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ABSTRACT

Physics Nobel laureate Giorgio Parisi recently proposed a novel approach to cooking pasta that is more energy-efficient: Bring the water to a boil, add the pasta, cover the pot with a lid, and turn off the heat source. This heat-off-lid-on (hofflon) method saves energy. Other suggestions recommend soaking dried pasta in cold water to shorten the cooking process. However, there is a paucity of research examining the impact of different cooking methods on pasta texture and quality. In order to gain a deeper understanding of the effects of different cooking methods on the texture and strength of the pasta, a series of experiments were conducted. The experiments demonstrated significant variations in mechanical properties, adhesiveness, and cohesion. The hofflon method requires a longer cooking time due to the gradual decline in temperature. The process of soaking increases the water content of the pasta prior to cooking, which subsequently affects the behavior of proteins and starch when heated. These effects influence the manner in which proteins undergo alteration, the formation of cross-links, and the gelatinization of starch. Pasta prepared using the hofflon method exhibits reduced cohesion and softness, resulting in a texture that is softer and more mushy than that of *al dente* pasta. Presoaked samples display increased stickiness and a mushy texture when compared to pasta prepared using the classic method and hofflon pasta. The results of this study indicate the promise of developing straightforward models to illuminate the unique roles of proteins and starch during the structural transformation.

I. INTRODUCTION

Pasta is a global success for four simple reasons. First, it is made with just a few ingredients: durum wheat flour (or other flours) and water. Second, it is easy to prepare. Third, traditional dry pasta lasts shows long shelf-life and can be easily stockpiled.[1] Furthermore, pasta can be accompanied by a variety of other foods, including vegetables, fish, and meat, to create a nutritionally balanced and well-rounded meal.[2,3] The preparation of "dry pasta" entails the incorporation of flour, predominantly derived from durum wheat, and water into a homogeneous mixture. This soft, viscoelastic, rubber-like material can be deformed and extruded.[4] Once the water has been removed by drying, the resulting solid is hard and brittle.[5] High-quality pasta requires low, but sufficient amounts of water during mixing to develop a viscoelastic gluten network and overall temperatures below 60 °C for the extrusion process.[6,7] After this, the pasta becomes dried also at temperatures below 60 °C to prevent starch swelling processes. Thus, the pasta undergoes a rubber-to-glass transition during production and a glass-to-rubber transition during cooking.[8]

Given these low drying temperature, the rubber-to-glass and reverse transition can be addressed to the protein network. In contrast, the starch remains crystalline during production but melts only during cooking.[9,10] However, the physical structure of the pasta indicates that a significant amount of energy is expended during the preparation stage. Additionally, the noodles themselves require a considerable amount of energy to be cooked before they can be served with sauces.[11]

Indeed, the traditional method of cooking pasta involves the use of a considerable quantity of water, e.g., 1 l for 100 g pasta, which is brought to a boil before durum pasta is added and the cooking process is completed in constantly boiling water. This process often lasts for more than 10 min, according to the shape of the pasta and the remaining water content, roughly between 8% and 12%.[12] Indeed, the traditional pasta cooking procedure involves the boiling water until the end of the cooking process. This guarantees the optimal texture profile and also ensures that the pasta does not stick together during the cooking process.[13,14] Fairhurst, London, and Bradhurst[15] have estimated in a popular article the various parts of energy consumption during traditional pasta cooking. Their results are summarized in Fig. 1. It is evident that the primary components are occupied by the water, during the process of boiling tap water, due to its high specific heat, and more importantly, to maintain the boiling temperature and the rolling boil of the water and pasta until it is finished.

In 2022, the Nobel laureate in physics re-posted a statement by Italian Chef Alessandro Busiri Vici, which proposed an alternative method for boiling pasta using less energy and resources Parisi.[16] Once the water has boiled, the pasta should be added. Subsequently, the pot must be covered, and the heat source switched off. Despite the potential for the temperature of the cooking water to decrease, the pasta should still be *al dente*, according to Parisi. This method will be referred to throughout this paper as "hofflon" for "heat-off, lid-on." It would indeed be beneficial to consider ways to reduce the environmental impact of agriculture. One potential avenue for doing so is to focus on resource savings.[11] This could be a simple and practical method to further save energy and resources in daily lives. Different estimates and calculations point in this direction, for instance, the Unione Italiana Food—Settore Pasta claims that 47% of energy consumption and carbon dioxide, CO_2, emissions could be reduced using this method.[17] Another widely used alternative approach is to presoak the dry pasta in cold water at room temperature for more than 1 h. The pasta takes up water, and this procedure reduces the cooking time significantly, almost by an order of magnitude. These alternative methods have quite some energy saving potential, as shown in Fig. 1. The Parisi method (hofflon) suggests to save about 60%, corresponding to the energy consumption during the entire cooking process, whereas the presoaking method is estimated to save about 40%–50%, depending on presoaking time and the amount of water used.

Despite the evident energy benefits, the question of the texture of the different cooking methods remains unclear. It is crucial to consider these aspects, as consumer acceptance is closely tied to the sensory experiences of pleasure, flavor release, and mouthfeel when pasta is cooked in alternative ways. It is intuitively clear that these alternative cooking methods modify the heat and water transport into the pasta. Consequently, it changes hydration, water absorption, and somehow the texture compared to the classical cooking method, i.e., steady-state cooking in boiling water.[18,19]

The majority of literature on the subject focuses on the assessment of production quality.[14] Nevertheless, several methods have been identified for assessing and comparing the quality of cooked pasta, which result in physical parameters. Texture profile analysis (TPA) provides physical information on the properties related to the mouthfeel of foods, including hardness and cohesiveness.[20,21] These properties compare to firmness and are associated with the breakdown of the food during oral processing, mastication and chewing.[22]

From the perspective of physics, further experiments are required to provide more fundamental information for the interpretation of molecular properties of food materials.[23,24] In particular, tensile tests are useful for determining the rubber-like behavior of longer pasta, such as spaghetti or tagliatelle. These tests reveal differences in large-scale properties, such as ultimate stress, maximum deformation, and failure. Although these appear to be less related to the breakdown processes in the oral cavity, the stress–strain relationship for the different cooking methods provides complementary molecular insights and will show the important role of the proteins in structure and texture formation. This is of special importance since most studies on model development most publications mainly consider the influence of the starch components.[18,19,25]

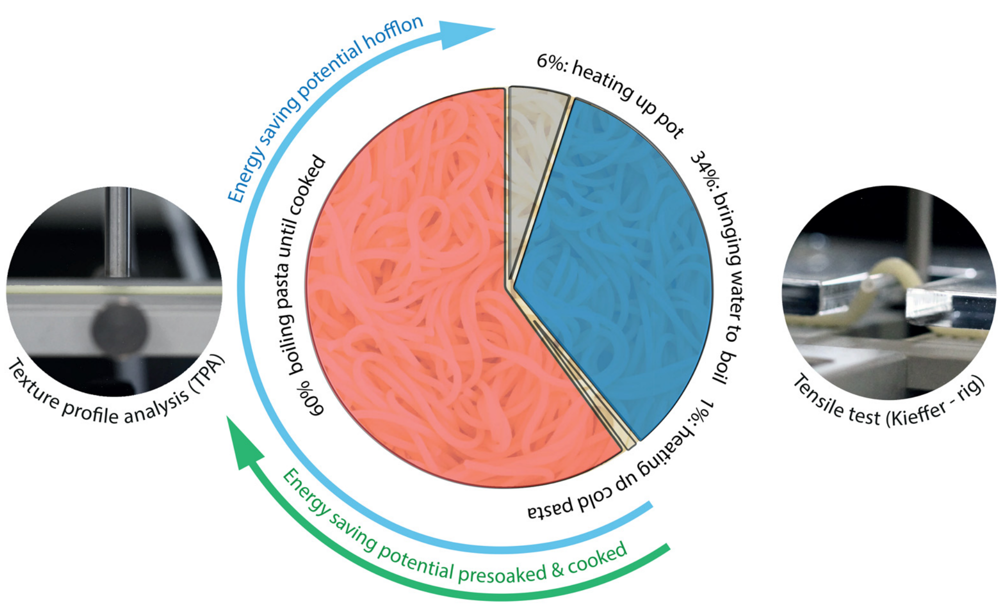

FIG. 1. Typical energy consumption during pasta cooking. The major part is used for boiling the pasta. Parisi's suggestion (hofflon method) shows the best energy saving potential, presoaking % cooking less. Data at the inner circle are taken from Fairhurst, London, and Broadhurst, University of Nottingham.[15] The main experimental methods to discriminate the physical properties are texture profile analysis and tensile tests, as indicated.

II. PHYSICAL ASPECTS OF PASTA: PROTEIN, STARCH, AND WATER

To gain deeper insight into these subsequent experiments and interpretations, a short introductory reminder of the molecular composition and physical function of the principal components, namely, proteins, starch, and water, is presented. These molecules serve to determine the overall structure.[9,10] When durum flour and water are mixed, the proteins interact partially with the water to form a gluten network with an elasticity comparable to rubber and polymer melts. Gluten is composed of two main types of proteins types: with many internal disulfide bridges self-cross-linked, globular gliadin and high and non-self-cross-linked low molecular weight linear glutenin. Whereas gliadin does not significantly swell in water, glutenin interacts with the hydrophilic (charged and polar) blocks of amino acids. Glutenin swells partially, takes up water partially, and forms a deformable elastic transient (polymer) network. The hydrophobic blocks of the glutenin chains minimize the unfavored interactions with water by forming β-sheets.[4,26]

Starch is mainly comprised of two types of polysaccharides, both of which are composed of glucose as a monomer unit, i.e., linear amylose and branched amylopectin. Typical durum starch grains consist of 15%–25% amylose with a linear structure including 1.000–10.000 glucose units. Amylopectin consists of 75%–85% straight chains with branches and helices containing 10 000–100 000 glucose units. Both molecules are densely compacted in grains and have a highly crystalline structure with a smaller amorphous part.[27] Given the hierarchical grain structure, starch cannot swell in cold water and the temperatures during dough mixing and drying. Starch grains act as micro-scale sized filler particles in the transient glutenin network, which interact, according to their surface properties with the glutenin chains. Dough networks thus are determined by a variety of molecular interactions: (1) during mixing, high molecular weight glutenins may form topological interactions, i.e., entanglements. (2) Electrostatic interactions between oppositely charged amino acids act as ionic cross-links. (3) β-sheets form "hydrophobic" interactions via cross-links with weaker strength. (4) Starch–protein interactions contribute significantly to the flow behavior of wheat dough.[4,28] Wheat dough thus shows specific viscoelastic properties[4,29] similar to highly concentrated solutions of macromolecules containing hard filler particles.[30]

During cooking, additional subsequent processes happen, which define the final structure and therefore the texture. One important step is the formation of covalent bond by disulfide bridges between different glutenin chains. Since the cysteine in glutenin chains are located close to the chain ends, the glutenin network is mainly end-linked and shows large meshed providing sufficient space to entrap starch grains and gliadin. This "vulcanization" reactions happen between 65 and 70 °C at time scales of around 5 min to 7 min.[31] This processes will turn the pasta into a viscoelastic soft solid with gel-type properties.

At similar temperatures and the intrusion of water, the crystalline parts of the starch will start to melt,[32] amylose and parts of the amylopectin undergo a helix to coil transition, the branches of amylopectin become disordered. Water will then be able to swell the starch granules and bind water by hydrogen bonds. The starch fraction gelatinizes. Pure starch samples, for instance, form pastes. The pasta turns to a weak, soft solid, with a pleasant, succulent mouthfeel.[23] Of particular significance for subsequent discussion is the observation that the melting point for starch is highly dependent on the water content. With increasing water content, the melting and gelatinization temperature drops considerably (see, for example,[9] for a summary). In the case of dry pasta, for example, with about 10% moisture content, the starch will not melt or gelatinize even at temperatures above 200 °C. This is in contrast to heating it in water, where the melting and gelatinization process begins at approximately 65 °C depending on the specific physical structure of the starch.

It is important to note that the final assessment of the pasta texture is taken by chefs. The cooking time will determine whether the pasta will be soft, pastry-like, and mushy or more attractive, with a central glassy, hard kernel remaining surrounded by a moist, rubber-like soft shell.[23,25] The latter is the defining characteristic of the Italian pasta *al dente*. Having these considerations in mind, experiments have been designed to compare the different cooking method classical, Parisi's hofflon and the presoaking method.

These experiments will primarily involve measuring the water content of the cooked pasta. In addition, compression tests will be employed, which are frequently employed in food science to extract typical texture parameters, such as hardness, adhesion, and others that can be related to the mouthfeel. However, the deformation behavior of pasta is controlled by a highly elastic protein network and non-crosslinked, but gelatinated starch, which contributes a significant plastic part to the deformation. Consequently, stress–strain (tensile) experiments have been conducted. These experiments will provide further insight into the molecular interplay between the principal components of the pasta.

III. MATERIALS AND METHODS

A. Materials and characterization

Dry spaghetti n°12 from F.lli De Cecco di Filippo (Fara San Martino, CH, Italy) bought from a local store were used for the experiments. The dry spaghetti is composed of durum wheat pasta with a flour gluten index: $\geq 70\%$, a flour yield from durum wheat: $\leq 67\%$, a percentage of flour at the presses with granulometry $>400\ \mu$m: $>40\%$, spaghetti, consistency holding after 20% overcooking (viscoelastographic measure): $>80\%$, and extruded through a bronze draw plate.

Moisture content was measured for dry and cooked pasta. As for dry pasta was measured as follows: 2 g of dry pasta was ground and sifted (<1 mm were used). The measured moisture content of dry pasta was $10 \pm 1\%$ using a halogen dryer (Excellence HS 153, Mettler-Toledo GmbH, Gießen, Germany). All samples with the EAN—13 80 01250 120120 were ordered in one charge. Ultra-pure (demineralized) water with purity based on resistivity at 25 °C of 18.2 M Ω cm obtained with a Milli-Q IQ 7003 (Merck KgaA, Darmstadt, Germany) was used for all experiments.

B. Pasta cooking method

Pasta samples of weight 150.1 ± 0.12 g were cooked in a beaker with 8 cm diameter and 32 cm height, and covered with aluminum foil for the hofflon method. A heating plate (IKA-Werke GmbH & Co. KG, Staufen, Germany) was used which incorporates a temperature sensor placed directly in the water. For stirring during cooking, a pair of tongs out of stainless steel and plastic ends with a length of 35 cm was used. To decrease interaction with moisture, those samples were vacuum sealed after weighing. For the presoaking method, separate samples were soaked in ultra-pure water 1.5 h before cooking in fresh water. The water-to-dried pasta ratio (WPR) during cooking was 10 L/kg, which is lower than the recommended 12 L/kg by the pasta company. Other experiments show that the WPR can be reduced even further to 3 L/kg.

To reduce total water boiling time, 1.3 L water was pre-boiled in a water boiler and then added to the beaker. The 1.5 L water was heated until the probe showed 98 °C. The heat plate was heated and held at 300 °C during water heating and the classical cooking method. The pasta was then added, followed by different steps depending on the cooking method (see Table I). The presoaking time was chosen to be 1.5 h.

The optimum cooking time (OCT) was determined after a modified version of the ISO 7304—1: Pasta should be evaluated every 30 s starting 2 min before suggested cooking time. The OCT is determined when an opaque core was just no longer visible when the pasta is squeezed between two glass plates. Because of common (culinary) standards, *al dente* pasta was aimed and prepared. This is the reason for the modified version used here to determine the OCT by using the cooking time before the opaque core vanished. This was assessed three times, and the average cooking time was used for the experiments. After cooking, the pasta was cooled to room temperture in a water bath. Afterwards, the sample was drained of excess water and transported to the testing machine. In the hofflon method the water temperatures decreases from 95 °C to 80 °C during cooking (see supplementary information for details).

C. Moisture analysis

Two grams of dry pasta were ground and sieved to use particles under 1 mm. Mettler Toledo has a procedure using 145 °C and a turn of criteria of 1 mg loss in weight after 50 s. Three full length strands of presoaked and cooked pasta were tested for 35 min with 135 °C. These parameters for cooked pasta were determined after different pretesting. Every preparation method was tested in duplicate.

D. Mechanical experiments

Compression and tensile tests were performed in a floor-standing AllroundLine Z005 (ZwickRoell GmbH, Ulm, Germany), by using the textXpert II software.

1. Compression tests

The compression test was performed with a stainless-steel cylindrical probe. Tensile tests were performed with a dough tensile test rig, which resembles the Kieffer dough and gluten extensibility rig.[33] The procedure for the compression tests was as follows: After placing the sample, the probe was gradually lowered until the measured force exceeded 0.003 N. Then, the probe height was slightly increased, and three compression cycles were initiated. The first and second cycles were analyzed to address a "two-bite test." The probe velocity was 50 mm/min, and the sample was compressed to 50% strain. A total of 15 samples were evaluated for each preparation method, with each method tested in duplicate. Physical parameters including hardness (HDN), adhesiveness (ADH), springiness (SPG), cohesiveness (COH), gumminess (GUM), chewiness (CHW), and stringiness (STG) were determined based on the considerations by Trinh and Glasgow[34] and Peleg.[21] The evaluated parameters relevant for pasta are visualized in Fig. 2 and summarized in Table II.

TABLE I. Optimal cooking times (OCT) and the cooking temperatures for each method. In the case of Parisi's hofflon method, the temperature drops from 95 °C down to 80 °C during the OCT.

	Classical	Hofflon	Presoaking
OCT (min)	13:30	15	3
Temperature (°C)	95	95 → 80	95
Stirring	4 times after 30 s	4 times after 30	4 times after 30

2. Tensile tests

For the tensile experiments, cooked pasta samples were sliced to fit the rig properly because it was originally designed for pasta dough analysis. Using various parts of a whole strand (excluding the ends) did not show differences. The sample was clamped, and the measurement started. The speed was 50 mm/min. Ten samples were used for each preparation method in order to obtain sufficient data for judgment. Every preparation method was tested in duplicate (see the supplementary material).

The evaluation of tensile parameters evaluated in the following are summarized in Fig. 3 for convenience. From the tensile force vs strain graph, two physical parameters were extracted. The maximum force F_{max} and elongation$_1$ show the strain before rupture. The parameter B_1 was calculated by the slope of a tangent on every point since the start of the measurement. The value for B_1 was set as soon as the slope of the applied tangent exceeded the value of 0.1. The values for B_1, F_{max}, and elongation$_1$ can be related to hardness and cohesion from TPA. Elongation$_2$ describes the strain during the breakdown of the sample, which occurs from the start to the finish of the rupture of each specimen. Higher values for elongation$_2$ indicate more cohesive samples.

E. Statistical treatment of data

Mettler Toledo provides a standard deviation of 0.05% for samples of 2 g. Further data analysis was performed using Origin Pro 2022 (Government) (OriginLab Corporation, Northampton, MA, USA). The confidence interval $p = 0.95$ was used. For the compression/TPA

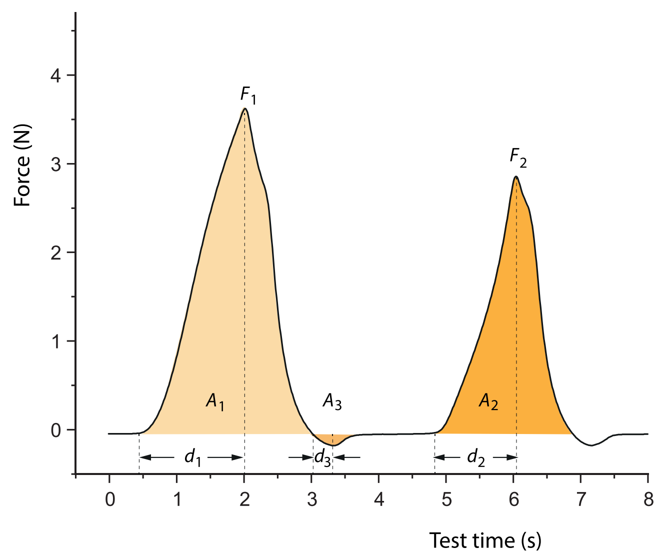

FIG. 2. A typical compression test is conducted in two steps/cycles, corresponding to two bites. The measured quantities are assigned accordingly for convenience.

TABLE II. Important texture properties from typical TPA profiles (Fig. 2) to distinguish pasta after the different preparation methods in physical terms.

Property	Location in TPA profile
Hardness/HDN (N)	F_1
Adhesiveness/ADH (J)	A_3
Springiness/SPG	d_2/d_1
Cohesiveness/COH	A_2/A_1
Gumminess/GUM	GUM = HDN · COH
Chewiness/CHW	CHW = HDN · COH · SPG
Stringiness/STG	STG = d_3/d_2

tests, an average curve was calculated using the average multiple curves tool with default settings.

Tensile test data could not be averaged by the usual features, due to strong heterogeneity of the noodles, even along one individual spaghetto (see supplementary material for the strong variations of the stress–strain curves). Data show high scattering; nevertheless, clear systematic trend between the three cooking methods can be observed and discussed. For reasons of better visibility, the graphs showing multiple measurements are shown without error bars. Statistical errors of averaged curves are standard deviation. To interpret data of tensile tests, the STDEV function of Excel (Microsoft Corporation, Redmond, USA) was used. The parameter B1 was calculated using a plug-in by OriginLab Technical Support. Properties such as those of SPG, which are calculated using disparate methodologies, were subjected to an error calculation utilizing the standard deviations with propagation of uncertainty. All data were rounded in accordance with the measurement uncertainty.

IV. RESULTS AND DISCUSSION

A. Moisture content at different preparations

The moisture content values from Fig. 4 indicate that presoaking pasta before cooking results in pasta with less water. This behavior can be explained by gel blocking.[7,35] The heated starches adsorb the water that was part of the gluten network. This results in starch gelatinization on the outer layer of the samples. Consequently, these starch grains reach a thermodynamic swelling equilibrium, which blocks further water transport inside the inner starch layers.[36,37] These starch grains cannot swell completely and remain ungelatinized. Due to the short cooking period of 3 min, gel blocking has a significant impact on the final water content of the pasta. A longer cooking time of, for instance, 15 min would ensure further diffusion of water within the inner layers of the samples, thus resolving the gel blocking, but at the expense of its final texture. The results from Fig. 4 also indicate that pasta cooked in the traditional way has a slightly higher moisture content than pasta cooked using the hofflon method. This could be addressed to the continuing decreasing temperature and decreasing thermal energy during the cooking process for the hofflon pasta. However, from the moisture content alone, traditionally and hofflon prepared pasta appears very similar. Counter-intuitively, presoaked and cooked pasta shows a significantly lower moisture content. This is due to the structural changes that occur during cooking, as discussed in Sec. II. Indeed for classical and hofflon cooked pasta, the water needs to be first diffuse in first, and melts and gelatinizes the starch. During the presoaking phase in cold water, water diffuses into and is gradually absorbed by the amorphous protein glass. Consequently, only the protein network undergoes a glass-to-rubber transition, wherein the starch phase remains partially crystalline. Nevertheless, the starch grains are already surrounded by water during the swelling of the protein network during soaking. This results in a reduction in the melting temperature of the starch grains. During cooking, the starch melts rapidly, starts to swell and competes with the protein network for water. The melting and

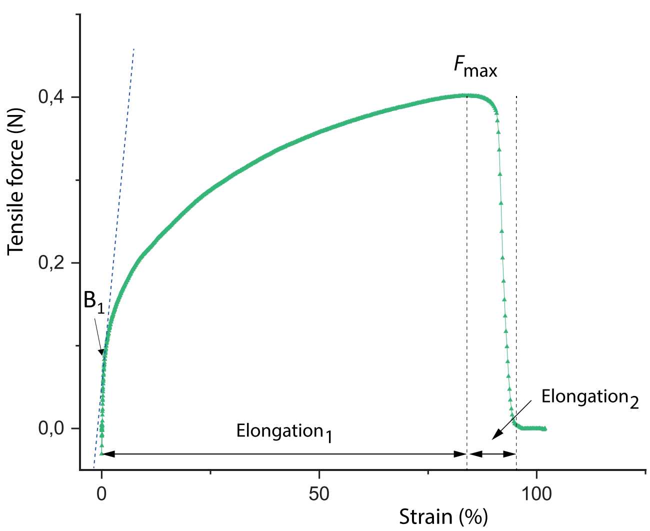

FIG. 3. Typical curve from the tensile tests. The values for the maximum force F_{max}, elongation$_1$, elongation$_2$, and the parameter B_1 which are discussed in the following are indicated.

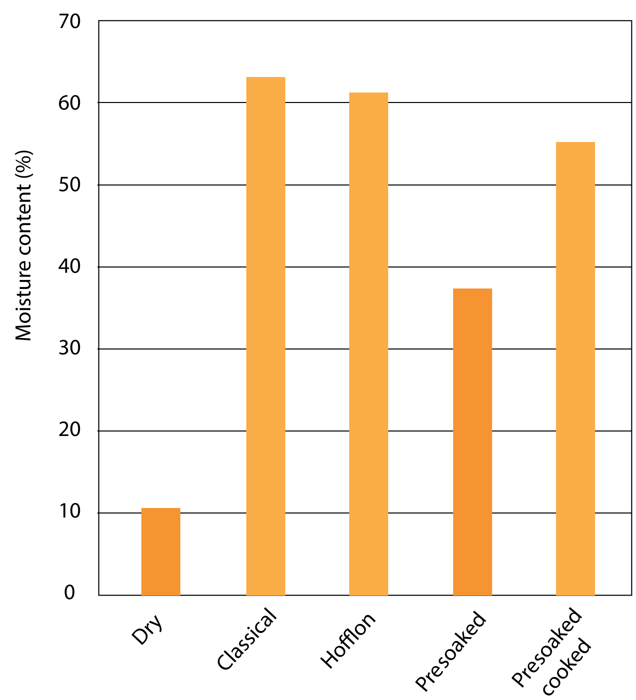

FIG. 4. Average moisture content for the dry, classically cooked, hofflon pasta. The moisture content of the presoaked is shown directly after presoaking and cooking.

swelling of starch draws water from the proteins and gelatinizes incompletely. As a consequence, the overall moisture content remains lower due to the short cooking time.

B. TPA, compression tests

The principal results presented in Fig. 5 illustrate the basic differences of the three distinct preparation methods, while the shapes of the curves of the hofflon and presoaked and cooked pasta show similar features. Additionally, the interval between 0.5 and 2.75 s or 5.5 and 6.75 s test time shows a similarity between all samples the large scattering in data (see Fig. 6). However, clear systematic differences between the cooking methods can be observed. This can also be attributed to the larger deviation of the presoaked and cooked measurements, as illustrated in Fig. 5 a comparison of pasta prepared by the classical method and by the hofflon method reveals further similarities in terms of peak force. However, the averaged curves differ systematically in shape, as well in the texture parameters introduced in Fig. 2 and Table II. The detailed results of the relevant parameters are summarized in Table III. The rounded hardness (HDN) values for the traditional, 3.6 ± 0.3 N, and the hofflon method, 3.3 ± 0.3 N, appear similar. Nevertheless, the mean values for the hardness (see Table III) indicate that pasta cooked in the traditional way is slightly harder than the hofflon pasta. The presoaked and cooked pasta shows surprisingly a similar hardness as the classical prepared noodles. Considering hardness only, both, classical and hofflon pasta, could be expected to provide a satisfactory *al dente* mouthfeel, as Parisi suggested.

The values for the adhesion, ADH, are similar for classical and hofflon prepared pasta and do not show significant differences. The absolute values of presoaked and cooked pasta show an increase which relatively to the other methods is a value of 0.060 ± 0.004 J significantly higher, compared to the values of the traditionally and hofflon prepared pasta. This parameter is assigned with the adhesion work required for the removal of the pasta from the surfaces of the tools. It can be crudely associated with the gluing of the pasta on the teeth, though it should be noted that the surface properties of the metal plates and the teeth are different. Presoaked and cooked pasta feels in consequence much stickier in the mouth than traditionally and hofflon cooked pasta.

The cohesion, COH, shows a trend for slightly higher values in the classically cooked pasta compared to the hofflon and presoaked and cooked case. Traditionally prepared pasta shows therefore a better mouthfeel and disintegrates later with increasing mechanical strain (or stress). This also contributes to a better mouthfeel associated with pasta. Pasta that is mushy in texture is not generally well-received by consumers.

However, Fig. 5 also shows a remarkable trend in the peak forces of the first and second cycles, indicating clear differences in the texture of the pasta with the different cooking methods. The traditional

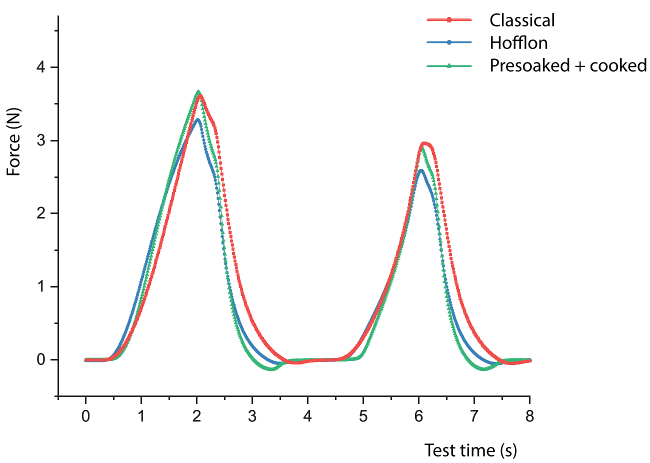

FIG. 5. Averaged curves of TPA for the different preparation methods. Mean values are shown only, and the range of the statistical error bars is shown in Fig. 6.

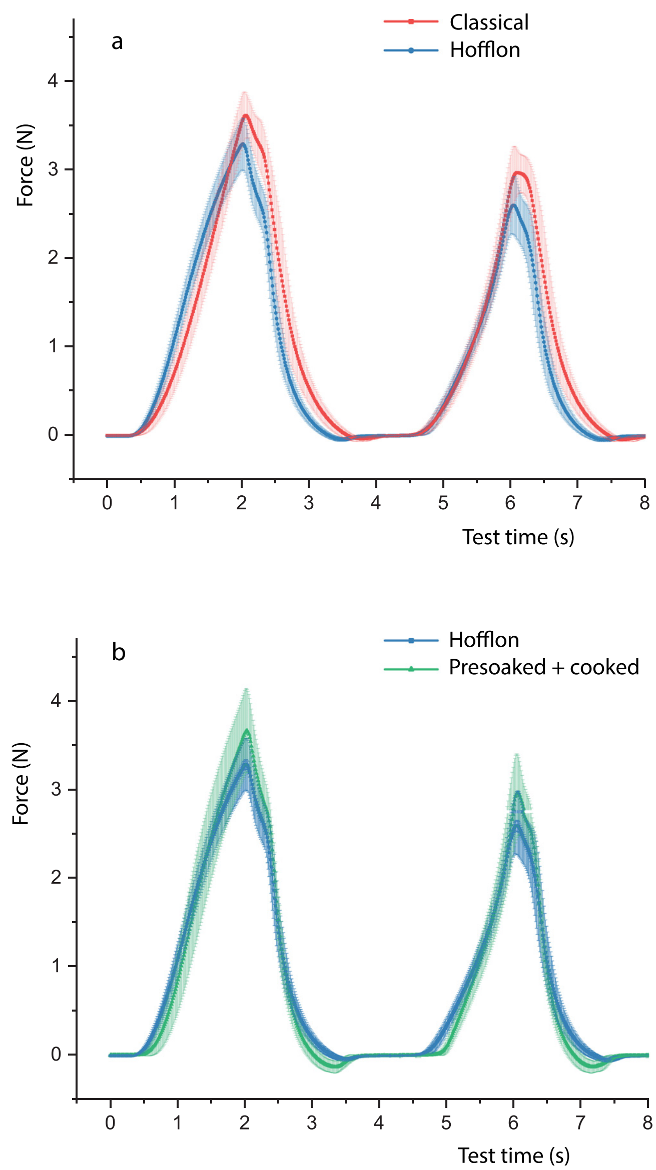

FIG. 6. Comparison between the classical traditional method and hofflon (a), and hofflon and presoaked (b) including errors for different samples.

TABLE III. Results of the texture parameter for the different preparation methods.

	HDN (N)	ADH (J)	SPG	COH	GUM (N)	CHW (J)	STG
Classical	3.608 ± 0.258	0.0167 ± 0.0014	0.932 ± 0.055	0.703 ± 0.068	2.538 ± 0.305	2.365 ± 0.241	0.185 ± 0.024
Hofflon	3.285 ± 0.292	0.0111 ± 0.0089	0.899 ± 0.068	0.604 ± 0.094	1.983 ± 0.355	1.783 ± 0.254	0.186 ± 0.063
Presoaked and cooked	3.665 ± 0.476	0.0602 ± 0.0038	0.801 ± 0.059	0.600 ± 0.138	2.202 ± 0.581	1.764 ± 0.411	0.280 ± 0.085

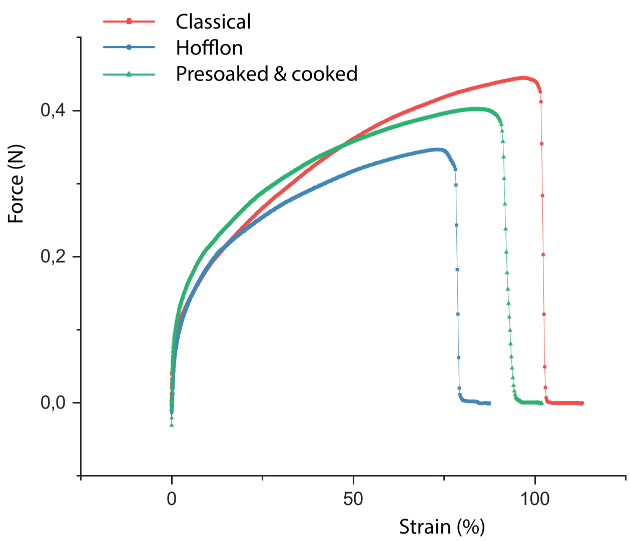

FIG. 7. Comparison of representative curves from force–strain experiments.

cooking method exhibits the lowest difference of the peak height with 0.6 N, while the presoaking techniques demonstrate the highest difference of 0.85 N. The hofflon method maintains an intermediate hardness of 0.75 N. This shows that the different preparation methods change the molecular structure distinctly.

TABLE IV. The extracted values from tensile curves for the differently prepared pasta.

	$\mathbf{B_1}$	F_{max} (N)	$\mathbf{e_1}$ (%)	$\mathbf{e_2}$ (%)
Classical	0.60 ± 0.03	0.43 ± 0.03	105 ± 12	6.9 ± 2.3
Hofflon	0.07 ± 0.03	0.33 ± 0.02	85 ± 12	12.9 ± 2.5
Presoaked and cooked	0.53 ± 0.25	0.36 ± 0.04	98 ± 11	12.8 ± 4.9

Moreover, the values of the gumminess, GUM, and chewiness, CHW, show a significant differences. The gumminess describes the force (and relative energy) to disintegrate foods, whereas the chewiness is associated with the force and energy to process the food in the mouth. The gumminess appears to be with 2.5 N higher for traditionally cooked but significantly lower for hofflon and presoaked and cooked pasta as shown in Table III. The results indicate that traditionally cooked pasta exhibits a more pronounced *al dente* behavior than other preparation methods, since more oral processing steps are required to break down the noodles in the mouth. This assertion is corroborated by the chewiness, which is also considerably higher for traditionally cooked pasta than for alternative, energy saving methods. The chewiness of traditionally cooked pasta is 2.4 ± 0.2 J higher compared to presoaked and cooked pasta and 1.8 ± 0.4 J compared to hofflon pasta.

The springiness, SPG, allows us to quantify the extent of the structural damage after the initial deformation cycle in a different

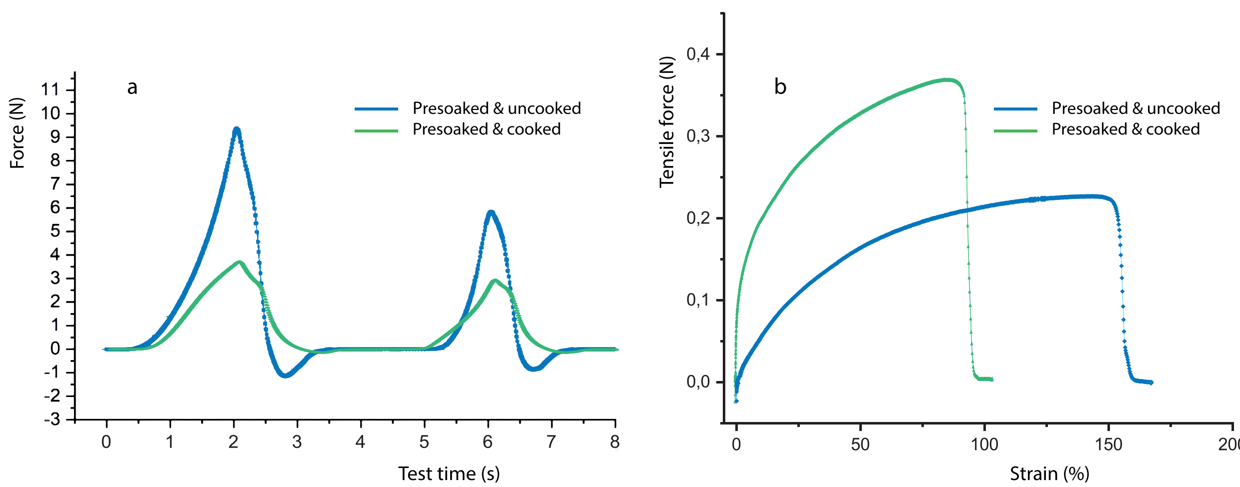

FIG. 8. Direct comparison between the soaked uncooked and the soaked and cooked pasta. (a) TPA tests and (b) tensile experiments, both in the same scales.

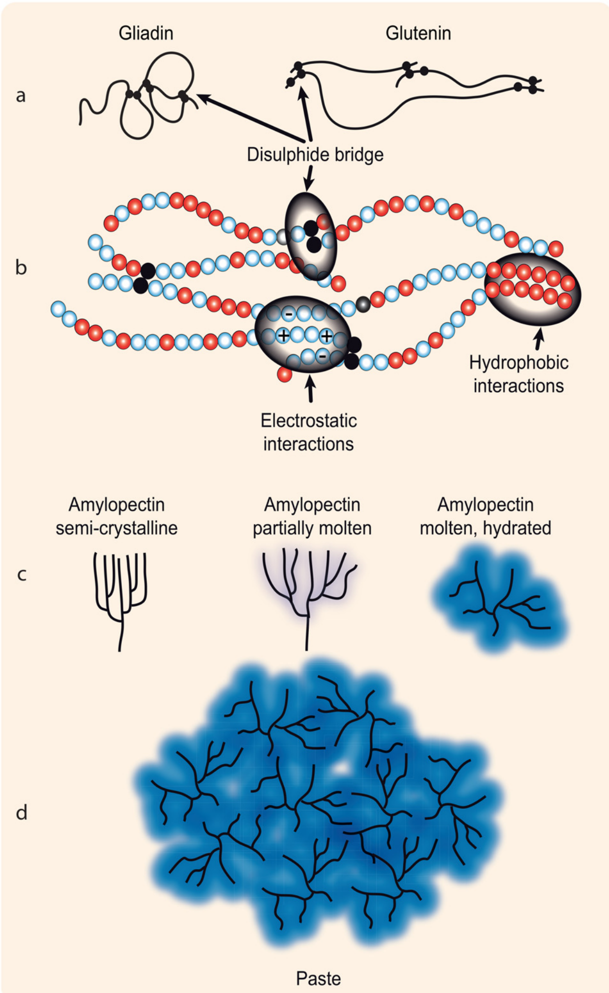

FIG. 9. Simplified sketch of the processes in pasta during cooking. (a) The main components from gluten are self-cross-linked gliadin and glutenin, which cross-links under heating by forming disulfide bridges at temperatures $T > 65 - 70\,^{\circ}$C. (b) Glutenin interacts as well by electrostatic and hydrophobic interactions. (a) Amylopectin is partially crystalline but melts above temperatures $T > 65\,^{\circ}$C and takes up water. (d) Visualization of a fully developed amylopectin paste, when different amylopectin molecules form a highly concentrated solution.

view. Indeed, the deformation ratio d_2/d_1 becomes successively smaller for the alternative cooking methods, namely, hofflon and presoaking and cooking, at least as a trend when their mean values are considered. This indicates that the differences in the force maximum result in higher damages in the structure of the cooked pasta. Additionally, the stringiness, STG, appears to be the highest for the presoaking and cooking method. Given that the distance d_3 represents the basis for the area of adhesion energy, it seems reasonable to conclude that components of the material (either starch or proteins) that contribute to adhesion are no longer responsible for maintaining the viscoelastic structural properties.

In consequence, the results from the TPA experiments suggest that hofflon pasta is slightly softer and mushier than traditional pasta, whereas presoaked and cooked pasta is much more stickier in the mouth. To gain further physical insight, it is beneficial to integrate these findings with those from the tensile experiments.

C. Tensile experiments

The wide dispersion of the stress–strain curves is considerable due to the heterogeneous nature of commercially produced pasta. However, a systematic examination of the different preparation methods makes it possible to identify significant differences. Figure 7 shows representative stress–strain curves illustrating the main differences between the preparation methods. The mean values for the parameters introduced in Fig. 3 and Table II extracted from the different measurements are listed in Table IV. The values for B_1 can be regarded as a rudimentary indicator of the transition from the linear (neo-Hookian) deformation regime.[38] It is notable that the hofflon cooked pasta exhibits the far lowest value, while the traditionally cooked pasta and the presoaking method are nearly identical. Given the other results obtained so far, this seems to be contradictory. Nevertheless, it indicates already that the hofflon methods increase the contribution to the plastic deformation at linear extension. Obviously, more starch grains are able to gelatinize under the longer cooking time for the hofflon method. In the traditionally cooked pasta, this is not the case. Consequently, it appears more resistant to deformation in the neo-Hookian regime, which is consistent with the behavior of the maximum forces F_{max} and the fracture strain elongation$_1$, called e_1 in Table III. The maximum force F_{max} is highest for the traditionally cooked pasta (0.43 N) and lowest for the hofflon case (0.33 N), whereas the presoaked and cooked pasta shows a value in between (0.36 N) at least in the trends. The elongation force maximum behaves similarly. The traditionally cooked pasta shows the highest deformation, e_1, while the hofflon pasta shows the lowest. The presoaked and cooked pasta is in between.

In addition, the elongation e_2, which describes the deformation corresponding between the maximum force and the final rupture of the pasta, is with about 7% lowest for the traditionally cooked case, and with about 13% larger for the two other preparation methods. Moreover, the visible negative slope in Fig. 7 for differently cooked pasta shows trends for all measurements. Generally, the classically cooked pasta shows the steepest decrease (slope $\approx$ 0.014), the hofflon pasta shows a lightly less steep decrease (slope $\approx$ 0.017), whereas the presoaked and cooked pasta shows with $\approx$ 0.036 least negative slope.

To understand the physics better, the different physical changes of the involved molecular components—water, starch, and protein—need to be considered. It is thus necessary to compare the tensile experiments for the soaked but uncooked and the cooked pasta directly. As already mentioned in Sec. II, proteins and starch react differently on water and temperatures. The glassy protein phase in dried wheat (durum) pasta can be rehydrated at room temperatures and undergo a glass-to-rubber transition, whereas the starch gelatinizes only at higher temperatures. Therefore, it is tempting to investigate the difference between presoaked uncooked and presoaked and cooked pasta first, as shown in Fig. 8. The results provide further definitive evidence to support the theories previously proposed and offer a deeper understanding of the distinct roles played by proteins and starch in the formation of the final pasta structures and, consequently, in the oral behavior. The TPA experiments demonstrate that the uncooked samples exhibit greater hardness than the cooked samples. This suggests

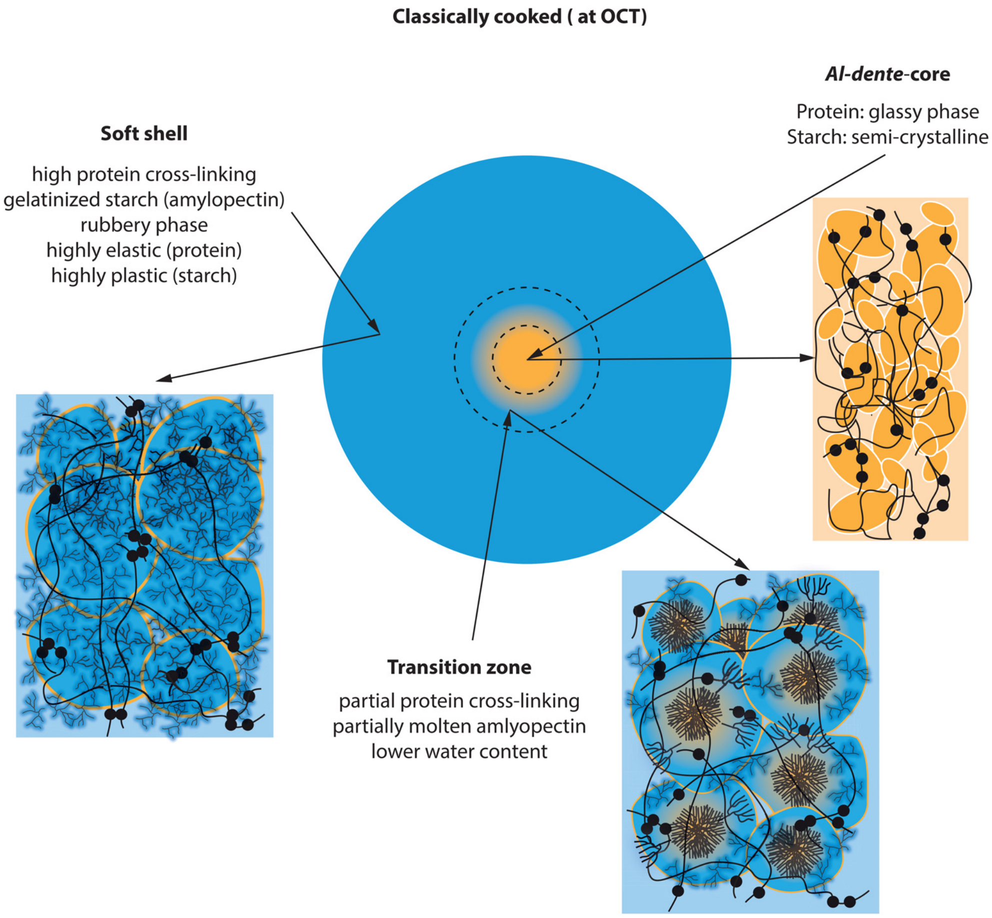

FIG. 10. A simple cartoon of traditional cooked pasta at the optimal cooking time with an *al-dente*-core in the center, which consists of a glassy protein phase, drawn as black lines with circles at the ends, which correspond to cysteine, which forms cross-links under heat. The core contains also practically native, hard, native starch grains shown by orange ellipses. The cooking process is gradual, and water diffuses toward the inside. In the outer rubber-like shell, most of the proteins are cross-linked, and the starch is completely gelatinized and binds water. In the transition zone, the water content decreases gradually. As a consequence, the molecular motion ceases, proteins are less cross-linked, starch grains are not swollen, and amylopectin melts only partially, but remains partially crystalline. The exact state depends on the distance from the glassy/semi-crystalline core.

that the hard starch particles are the primary determinant of hardness in the compression experiments. In contrast, the uncooked samples exhibit significantly lower forces compared to the cooked specimens, which suggest the flow behavior of transient, uncross-linked proteins. This is further supported by the observation of a considerably higher fracture deformation in the tensile experiments. Furthermore, the discrepancy of approximately 2.6 N between the maximum force of the initial and subsequent peaks in the TPA curves of the soaked but uncooked sample indicates an inadequate level of cohesion in the just-soaked pasta. Furthermore, the adhesiveness, defined by the area of the very pronounced minima in the TPA experiment, is significantly greater for the soaked and uncooked pasta compared to the cooked samples. It is evident that cross-linking reduces the high stickiness, although it remains still higher than that observed in traditionally cooked and hofflon case.

In summary, the experimental results indicated that classically cooked pasta exhibited greater resistance to deformation, suggesting a harder and firmer texture. The lower cohesiveness during breakdown, visualized by the elongation e_2, and the higher chewiness and gumminess indicated a "crunchier" texture during chewing. In contrast, the hofflon pasta is observed to be softer, stickier, and mushier. These results indicate that, depending on the physical parameters used as a reference, the presoaked and cooked pasta exhibits similarities with hofflon pasta or acts as an intermediate. This apparent contradiction between the TPA results in the hardness, see Table III, and the aforementioned trend in the tensile experiments is, upon closer examination, revealed to be superficial, as will be seen when the experimental results will be jointly discussed in a simplified interpretation of the structural changes on the molecular level.

V. MOLECULAR INTERPRETATION

These experiments allow to develop simplified models of the structural differences. Of particular importance is the mixture of glutenins present in wheat protein, as they are long, not significantly cross-

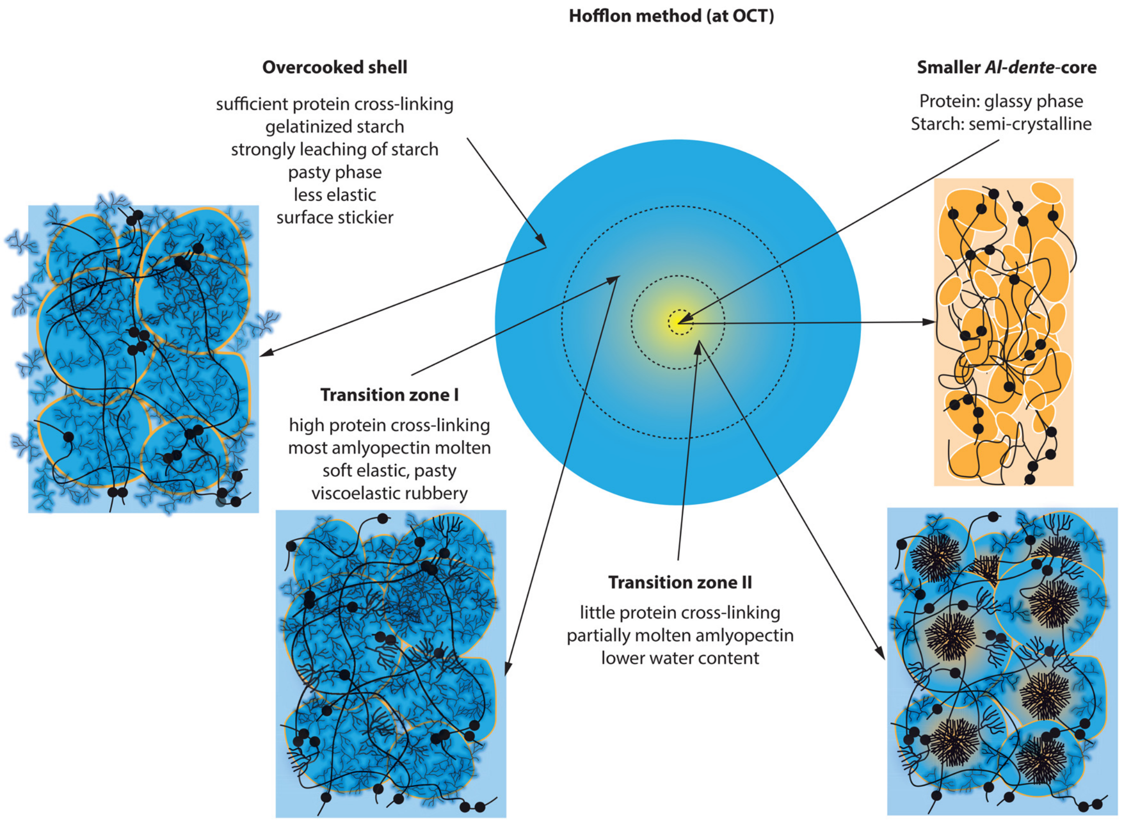

FIG. 11. Simple model of the hofflon cooked pasta. The outer shell is opposed to hot water for longer times, which corresponds to a slight overcooking. The *al-dente*-core is thinner caused by the longer heating time at temperatures enabling protein cross-linking and starch gelatinization. Two transition zones can be assigned, zone II close to the core. Overcooking at the surface induces the onset of starch leaching, which makes the outer shell softer and more pasty. Transition zone I resembles the outer shell of the traditional pasta, whereas transition zone II corresponds to the transition regime or classically cooked pasta.

linked, and capable of forming permanent cross-links between their chain ends through the formation of widely meshed rubber-like, swollen gels. Starch in grains shows a defined multi-scale structure, but does not cross-link permanently.[9,39] The main component is highly branched amylopectin, which forms highly viscous pastes, but binds large amounts of water, when the crystalline parts amylopectin melts and water can be taken up by hydrogen bonds with the OH-groups of the glucose monomers. Starch grains break up, amylopectin gets released and gelatinizes. Linear amylose chains rearrange, bind water as well, and gain entropy during cooking, but will play a minor role to structural changes compared to the branched amylopectin. For convenience, the processes relevant for the following are depicted in Fig. 9.

A. Traditional pasta cooking method

When pasta is immersed in boiling water, the noodles adopt the temperature quickly and water transport starts immediately.[40] The proteins undergo a fast glass-to-rubber transition. The starch melts, swells, and gelatinizes quickly, and simultaneously the transient protein network cross-links. At the optimal cooking time, the pasta appears *al dente*, in the center of (ideally) each spaghetti remains a core of amorphous proteins and still crystalline starch.[9]

As shown in Figs. 5 and 7, the classically cooked pasta shows the highest hardness, the highest $F_{\max}$, and the largest deformation e_1. This phenomenon can be attributed to the high cross-linked state of the outer regions and the sufficiently gelatinized starch, which facilitate extensive deformations even in the absence of support from the glassy, semi-crystalline core, as sketched in Fig. 10.

The high and fast protein cross-linking rates in steadily boiling water at the outer (surface) region prevents accumulation of starch grains and their extended leaching. Therefore, the traditional cooked pasta appears less adhesive and thus less sticky, despite the high water content, at least for the OCT. However, the overcooked pasta will become more adhesive, sticker, and mushier, mainly due to kinetic effects, hydrolysis and diffusion of (linear) starch.[25]

B. Hofflon method

During the hofflon preparation, the temperature decreases from about 95 °C to about 80 °C, which is still higher as required for protein cross-linking and starch gelatinization. This suggests that, at the outset, it may be anticipated that comparable processes will occur at the molecular level as in the traditional case. Nevertheless, the kinetic energy decreases about $20\, k_B T$, resulting in a longer OCT. Therefore,

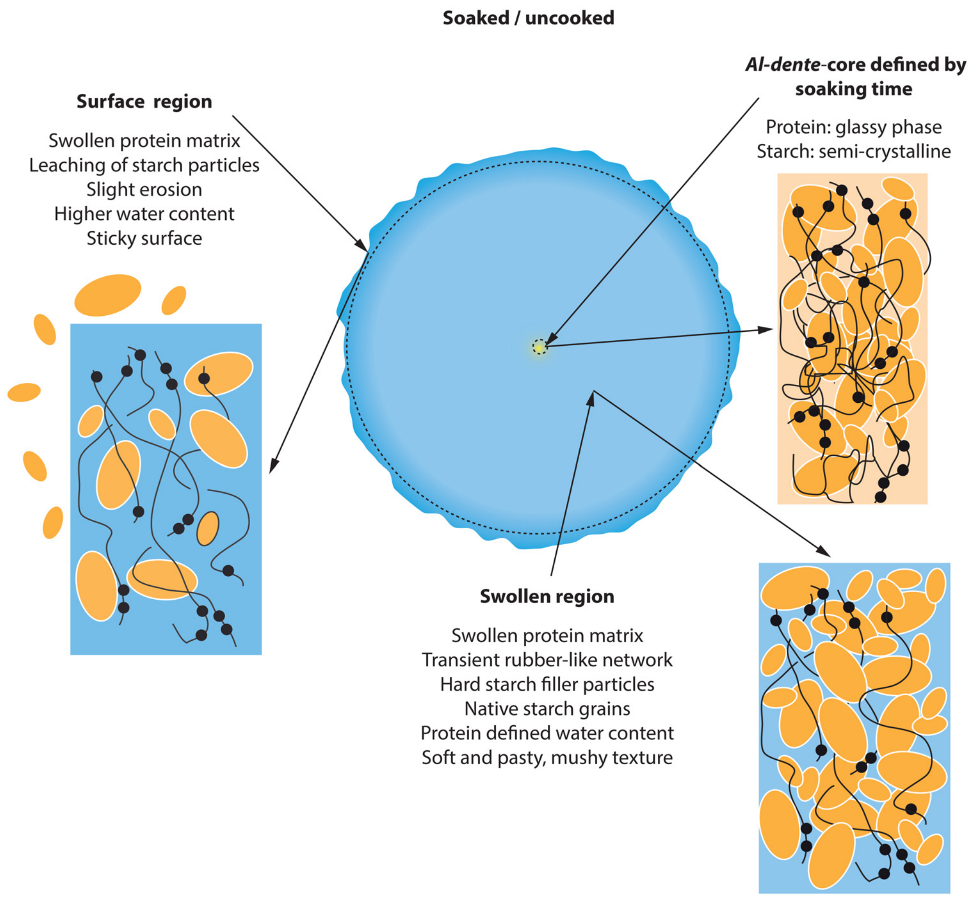

FIG. 12. Simple model of the soaked but uncooked case. The long contact with water softens the pasta strongly. Increasing water turbidity indicates the leaching of insoluble, hard starch grains from the perimeter of the pasta. Thus, more water can swell the initially amorphous protein glass. Mobile proteins with hydrophobic, polar, and charges exposed to then surface induce stickiness. The surface becomes more irregular, but with higher water content compared to the inner regions, where the swelling ratio is determined mainly by the hydrophilic fractions of the proteins. The diameter of the remaining glassy and semi-crystalline is determined by the soaking time.

it can be expected that the transition zone between the soft shell and the beginning of the core region becomes wider, whereas the *al-dente*-core size decreases, which results in a less pronounced *al dente* behavior as suggested by the experiments shown in Fig. 5 and Table III.

The hofflon preparation gives thus rise to two transition zones, as can be concluded by the enhanced difference of the maximum force of the two peaks in the TPA two-bite-cycle. The first is the intermediate state between the soft viscoelastic outer shell and the beginning of the core region compared with the outer rubber-like shell of the classical cooked pasta. The second zone closer to the *al-dente*-core corresponds to the transition zone of the traditionally cooked pasta as indicated in Fig. 11.

Due to the slight overcooking of the outer parts and the appearance of the two transition regimes, the cohesiveness seems to be reduced. The slight reduction in cohesiveness observed for the hofflon, coupled with the emergence of visible adhesiveness in a majority of hofflon experiments, suggests the onset of starch leaching. This results in the presence of more soluble starch at the surface and the surrounding water, which is subjectively visible in higher turbidity at the OCT. Consequently, the hofflon cooked pasta presents itself as exhibiting a slightly higher degree of stickiness and viscosity in the oral cavity, despite a comparable degree of cross-linking as in the traditional case.

C. Presoaked and cooked

This method is particularly instructive for the physics, although it presents the least favorable results in terms of texture and mouthfeel. The advantage is that soaking in cold water acts only on the proteins, initial rehydration, and temperature effects. This allows for the glass-to-rubber transition and protein cross-linking/starch gelatinization to be considered separately. Therefore, the results of these tensile tests provide useful physical information and allow further understanding.

The extraction of the maximum forces F_{max} and the elongation e_1 from these experiments provide clear evidence of the different physical processes involved. The presoaked, uncooked pasta shows with $F_{max} = 0.24 \pm 0.05$ N significantly lower forces than the same samples but cooked with $F_{max} = 0.36 \pm 0.04$ N. The elongation for the uncooked, presoaked samples can be with a value $e_1 = 160 \pm 23\%$ extended much wider than the cooked version with $e_1 = 98 \pm 11\%$.

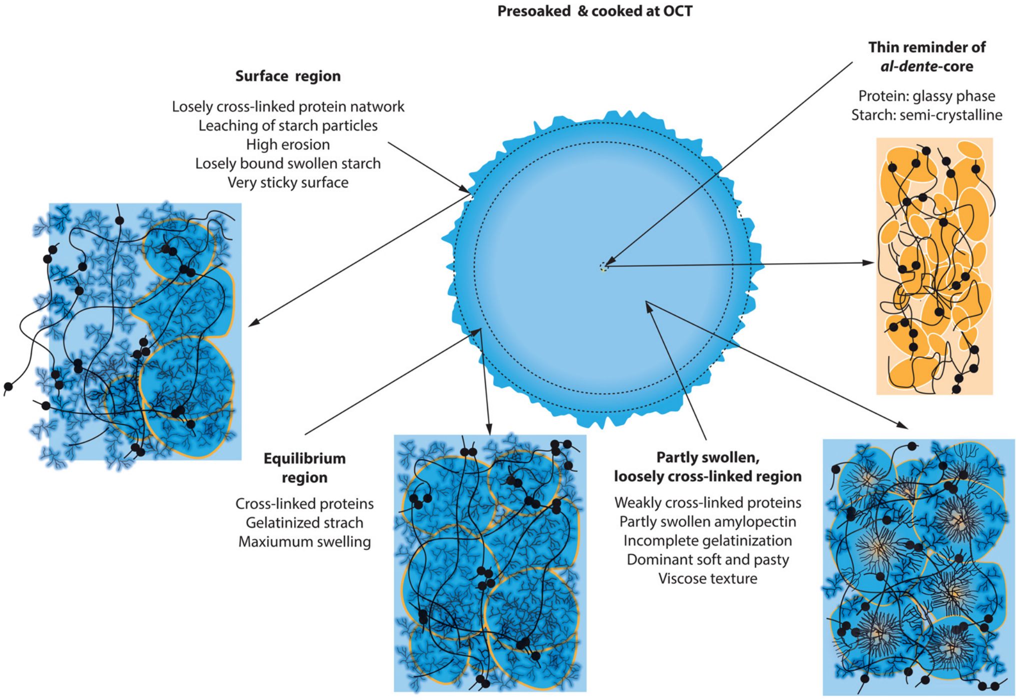

FIG. 13. Simple model for the presoaked and cooked case. The outer region shows a very sticky behavior. Loosely linked amylopectin, amylose (not drawn), and uncross-linked, dangling proteins cause high adhesion and a mushy surface. The highly cross-linked and gelatinized layer just below the surface is fully gelled and blocks further water transport into the pasta. The region to from the gel to the thin remnant of the core is incompletely cross-linked and not fully swollen, because the water content by the previous soaking is not sufficient.

These experimental results indicate that the uncooked soaked pasta can be viewed as a swollen, uncross-linked protein network, filled with reinforcing hard starch particles.[10] As shown in Fig. 9, the proteins interact among themselves by entanglements, electrostatic, and hydrophobic interactions, which define an elastic contribution in the tensile experiments via physical cross-links.[4] Furthermore, the proteins interact with starch particles at their surfaces. As the applied force increases, the proteins deform, and some of the physical cross-links open successively according to their binding energy. This phenomenon is associated with the bending point, B_1, which appears at much lower strains compared to the cooked samples, as shown in Fig. 8. As the force–strain experiments show, the uncooked soaked pasta appears very mushy (although in the mouth when orally tried). These results can be summarized in a naive model shown in Fig. 12. Heating the presoaked pasta has two effects. First, the formation of cysteine disulfide bridges permanently cross-link the high and low molecular weight glutenin at the ends. As a result, the elastic modulus increases significantly. On the other hand, the protein network can no longer be deformed to the same extent as the transient swollen protein gel before heating. As a result, the modulus increases with decreasing deformability and fracture occurs earlier. On the contrary, the crystalline starch melts, swells under water absorption, and gelatinizes. The hard filler thus becomes a soft, quasi plastically deformable matrix that acts as a "soft plasticizer" during deformation.

Surprisingly at first glance, the 1.5 h soaking and 3 min cooking time results in a lower moisture content compared to the traditional and hofflon cooked pasta, as shown in Fig. 4. This is easy to understand on a molecular level. During soaking, the water only rehydrates the amorphous protein matrix, but has no effect on the starch grains. However, the water diffuses through the entire volume of the pasta. Therefore, the hydrophilic nature of the proteins mainly defines the equilibrium concentration inside the pasta. However, water is known to have a high specific heat capacity and heat conduction, thus reducing the cooking time. On the other hand, the partially crystalline starch grains melt, swell, and gelatinize first in the outer areas, close to the surface of the pasta. At the same time, the proteins cross-link permanently. This quickly forms an equilibrium gel at the outer parts of the pasta, blocking water diffusion deeper in the pasta while allowing heat to diffuse further inside. The starch melts and gelatinizes according to the lower water content defined by the soaking process. As a result, the gelatinization process is not complete, the moisture content remains lower, and the protein network and incompletely gelatinized starches appear more adhesive, stickier, and mushier. A sketch of these ideas is presented in Fig. 13. Additional effects happen at the surface. During the extended exposure in time to the cold water, the starch grains form the surface region leach to the water, making space for the proteins. The hydrophilic parts of the mainly unstructured glutenin gain in dynamics, which prevents the surface proteins to cross-link completely within the equilibrium gelatinized remaining starch. Thus, the surface of the soaked pasta may show more free parts of the proteins as well as starch. These molecules are likely to contribute to the significant high adhesion as shown in Table III. The comparable value for the hardness of presoaked and cooked and traditionally cooked pasta can be drawn just to the result of the significantly reduced moisture content shown in Fig. 4.

The resulting unpleasant mouthfeel is also expressed by the reduced springiness, the higher stringiness, and the low chewiness in the TPA experiments. The different structure of the presoaked and cooked pasta is supported by the largest difference in the force maxima in two TPA cycles, the lowest water content, and the "soft fracture" expressed by the tensile experiments. This pasta shows from the three methods the least resistance in the mouth; the structure is easily destroyed.

VI. CONCLUSION

While alternative methods undoubtedly conserve energy, about 60% for the hofflon method and 40% to 50% for the presoaking technique, this benefit is accompanied by considerable losses in texture and, consequently, in flavor and mouthfeel. In addition, the surface properties of the pasta exhibit marked differences, resulting in modified adhesion of pasta sauces due to underlying physical principles. Nevertheless, a straightforward technique allows for the preparation of perfectly *al dente* pasta while conserving energy. The rolling boil of a large amount of water required in many instructions is primarily a means of preventing the pasta from sticking together due to the strong convection caused by a significant amount of water movement. By replacing the rolling boil with hand stirring, the amount of water can be reduced by up to 90%. Additionally, readily prepared sauces can be added just before the OCT, the "*al dente* time," offering further benefits. The leached starch (and proteins) contribute to a creamy texture of the sauce, enhance the taste by the previously added salt, and facilitate a perfect adhesion of the sauce at the noodle surface. This might be a delicious compromise.

In addition to these considerations pertaining to the culinary aspects of pasta, these insights have also facilitated a more profound understanding of the physical interactions between proteins and starches in pasta. It is noteworthy that these concepts are not exclusive to noodles but are rather pertinent to a broader range of grain-based foods and their processing.

SUPPLEMENTARY MATERIAL

See the supplementary material for the complete experimental details are presented. I. Change of cooking temperature during hofflon cooking (only mean values are presented in Table I of the supplementary material). II. All different graphs which show the scattering of the experimental data concerning the texture analysis experiment. The wide data scattering is caused by the large heterogeneity in the pasta, even between individual noodles (Fig. 1 in supplementary material). III. All graphs of the tensile tests are shown in Fig. 2 in the supplementary material. This illustrates the choice of the typical curves which have been shown in, for example, Figs. 3, 12, and 13. IV. All experimental results for the tensile experiments of presoaked uncooked and presoaked and cooked samples and the choice how typical curves emerged from the experiment referred to Fig. 8.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Phillip Toultchinski: Conceptualization (equal); Data curation (equal); Investigation (equal); Software (equal); Writing – original draft (equal). **Thomas A. Vilgis:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Software (equal); Supervision (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The paper will have supporting additional information.

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