leading to off-flavor development and textural changes.

Restricting molecular mobility and compartmentalizing may be achieved by control of the microstructure during processing. Formation of amorphous glassy phases as a means of reducing mobility and slowing reaction kinetics has been a major subject of food research during the last decade and will not be dealt with here (Slade & Levine, 1991). Proper structuring of multiphase foods may provide increased stability or protection as well. In emulsions the antioxidant effect of α-tocopherol is much higher when solubilized in layers of lecithin outside the oil droplets when the same amount of antioxidant is dissolved in the oil phase (Ruben & Larsson, 1985). The use of edible films is an effective form of compartmentalizing phases or domains at the macroscale for increased stability (Koelsch, 1994).

Microbiological safety relies on the ability to control microbial growth in each microscopic location of the food. The physical structure of a food can have an effect on the local chemical environment perceived by the microbial cells and in their proliferation. For example, gel networks immobilize bacterial cells significantly decreasing their growth rate. In emulsions the presence of oil droplets restricts expansion of the bacterial colony in the aqueous phase, thus reducing growth rate and bacterial count (Robins & Wilson, 1994).

3. Transport phenomena

Transport phenomena is central to food engineering. The effect of structure in transport phenomena in foods has been addressed in several publications (Aguilera & Stanley, 1999; Gekkas, 1991; Saravacos & Maroulis, 2001). The following discussion is restricted to diffusion but it may apply as well to heat and momentum transfer.

3.1. Mass transfer by molecular diffusion

Molecular or Fickean diffusion in the fluid phase is widely accepted by food engineers as a predominant mechanism of mass transfer within solid foods (e.g., drying, leaching). Fick's first law states that within a continuous medium and under the presence of a *concentration gradient*, the net migration of solute molecules due to random movement occurs from a region of high concentration to one of lower concentration. Thus, the driving force for diffusion is a concentration (or chemical activity) gradient. Fick's second law, also called the *diffusion equation*, states that the rate at which this process proceeds at a point in space for diluted binary systems (i.e., a solute and a large portion of solvent) is proportional to the variation of the slope of the concentration gradient. The constant of proportionality is defined as the diffusion coefficient D, or *diffusivity* (Crank, 1975; Cussler, 1997). Food engineers have made extensive use of the approximation for long times of the solution to the diffusion equation for a regular geometry (infinite slab and cylinder, sphere) to calculate an *apparent* or *effective diffusion coefficient* D_{app}. Analytical solutions of Fick's second law under specific boundary conditions lead to expressions (if some simplifying assumptions are considered!) from which the term D_{app} can be calculated form the slope of a graph of *log* of the extension of mass transfer versus time (Schwartzberg, 1987). The perverse inference of calculating a D_{app} (which may be correctly defined as a *mass transfer coefficient*) from experimental data is that no effort is made to unveil the actual mechanism for mass transfer. In fact, some researchers have correctly noted that it is worthless to calculate diffusion coefficients unless the structure is resolved (Geurts & Oortwijn, 1975). The subject of the effect of food microstructure on the diffusion coefficient (when diffusion is the prevalent mechanism) is discussed in Aguilera and Stanley (1999). Readers may find interesting to know that the widespread application (and teaching!) of diffusion theory as a mechanism of mass transfer in biology is being questioned (Agutter, Malone, & Wheatley, 2000).

Alternatively, the actual diffusion coefficient in a biphasic solid containing platelets or spherical inclusions may be derived from D values in the individual phases if the structure is resolved, as discussed in Cussler (1997). Crossley and Aguilera (2001) considered architectural effects of the structure in solvent extraction of a solute from a flake (slab) having interspersed impermeable platelets (Fig. 3). When platelets are arranged parallel to the diffusion path (segmented line) tortuosity is one and the ratio D_{eff}/D decreases linearly as the volume fraction of platelets increases. When platelets are placed perpendicular to the direction of diffusion D_{eff}/D depends strongly on α, the aspect ratio of the platelets and the dependence with ϕ_{f} becomes nonlinear. Hence, in simple structures as the case presented the reduction in observed (or measured) diffusivity can be ascribed solely to structural effects. This fact has been acknowledged (but not resolved) in the case of moisture diffusivity in solid foods, where a wide variation of data is reported in the literature (Saravacos & Maroulis, 2001). The authors state that "...the physical structure of solid foods plays a decisive role not only on the absolute value of moisture diffusivity but also on the effect of moisture content and temperature on this transport property".

3.2. Mass transfer in porous and cellular foods

Mechanisms other than diffusion may be responsible for bulk transfer of a liquid phase (e.g., water, oil) in cellular foods and those of particulate nature (e.g., chocolate) which present pores or capillaries in their microstructure. In these cases two additional driving forces for bulk mass transfer acting at the microstruc-

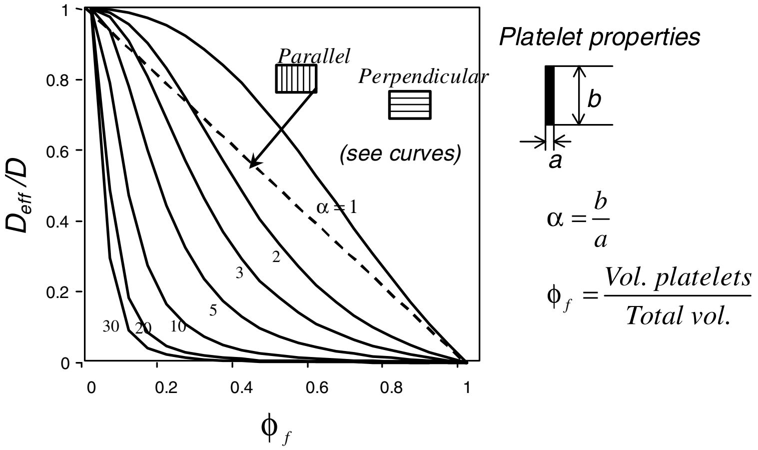

Fig. 3. Curves showing the correlation between D_{eff}/D and volume fraction of impermeable platelets in a slab (ϕ_{f}) for different aspect ratios α of platelets. The effective diffusion coefficient varies sharply with ϕ_{f} when platelets are placed perpendicular to the diffusional flow.

tural level are pressure gradients and capillary forces. Infiltration of oil into the crust of a fried product during cooling has been ascribed to a pressure difference appearing from the vacuum produced in the inner pores of the crust when steam condenses (Bouchon, Aguilera, & Pyle, 2004). Similarly, the exchange of gas or liquid occluded in the pores of a cellular matrix (e.g., fruit piece) for an external liquid phase in vacuum impregnation is also driven by a pressure difference (Fito & Chiralt, 2000). In this case flow may also occur due to the contraction of intercellular spaces by viscoelastic effects in the food matrix.

Capillary flow in fine pores and cracks is ubiquitous in nature. It has also been reported to be the mechanism in "dunking" or the wetting of cookies with hot coffee or tea to improve flavor release (Fisher, 1999). In fact, the predominant mechanism of liquid penetration into a food powder during dehydration is mediated by capillary forces (Hogekamp & Schubert, 2003). It appears that the undesirable migration of the liquid fraction of cocoa butter to the surface of chocolate (blooming) is also in part driven by capillary forces since chocolate is a particulate medium. Summarizing, knowledge of the microstructure in which mass transfer takes place may assist in finding the mechanisms and their relative contributions to the transport phenomena, and in better modeling.

3.3. Drying: physical and biochemical stability

Drying has been a technology in which a trade-off is often made between increased stability at low moisture contents and the associated structural changes. For the chemical engineer the critical parameters derived from the drying process are the drying rate and the apparent moisture diffusivity of the product. However, for the food technologist properties such as color, shape (shrinkage) and rehydration capacity are determinant for the quality of the dried product.

Shrinkage during dehydration of high moisture tissues occurs when the viscoelastic matrix contracts into the space previously occupied by the water removed. Efforts to relate structural changes in plant material to a glass–rubber transition have not been conclusive (Karathanos, Anglea, & Karel, 1996). In spite of the enormous importance in food quality, shrinkage of fruits and vegetables has been often studied by crude direct measurements or inferred from changes in related parameters such as porosity and density. The problem is that changes in structural dimensions during drying are not isotropic. With the advent of image analysis more precise data for shrinkage are becoming available. Mulet, García-Reverter, Bon, and Berna (2000) investigated shape changes along the drying process of potato and cauliflower by image analysis. Ramos, Silva, Sereno, and Aguilera (2003) studied shrinkage in grape slices at the microscopic level by image analysis, quantifying several parameters directly related to cellular dimensions. Fractal analysis and Fourier descriptors derived from image analysis, among others, may provide precise numerical data of shape changes during drying and assist in correlating them with process conditions and rehydration properties.

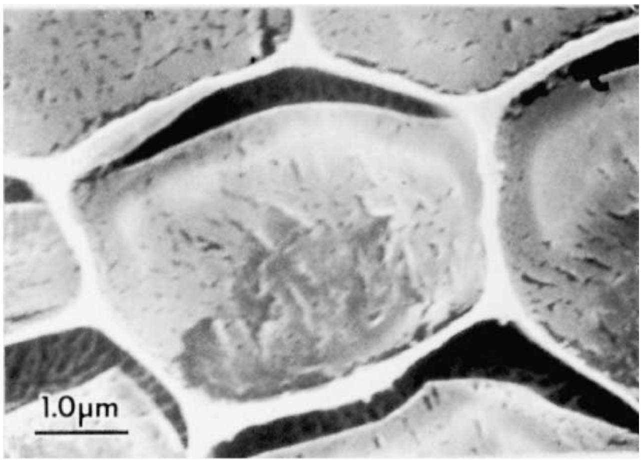

Fig. 4. Cryo-SEM showing segregation of solids in a protein/water solution due to freezing. The concentrated solid matrix appears as an hexagonal wall while the slightly etched central area is ice. Upon sublimation (e.g., freeze–drying) the center will become an air cell.

Freeze–drying is considered in the biotechnology and pharmaceutical industries as a mild dehydration process. However, there are two important structural phenomena related to freeze–drying that may affect the quality and stability of dry biomolecules and drugs. One is collapse or the loss of cake structure when the temperature of the dried portion increases above the glass transition temperature of the material. The increased mobility of this rubbery zone can accelerate protein degradation (Franks, 1990). The other is interfacial effects at the ice/freeze-concentrate interface after freezing (Fig. 4). There is growing evidence that loss of protein activity is due to accumulation and unfolding of molecules at this interface which upon drying becomes a solid/air interface (Millqvist-Fureby, Malmsten, & Bergenstahl, 1999). This effect is more pronounced in rapid freezing producing small crystals and higher interfacial area, which was supposed to be a better method than slow freezing. Again, deleterious effects do not depend on the level of process variables but on the microstructure formed.

4. Product properties

4.1. Texture

Most textural attributes of foods are perceived through mastication, a process by which a solid food is torn, ripped, crushed and ground, mixed with saliva so that a bolus is formed that can be swallowed and digested. According to Bourne (2002) the texture of foods is derived from their structure. He cites work in which blindfolded people identified less than half of the foods (mainly fruits and vegetables) they were presented when samples had been pureed in order to eliminate all traits of the original structure. In fact, a major drawback of some emerging technologies (e.g., high pressures) when applied to plant material is structure breakdown. High pressure treatments above 200 MPa result in severe texture loss in fruits and vegetables due to rupture of cellular membranes and loss of turgor pressure (Ludikhuyze & Hendrickx, 2001).

Textural perception occurs mostly in the mouth which is a very biased sensor. For instance, the presence of particles (or graininess) may be desirable in the case of a bean paste or undesirable in most foods including sweetened condensed milk, ice cream and chocolate where the threshold of size detection is between 10 and 50 μm but decreases with increasing degree of circularity (Imai, Saito, Hatakeyama, Hatae, & Shimada, 1999). Under certain formulations small particles may contribute to the perception of creaminess in several food systems (Kilcast & Clegg, 2002).

Structure has a large effect on the sounds produced and the auditory perception when biting into foods. The sound emitted by fresh vegetables and fruits is the result of the rapid release of turgor pressure inside cells and a sound wave is produced (Vickers & Bourne, 1976). In dry cellular products (e.g., some snacks) the sound pressure wave is produced by the snapping back of walls that bend before breaking (Duizer, 2001).

4.2. Structure and physical properties

Spectacular advances in materials science during the last decades have emanated from the understanding of the structure of a material, its relation to properties (so-called structure–property relationships), and how to engineer and control those properties. Material scientists are quite successful at doing this because the microstructures of metals, ceramics and polymers are more or less homogeneous. A large collection of data on physical properties of foods (e.g., thermal, rheological, mechanical, color, etc.) exists in many books and publications but its relation to microstructure is minimal.

One simple example, but still qualitative, is the relation between the puncture force and the microstructure of cooked legumes. Legumes and other pulses stored at high temperature and humidity are susceptible to the hard-to-cook phenomenon (Aguilera & Stanley, 1999). Beans with this defect to not soften sufficiently during cooking because they do not imbibe sufficient quantities of water. Consequently, they exhibit a much higher puncture force (i.e., several times higher) when tested instrumentally. Microscopic observation of cooked beans demonstrates a major structural difference between soft and hard beans. The middle lamellae between cells is largely dissolved in soft beans during cooking while it remains and binds the cells together in hard beans (Fig. 5). Softness during mastication is mechanically related to the sliding of individual cells one past another (like a wall made of Lego cubes) when a force is applied while hardness is the result of fracture across the cellular material. However, there is still much work to be done in understanding the role of structure in the sensorial properties of foods.

5. Engineered structures

Many food processing operations aim at creating the microstructure that provides products with desirable traits and functional properties. By *structure engineering* is meant the generation of microstructures based on fundamental knowledge (e.g., colloid science), use of appropriate ingredients and controlled application of processing variables such as shear or temperature (Aguilera, 2000; Hermansson, 2000). Different microscopy techniques together with advanced physical methods are used to follow structure formation until it perform as desired. Two areas that may benefit from this bottom-up approach are presented below.

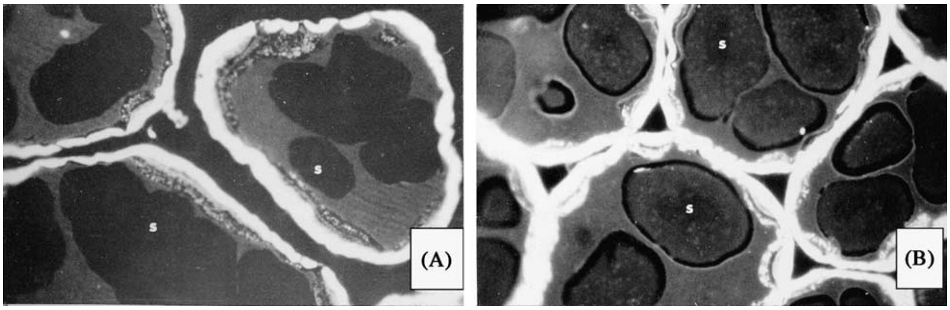

Fig. 5. Microstructure of cooked beans and instrumental texture. (A) Soft bean (note separation between cells); (B) Hard bean. s = starch granule (Source: Aguilera and Stanley, 1999).

5.1. Encapsulation

The term *encapsulation* is often used in powder technology to describe the process of forming an amorphous polymeric coating around a core to control mass transfer and provide protection in the dry state from environmental chemical and physical stresses (Vilstrup, 2001). Common polymeric walls used in foods include proteins, sugars, dextrins and starches (Aguilera & Stanley, 1999; Gibbs et al., 1999). The contents of a microcapsule (e.g., flavors, enzymes, drugs, etc.) are released either by dissolving it in water or by mechanical means. As important as the mechanism of release is the timing and location where it occurs, for example, the content may remain intact during food preparation but be released in the mouth or in the digestive system. Tailoring the functionality of powders requires full appreciation of material properties, particle architecture and microstructure, and fundamentals of mass transfer (Thies, 2001). The major goal is to correlate the microstructure with stability, whether physical (e.g., caking) or chemical (e.g., aggregation of proteins in the dry state), and/or with functionality (e.g., solubility or release behavior). A case in point is the stability of protein drugs in controlled-release systems where the microstructure of the delivery device, normally microspheres, may play an important role in the stability of the drug (Fu, Klibanov, & Langer, 2000). The subject of properties of powders and structure is discussed by Dodds (2001).

5.2. Structuring air and water

To the food processor air and water are inexpensive ingredients while for weight conscious consumer they provide no calories. Air bubbles are important structural elements in solid foams such as bread, snacks, and meringue and in liquid foams such as whipped cream and those in beer and *Cappuccino* coffee.

Entrapping abundant amounts of water in matrices is one alternative to develop low-calorie products. Proteins and polysaccharides have been used for centuries as gels that immobilize large quantities of water. The novelty is that pairs of these biopolymers in solution almost always phase-separate in a process that is kinetically-controlled. In the transit to the equilibrium state many microstructures appear that can be trapped, for example, by gelation of one of the phases, thus controlling the morphology and properties of the system (Loren, Langton, & Hermansson, 1999). Another area of research that offers opportunities for entrapping large quantities of water is that of liquid crystalline lamellar phases. On cooling the phase transform into a so-called α-gel state, particularly suitable to form stable foams. This phase is thermodynamically unstable and further transforms into the coagel phase, in which monoglycerides are crystallized into plate-like crystals entrapping large quantities of water and acquiring a fat-like consistency. Applications extend to dressings, mayonnaises, sauces, processed cheese, meat products and fat spreads (Heertje, Roijers, & Hendrickx, 1999).

5.3. Molecular gastronomy

The culinary arts have empirically produced many structures that provide pleasant visual and textural sensations. As more ingredients, new cooking hardware and regional preferences begin to emerge we must team up with chefs and cooks to understand how these structures are formed and breakdown to give us the eating pleasure.

Recipes are to the amateur cook what blueprints are to the engineer... only that less precise and fundamental. The term *molecular gastronomy* was coined in 1992 by Nicholas Kurti, an Oxford physicist and gourmet, to mean the application of scientific (and engineering) principles to the understanding and improvement of gastronomic food preparations. One major aim of molecular gastronomy is to achieve new structures and textures by applying techniques such as drying, liquefying, gassing and freezing. It also addresses subjects such as heat transfer to foods in ovens, use of scientific instrumentation in the kitchen and novel techniques such as the use of vacuum (This, 2002). The author had the opportunity to attend one of Dr. This' monthly meetings with renowned French chefs in Paris. The subject was crackling on the surface of a French cookie (*macarons*) during heating in the oven. It was evident that a quantitative measurement of the shape and area of cracks as well as precise description of the heating conditions would have helped in elucidating the problem. With the explosive growth of gastronomy around the world the development of intelligent kitchenware and sensors as well as the use of video-cameras and computers in the kitchen are starting to appear.

6. Quantifying structure

It would be an oversimplification to assume that the use of more powerful and sophisticated microscopes automatically leads to a better knowledge of the microstructure of foods. Unfortunately the human visual system is not very suited to make objective and quantitative determinations of the image features we see under the lens of a microscope. As stated before, engineers work with physical models and mathematical relationships that quantitative information and numerical data from an image when modern microscopes are coupled to software programs for image analysis.

Image analysis relies heavily on computer technology to recognize, differentiate and quantify images. At the first level of analysis are commercial software that

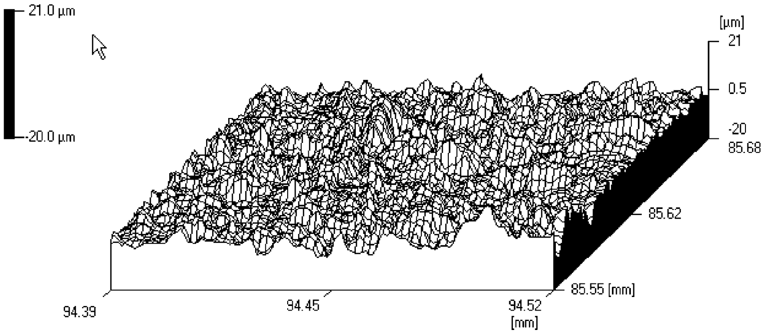

Fig. 6. Surface topography of bloomed chocolate as measured by laser microscopy and analyzed by SURFRAX®. Courtesy of R. Quevedo (2002).

perform basic tasks e.g., image editing, segmentation, object selection and measurement of geometrical features. The second level are algorithms that allow fractal analysis such as the one presented in Fig. 6 to quantify the roughness of the surface of bloomed chocolate. A still higher level of analytical complexity are algorithms for shape recognition and classification of objects into a specific class (Costa & Cesar Jr., 2000). Texture features and patterns of an image can also be quantified using appropriate parameters, for example, by the statistical relation between the gray level of pixels comprising an image (Haralick, Shammugam, & Dinstein, 1973).

7. Conclusions

Through the many examples presented including typical engineering subjects such as diffusion and physical properties, to nutrition and gastronomy, it has been demonstrated that structure is a key parameter in our understanding of the behavior of foods. We are now at a point where food structure may be studied at almost any dimensional level, often in real time and with minimal intrusion. Quantification of structural features using images obtained at the relevant scale opens new opportunities for engineering analysis, that of linking structure to properties and understanding basic mechanisms of physicochemical changes. Food engineering is going micro!

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