

Influence of High-Temperature Drying on Structural and Textural Properties of Durum Wheat Pasta

C. Zweifel,¹ S. Handschin,¹ F. Escher,¹ and B. Conde-Petit^{1,2}

ABSTRACT

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Starch and protein are the main polymeric ingredients of pasta and they determine the structural and textural properties of cooked pasta. The present investigation sought better understanding of the impact of high-temperature (HT) drying on the starch and the protein fraction, and their role in structure and texture of pasta. Durum wheat spaghetti was prepared in a pilot-plant installation. The drying conditions were selected for the HT phase at 80 or 100°C applied at high, intermediate, or low product moisture content. Spaghetti dried at 55°C served as a reference sample. The color of dry pasta was measured and the changes in the starch and protein fractions were determined by protein solubility, light microscopy, confocal scanning laser microscopy (CSLM), cooking tests,

and texture measurements. HT drying at 100°C and low product moisture promoted browning of pasta. At the molecular level, HT drying promoted protein denaturation. At the microscopic level, HT drying contributed to a better preservation of the protein network and reduced swelling of starch and disintegration of granules. At the macroscopic level, HT drying enhanced the firmness of cooked pasta and reduced surface stickiness. In general, the changes were more pronounced by increasing the drying temperature from 80 to 100°C and by shifting the HT phase from an early to a late stage of the drying process. The drying conditions are determinant for the phase morphology of protein and starch in cooked pasta which, in turn, govern the textural properties of pasta.

The structural and textural properties of pasta are influenced by several factors, the most important being the properties of the raw material and the drying conditions. In the past 20 years, low temperature (LT) drying at 40–50°C has been more and more replaced by high-temperature (HT) drying at 60–100°C. The main advantages of HT drying are increased microbiological safety, higher productivity, and improved textural properties of pasta. The latter aspect has stimulated the research on protein and starch transformation during drying and cooking of pasta (Resmini and Pagani 1983; Pagani et al 1986; Feillet et al 1989; Cunin et al 1995; Vansteelandt and Delcour 1998). While earlier studies focused on the cooking behavior and the textural properties as induced by HT drying (Dexter et al 1981), more recent investigations also emphasize the relationship between processing conditions, structure, and nutritional properties of starch in pasta (Fardet et al 1999). Besides texture, the color of pasta is also affected by HT drying. Increased yellowness may be due to partial inactivation of endogenous lipoxygenase, preventing carotenoid bleaching. On the other hand, HT drying at low product moisture content promotes the development of a red-brown color; the formation of melanoidins is related to advanced Maillard reaction (Abecassis et al 1984; Acquistucci 2000).

Pasta can be considered a mixed polymer system with starch and protein being the main structuring agents. The minimum formula for pasta production contains semolina (purified middlings of durum wheat) and water at a concentration of ≈ 30 g/100 g, wb. The main objective of adding water is the plasticization of wheat proteins that allows shaping of pasta by an extrusion or sheeting process. During the subsequent drying step, the product is stabilized by transforming it from the rubbery to the glassy state. During HT drying, both protein and starch transformations occur. A valuable tool for understanding and predicting polymer transformations as a function of temperature and moisture conditions are state diagrams such as those developed for gluten by Kokini et al (1994). These authors defined a protein reaction zone at $>80^\circ\text{C}$ and moisture contents >15 g/100 g, wb, where the proteins have enough mobility and reactivity to aggregate through cross-links. HT drying increased the extent of protein denaturation as detected by the solubility of gluten in acetic acid (Aktan and Kahn 1992).

The denaturation of wheat protein promotes cross-linking of the two gluten proteins, glutenin and gliadin, through disulfide bonds, which increases the rigidity of the protein network (Schofield et al 1983; Weegels and Hamer 1998). Likewise, Zweifel et al (2000) discussed the transformations of starch during HT drying based on a state diagram of starch. The temperature moisture conditions during HT drying favor an annealing of starch at limited moisture levels leading to molecular rearrangements of the starch polymers within the starch granules. Annealing refers to hydrothermal treatments at temperatures below the melting temperature (T_m) and above the glass transition temperature (T_g) of starch (Wunderlich 1976). In contrast to the general polymer literature, annealing at low moisture conditions is often called heat moisture treatment in the starch literature. Several authors found that annealing during HT drying of pasta increases the gelatinization temperature of starch (Cunin 1995; Vansteelandt and Delcour 1998; Yue et al 1999; Zweifel et al 2000). Investigations on hydrothermal treatments of pure starch show that large differences in the physical properties may be induced depending on the processing conditions, in particular the temperature, moisture, and time conditions (Jacobs and Delcour 1998).

During cooking of pasta, starch gelatinizes and proteins coagulate, generating the typical texture of pasta. The internal framework of pasta is characterized by a large structural difference between the external and the central zones. Optimally cooked pasta exhibits a pronounced gradient in moisture distribution, the water content decreases from 90 to 39 g/100 g, wb, from the outer layer toward the center (Conde 2001). The transformation of starch coincides with the inhomogeneous moisture distribution and varies from strongly swollen in the external zone to limited swelling in the center (Cunin et al 1995). The al dente texture is characterized by a rather soft but coherent external zone and a firm core that gives a certain level of cutting resistance (Frey 1970). By analogy to material science, pasta can be described as composite. Composites are characterized by mechanical properties that can not be achieved with the individual structuring agents alone but are dependent on the interface between the components (Kim and Mai 1993). There are indications that the adhesion strength between starch and protein increases during HT drying as the extractability of starch from pasta decreases during drying (Vansteelandt and Delcour 1998). This means that the structural and textural properties of pasta can not be viewed simply as the sum of protein and starch properties.

Numerous publications have investigated the influence of HT drying on the cooking behavior and textural properties of pasta. However, the influence of protein and starch transformations on

¹ Institute of Food Science and Nutrition, Swiss Federal Institute of Technology (ETH) Zurich, CH-8092 Zurich, Switzerland.

² Corresponding author. Phone: +41 1 632 37 31. Fax: +41 1 632 11 23. E-mail: beatrice.conde@ilw.agr.ethz.ch.

MATERIALS AND METHODS

Durum Wheat Semolina

Commercial durum wheat semolina was delivered from Swissmill (Zurich, Switzerland). According to the manufacturer, the durum wheat semolina consisted of a 55:45 mixture of Canadian Western amber durum and U.S. amber durum. The moisture content of the semolina varied from 10.8 to 12.5 g/100 g, wb, protein content from 13.9 to 14.3 g/100 g, db, and ash content from 0.76 to 0.84 g/100 g, db. The particle size distribution was 500 μm ($\approx 3\%$), 400 μm ($\approx 18\%$), 315 μm (25–35%), 200 μm (37–47%), and 125 μm ($\approx 3\%$).

Pasta Processing and Drying

Spaghetti was prepared by cold extrusion and subsequently dried as described by Zweifel et al (2000). Pasta was dried with high-temperature (HT) drying profiles with a maximum temperature of 80 or 100°C. High drying temperatures were applied in an early (eHT), intermediate (iHT), or late stage of the drying cycle (lHT). Pasta dried at low temperature (LT) (55°C) served as a reference sample. For all drying profiles, the relative humidity was kept constant at 80% rh and lowered to 60% rh during cooling. During drying, samples were collected at regular intervals and the moisture content was determined by drying ≈ 3 g of sample at 120°C for 10 min on an infrared balance (8LP16, Mettler-Toledo,

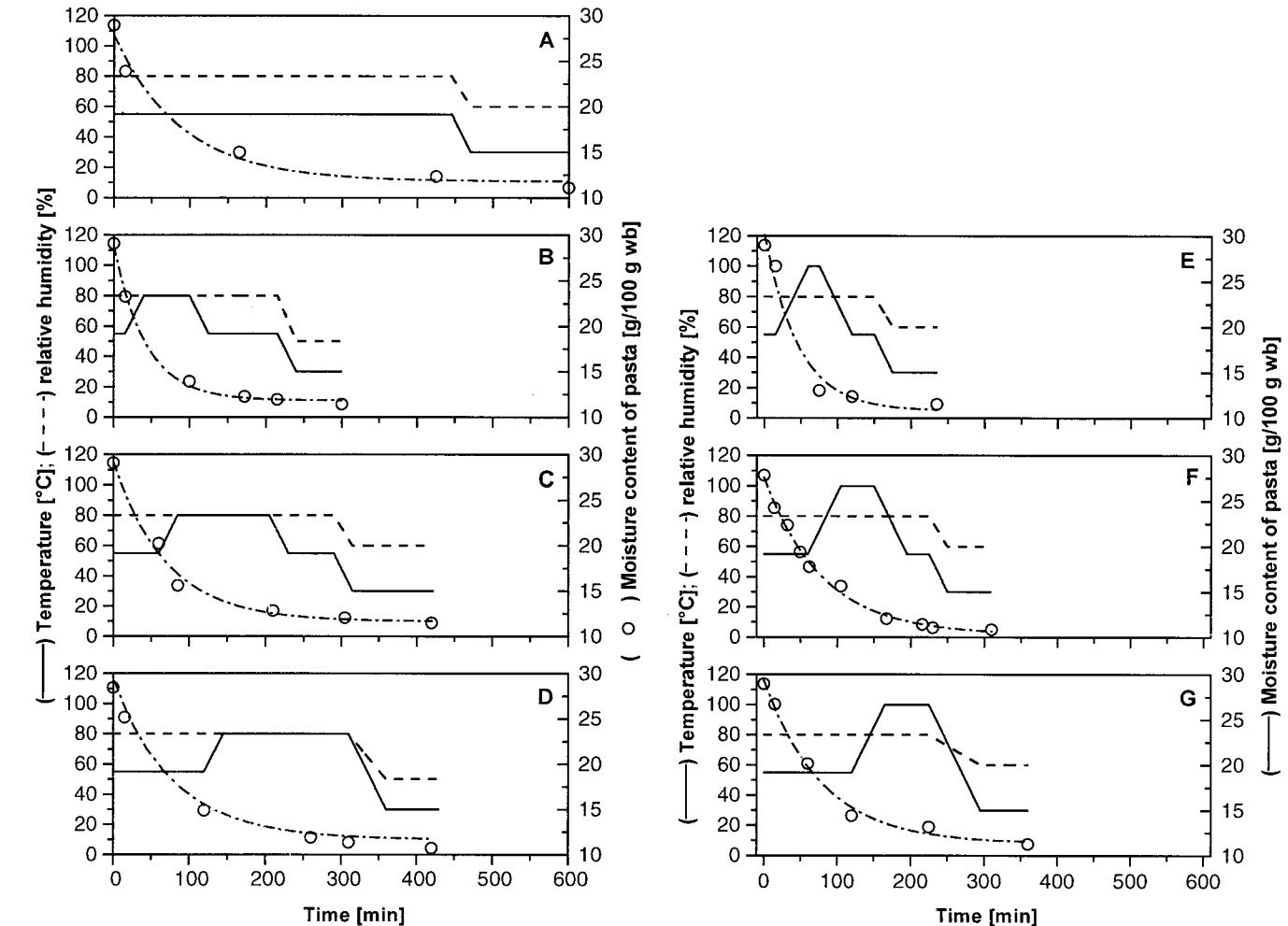


Fig. 1. Temperature-humidity profiles and drying curves during pasta drying: reference drying at 55°C (A) and high-temperature (HT) drying at 80°C and high (B), intermediate (C), and low moisture (D) conditions, and HT drying at 100°C and high (E), intermediate (F), and low moisture (G) conditions, respectively. Trend curves describing changes in pasta moisture content during drying are superimposed on experimental points.

Greifensee, Switzerland). The diameter of dried spaghetti was 1.63 ± 0.02 mm.

Color Measurements

Spaghetti color was determined with a Hunterlab color difference meter (ColourQUEST 45/0, Hunter & Caprez, CH Zumikon) by a method adapted from Walsh (1969). Dried spaghetti was cut into pieces ≈ 1 –2 cm and transferred to a beaker (13.5 cm diameter). To reduce the influence of daylight, the wall of the beaker was darkened with black paper. Four readings were taken for each filling and the beaker was rotated 90° between each reading. The results are presented on the CIE 1976 $L^*a^*b^*$ space and represent the average of three to five batches.

Determination of Gluten Denaturation

Gluten denaturation was determined by adapting the method of Pence et al (1953). Spaghetti (40–60 g) was first reduced to small pieces (Moulinette S, Moulinex GmbH, Solingen, Germany) and then milled to pass through a 0.5-mm mesh screen on a centrifugal mill (type ZW1, Retsch GmbH & Co, Haan, Germany). For determining glutenin extractability, 2 ± 0.005 g of milled pasta sample was weighed into a 50-mL plastic centrifuge tube with 40 mL of 0.5M acetic acid and extracted for 2 hr at setting 120 on a mechanical shaker (Bender and Hobein, Zurich, Switzerland). For determining gliadin extractability, 4 ± 0.005 g of milled pasta sample was extracted with 40 mL of 70% aqueous ethanol and adjusted to pH 5.5 with 0.05M acetic acid solution. After centrifugation (Avanti J-25 I Zentrifuge, Beckman, Palo Alto, CA) at $7,000 \times g$ for 45 min at 5°C , the supernatant was analyzed for nitrogen by the Kjeldahl method (Approved Method 46-10, AACC 2000). The results are expressed as the average of two determinations. The standard deviation of the soluble glutenin and gliadin content was $<1.5\%$ of the mean.

Determination of Cooking Properties

Spaghetti was cooked in deionized boiling water as described by Dürr and Neukomm (1973). The optimal cooking time (al dente point) was determined by compressing a spaghetti strand between two glass slides in 30-sec intervals. The optimal or al dente cooking point was reached when the white center of ungelatinized starch had just disappeared.

For determining the water uptake index, spaghetti was cooked to the al dente point. After cooking, the spaghetti was cooled by immersion in 600 mL of tap water at room temperature, thereafter, excess water was removed with a sieve. The weight of cooked pasta was registered and the dry matter content was determined by

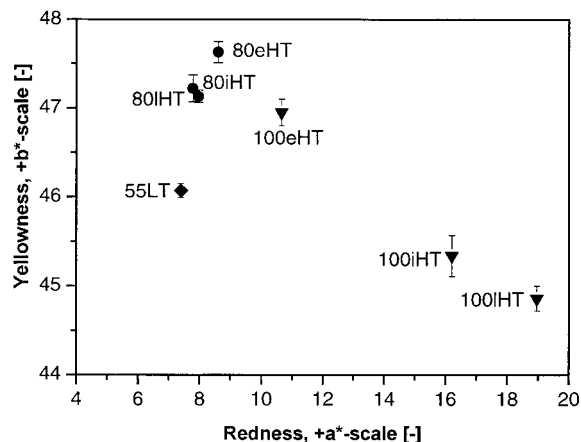


Fig. 2. Influence of high drying temperatures on redness (a^*) and yellowness (b^*) of spaghetti dried at different conditions. High-temperature (HT) drying applied in early (eHT), intermediate (iHT), or late stage (lHT); pasta dried at low temperature (LT) (55°C). Average and standard deviation of three to five batches, with four measurements each.

drying at 133°C for 90 min. The water uptake index (%) was calculated by relating the weight of cooked pasta to the dry matter content of cooked pasta. The results are expressed as the average of three to six determinations.

Bright-Field Light Microscopy

Spaghetti samples were cooked to the al dente point in deionized boiling water. The cooking process was stopped by transferring the samples into water at room temperature for 1 min. Spaghetti was cut into small pieces, covered (Tissue-Tek O.C.T. compound, Miles, Kankakee, IL), and then frozen with carbon dioxide. The samples were cut in a cryostat (Reichert-Jung, Leica, Vienna, Austria) at -20°C into sections $9\text{-}\mu\text{m}$ thick. The frozen samples were mounted on microscope slides that had been covered with a solution of glycerol and gelatin to improve the adhesiveness of the cryosections during staining. Protein was stained with aqueous light green solution (1 g/L, Fluka Chemie AG, Buchs, Switzerland) for 30 min, and starch was stained with iodine in a diluted (1:1, v/v) Lugol's solution (stock solution I_2 , 14 mM, KI, 44 mM, Fluka Chemie AG, Buchs, Switzerland) for 15–20 sec. After each staining step, the slides were rinsed in water. The samples were covered with a droplet of glycerol and water solution (1:1, v/v) and a cover glass before examining under the microscope. All sections were examined using an Axioplan photo microscope (Zeiss Ltd., Oberkochen, Germany). Data were recorded by a 3CCD camera (C5810, Hamamatsu Photonics, Hamamatsu City, Japan). Contrast and brightness were adjusted using the Adobe Photoshop software program.

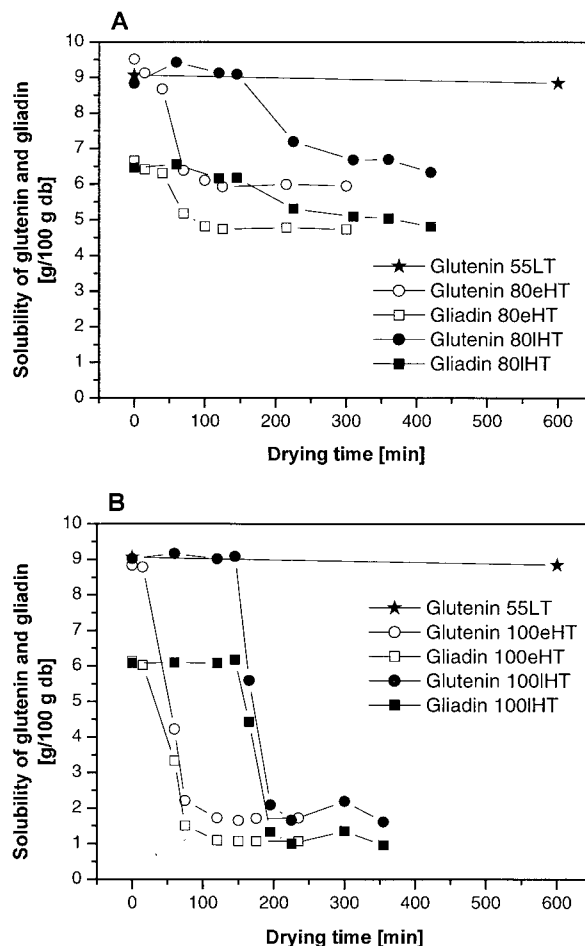


Fig. 3. Denaturation of glutenin and gliadin by drying at 80°C (A) and 100°C (B) as detected by the loss of protein solubility. High-temperature (HT) drying applied in early (eHT), intermediate (iHT), or late stage (lHT); pasta dried at low temperature (LT) (55°C). Average of two determinations.

Confocal Laser Scanning Microscopy

Spaghetti samples were cooked, frozen, and cut as described for bright-field light microscopy. Autofluorescence of the samples was removed by bleaching in 10 mL of aqueous solution of Heparin (500 iU/mL, Liquemin, Roche, Basel, Switzerland) for 30 min, followed by rinsing with deionized water for 30 min. The protein fraction was stained with 0.1% acid fuchsin (0.01 g of acid fuchsin in 1% acetic acid) (Sigma-Aldrich, Buchs, Switzerland) for 10 min. The images were recorded on a CLSM equipped with a Leica TCS-SP spectrometer mounted on a upright DM RXE fluorescence light microscope (Leica Lasertechnik GmbH, Heidelberg, Germany) in the epi-fluorescence mode. The samples were mounted on glass slides and covered with deionized water and a cover glass. Samples were illuminated with a Krypton laser at 568 nm; the emission maximum was 620 nm. The bandwidth for recording the fluorescence images was set from 600 to 620 nm. Approximately 40 images were recorded per stack, covering a depth of ≈ 40 μm in the sample. The conversion from stack to projection pictures were processed with the NIH Image shareware program (National Institutes of Health, Bethesda, MD). CLSM images were digitized at 1024×1024 pixels.

Instrumental Texture Determination

Firmness and relative depth of penetration of spaghetti samples were determined with a cutting test adapted from Dürr and Neukom (1973). Pasta was cooked to the al dente point and cooled in water at room temperature for 1 min. Instrumental characterization was made using a Zwick universal testing machine (model 1445, Zwick, Ulm, Germany). A “dental” or blade type tool (13 mm wide, 1 mm thick) was lowered into the sample at constant speed of 200 mm/min. The maximal penetration force and the relative penetration depth at a load of 0.1 N were evaluated. The results are expressed as average of 20 measurements.

To determine pasta surface stickiness, spaghetti was cooked for 1 min longer than the al dente point and excess water was removed by shaking in a sieve for 15 sec. The samples were kept for exactly 5 min in a covered beaker before measurement. Then they were aligned side by side on a grooved plastic pad and compressed using a circular brass plate (9.7 cm diameter) with a speed of 10 mm/min. Once a compression force of 80 N was reached, the deformation was kept constant for 2 sec and the plate was subsequently retracted from the sample at a speed of 6 mm/min. The tensile force during separation of the probe from the sample was recorded, and the area under the curve was evaluated as a measure of stickiness. Results are expressed as average of five to eight determinations.

RESULTS AND DISCUSSION

Pasta was dried with seven different drying profiles (Fig. 1A–G). Samples dried at low temperature (55°C) served as reference. The main difference between different HT drying profiles was the time at which the HT phase, with a maximum at 80 or 100°C , was applied and the duration of the respective HT phase. In all drying cycles, an early (eHT) phase reduced the product moisture content from 27 to 13 g/100 g, wb; an intermediate (iHT) phase from 20 to 13 g/100 g, wb; and a late (lHT) phase from 15 to 13 g/100 g, wb. The final moisture content of spaghetti was 11.2 ± 0.16 g/100 g, wb. Depending on the drying temperature, the total drying time varied from 4–10 hr. Thus, the applied drying profiles do not allow total separation of the effects of temperature and time.

Visual inspection of the spaghetti showed that all samples were free of cracks, and no crack formation was found during a five-week storage period. HT drying had an influence on the color of pasta as shown in Fig. 2. All drying profiles at 80°C (80eHT, 80iHT, 80lHT) and drying at 100°C with an eHT phase (100eHT) led to a small but significant increase of yellowness compared with the reference dried at 55°C (LT). Drying at 100°C increased pasta redness in the order $100\text{eHT} < 100\text{iHT} < 100\text{lHT}$. The results agree well with literature data (Abecassis et al 1989; Acquistucci 2000) and confirm that moderate HT drying conditions increase the yellowness, most probably due to a partial inactivation of lipoxygenase. Drying at 100°C promotes the Maillard reaction and the formation of red-brown melanoidins if HT is applied at low moisture levels.

Protein Fraction Changes During Drying

The extent of protein denaturation during HT drying of pasta with eHT or lHT phases, as determined by glutenin and gliadin solubility, is presented in Fig. 3 for drying at 80 and 100°C . During drying at 55°C for 10 hr (55LT), almost no changes in the extent of glutenin denaturation occurred. The sum of the gliadin and glutenin content is 15.5%, which is slightly higher than the total protein content of semolina (14.3%). This is most probably due to an incomplete separation of the two proteins, that is to a partial coprecipitation of gliadin and glutenin during the separation process. For all HT drying profiles, the solubility values remained fairly constant during the predrying phase at 55°C . From the point where the temperature was raised to 80 or 100°C , a decrease of glutenin and gliadin solubility was observed, the decrease being more pronounced for drying at 100 than at 80°C . Drying at 80°C

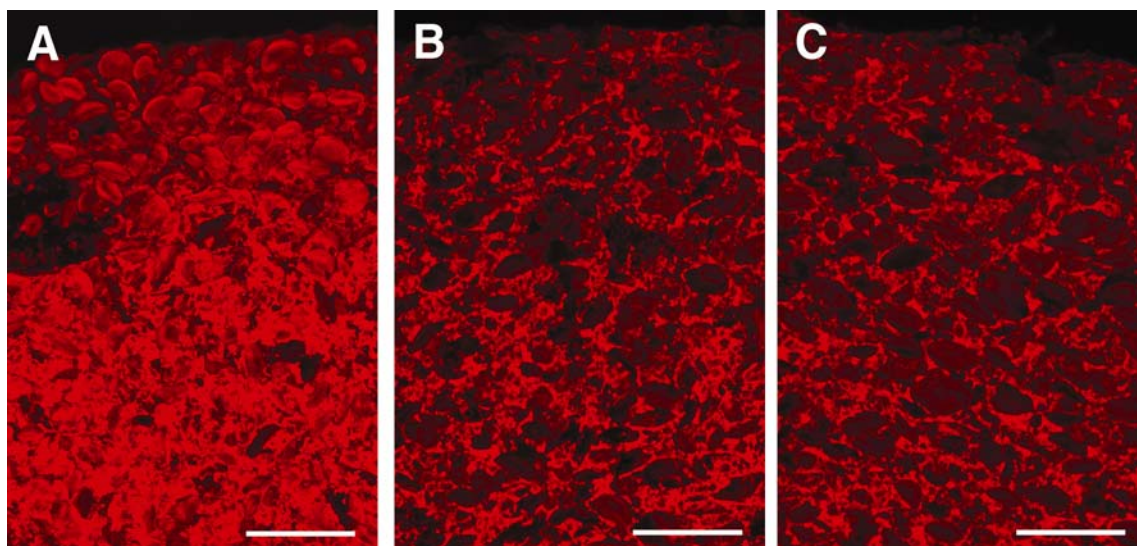


Fig. 4. Confocal scanning light micrographs of the outer layer of dry pasta dried at 55°C (A), with early (eHT) drying at 100°C (B), and late (lHT) drying at 100°C (C). Scale bar = 25 μm .

reduced the extractability of glutenin and gliadin by 35 and 25%, whereas drying at 100°C reduced the soluble protein content by 90 and 65%, respectively. Drying at eHT and IHT phases resulted in similar denaturation rates during the HT phase and similar levels of protein solubility at the end of drying.

These results confirm earlier studies that found that the extractability of gluten proteins, in particular that of the glutenin fraction, decreases on heating at 80°C (Pence et al 1953; Schofield et al 1983; Aktan and Khan 1992; Weegels and Hamer 1998). The finding that drying pasta at 55°C did not induce significant protein denaturation, whereas drying at 80 and 100°C promoted the denaturation of wheat storage proteins, agrees with the state diagram of wheat storage proteins established by Kokini et al (1994). The reduced solubility of wheat storage proteins in HT drying of pasta can be explained by an enhanced aggregation of the denatured proteins.

The microstructure of the protein phase of spaghetti dried at different conditions was investigated by confocal laser scanning

microscopy (CLSM). The micrographs of spaghetti dried at 55°C and of spaghetti dried with an eHT and a IHT phase at 100°C are shown in Fig. 4. The protein fraction was stained with acid fuchsin and the images were recorded in the epi-fluorescence mode. The images present the projections of all slices of optical sections and show the outer zone of cross-sections of dried spaghetti. Control experiments confirmed that the autofluorescence of wheat was completely removed by bleaching with Heparin (micrographs not shown). The bright red phase on the micrographs corresponds to the protein network, whereas the dark areas reflect the location of the starch granules.

The starch granules are fully encapsulated by a dense and continuous protein network. Unexpectedly, in spaghetti dried at LT (Fig. 4A), the starch granules are also clearly recognizable, in particular in the outer layer, although acid fuchsin does not stain starch. In pasta dried at HT (Fig. 4B and C), a continuous protein phase is visible, and the space occupied by the starch granules is only slightly contrasted.

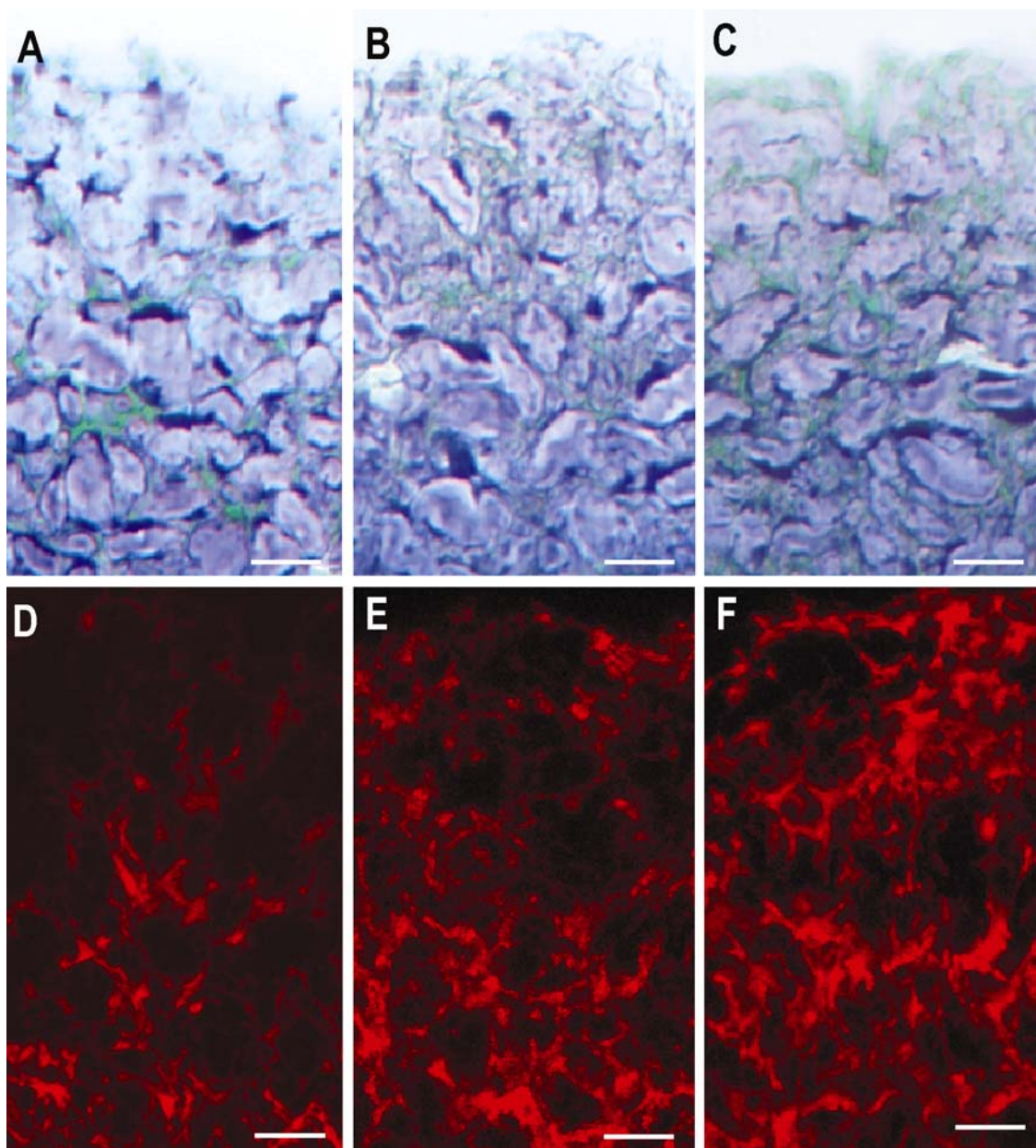


Fig. 5. Light microscopy (upper row) and confocal scanning laser microscopy (CSLM) (lower row) of the outer layer of al dente cooked pasta dried at 55°C (A and D), early drying at 100°C (B and E), and late drying at 100°C (C and F). Scale bar = 25 µm.

It is conceivable that in pasta dried at LT, the surface proteins of starch granules (Seguchi and Yoshino 1999) contribute to the visualization of the starch granules. In contrast, in pasta dried at HT, the starch granules are not visible; most probably because the thermal treatment induces a slight swelling of the starch granules and thus a disruption of the surface protein layer. A slight swelling of the starch granules in pasta dried at HT is confirmed by the morphology of the dispersed starch granules that appear elongated compared with the round granules in pasta dried at LT. This morphological transformation of starch during heating of pasta has also been described by Thorvaldsson et al (1999). The continuity of the wheat protein phase is not lost during HT drying, but it is reasonable to assume that two factors contribute to a decrease in volume of the gluten phase of pasta dried at HT in contrast to pasta dried at LT (55°C): 1) a slight swelling of the dispersed phase (starch granules), and 2) the denaturation of gluten proteins that involves a contraction of the network.

Microstructure of Cooked Pasta

The characterization of the microstructure focused on the external and intermediate zones of cooked pasta, which are sensitive to changes of the polymeric ingredients. Figure 5 shows micrographs of cryosections of the external zone of spaghetti dried at different conditions. The pasta was cooked to the al dente point, cryosectioned, and assessed by light microscopy and CSLM. With light microscopy (Fig. 5A–C) both starch and protein were visualized by staining with iodine and light green, respectively, whereas with CLSM (Fig. 5D–F), only the protein fraction was labeled with a fluorescent dye.

The light micrograph of spaghetti dried at LT and optimally cooked shows strongly swollen starch granules (Fig. 5A). In the surface layer, the starch granules have lost the granular shape and are partly fused together, whereas toward the center of the pasta strand, the starch granules are less swollen. The starch fraction is phase-separated, and amylose-rich phases that stain blue with iodine are recognizable in the intergranular space. The swollen starch granules are amylopectin-rich as revealed by the violet staining. In pasta dried at 100°C, the extent of starch swelling is lower than in pasta dried at LT, the effect being more pronounced for pasta dried with an IHT phase (Fig. 5C) rather than with an eHT phase (Fig. 5B). Extensive amylose leaching is recognizable in pasta dried with an eHT phase (Fig. 5B), whereas little accumulation of amylose in the intergranular space is found in the pasta dried with an IHT phase (Fig. 5C). The protein phase in cooked pasta is better visualized by CSLM and reveals that the protein network is partly disrupted toward the surface of pasta and has lost its continuity (Fig. 5D). Toward the center of the pasta strand, the protein network is better preserved. The CSLM micrograph of pasta dried at IHT reveals that the protein network is well preserved during cooking and that it has not lost its continuity (Fig. 5F). A peculiarity of pasta dried with IHT is that the microstructure is preserved even after prolonged cooking (Zweifel 2001). The microstructure of the protein network of pasta dried with eHT is between that of pasta dried with LT and IHT. It should be added that in the center of cooked pasta, the phase distribution is similar to that of uncooked pasta. Protein presents the continuous phase and the starch granules form a dispersed phase due to their limited swelling (micrographs not shown).

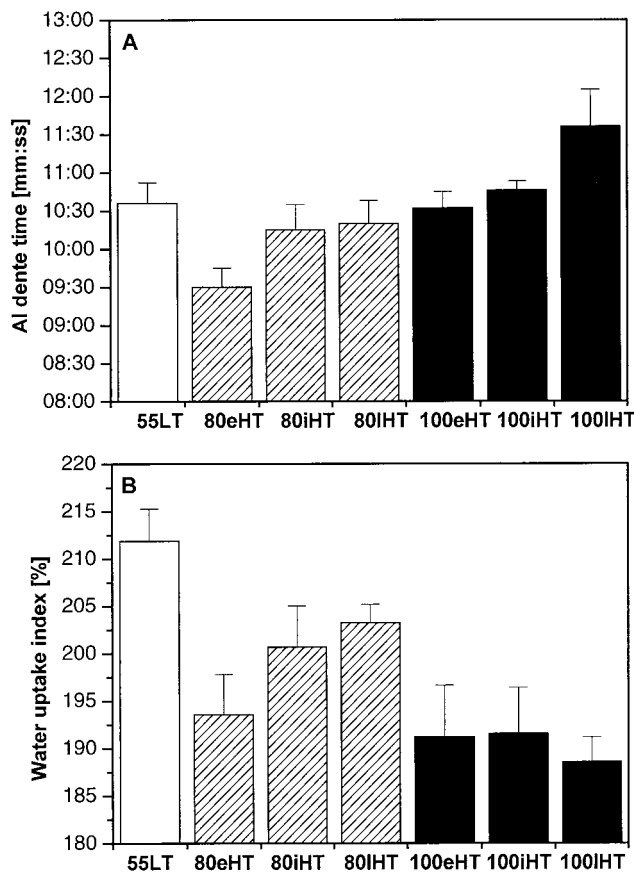


Fig. 6. Cooking time (al dente) (A) and water uptake index (B) of pasta dried at 55, 80, and 100°C applied in early (eHT), intermediate (iHT), or late stage (IHT) of drying cycle (high, intermediate, and low moisture conditions, respectively). Average and standard deviation of three to six determinations.

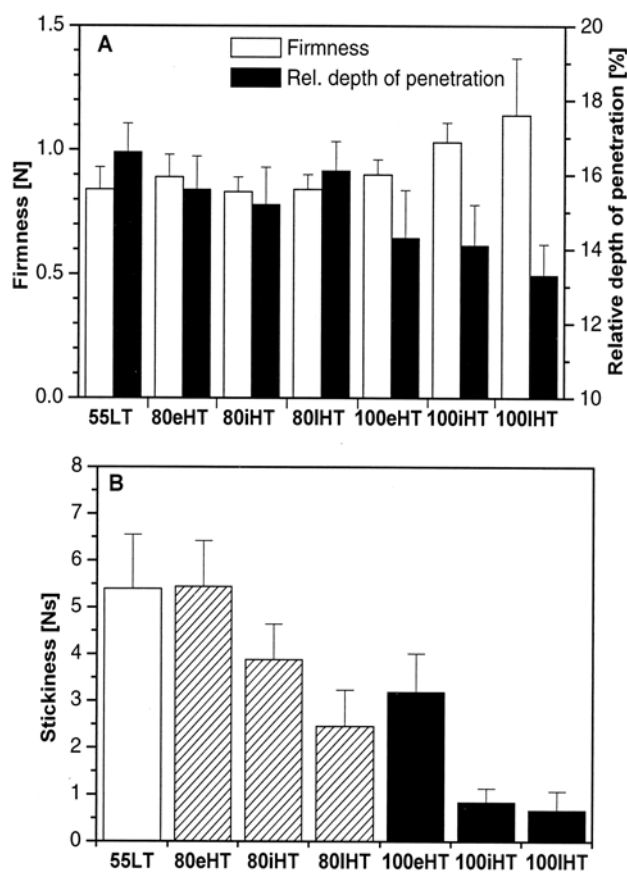


Fig. 7. Firmness and relative depth of penetration at 0.1 N (A) and stickiness (B) of pasta dried at 55 (LT) or 80, and 100°C with early, intermediate, and late high-temperature conditions (eHT, iHT, and IHT, respectively). Average and standard deviation of 20 (A) and five to eight (B) determinations, respectively.

The continuity of the protein network in the external zone of cooked pasta increases in the order $LT < 100eHT < 100IHT$, and the extent of starch swelling and phase separation decreased in the same order. Resmini and Pagani (1983) also showed that HT and low moisture drying better preserves the protein network during cooking than HT and high moisture drying, which correlated with the extent of protein denaturation. In the present study, large differences in the continuity of the protein phase were found between pasta dried with eHT and IHT, although the extent of protein denaturation was similar. One possible explanation is that drying at high product moisture (eHT) involves starch swelling, which promotes the formation of a continuous starch phase during cooking. Several authors found changes in the starch fraction during HT drying as detected by DSC (Vansteelandt and Delcour 1998; Yue et al 1999). In a previous publication, using the same drying profiles, we showed that HT drying of pasta induces a loss of order of starch during the predrying phase followed by an increase of polymer order during the HT phase (Zweifel et al 2000). However, the understanding remains poor for the effect of starch modification during drying on the properties of cooked pasta at the micrometer scale. For instance, it is not clear if drying pasta with eHT and IHT results in different starch modifications, specifically swelling capacity and amylose solubilization. HT drying induces changes in both the protein and the starch fraction, which in turn determine the microstructure of cooked pasta. LT drying does not induce protein denaturation and results in a weak protein network. Thus, starch swelling during pasta cooking leads to a disruption of the protein network and a phase inversion in the outer layer of the pasta strand. In contrast, thermal denaturation of protein at low moisture conditions, as during IHT drying, results in an extensively cross-linked protein phase that maintains its continuity during cooking. The extent of changes were most pronounced in pasta dried with IHT, where a continuous protein network prevented the formation of an extended starch network. It is very likely that the preservation of the protein network in pasta dried with IHT is also favored by rearrangements in the starch fraction during drying that reduce the swelling capacity of starch. However, if HT is applied at high product moisture (eHT), a slight swelling of the starch granules may contribute to the formation of a bicontinuous starch protein structure during cooking of pasta.

Cooking Behavior and Textural Properties of Pasta

Figure 6A and B presents the al dente cooking time and the water uptake indices for pasta dried at different conditions. The optimal cooking time of the reference sample dried at 55°C was ≈ 10 min and 30 sec. The lowest al dente time was for pasta dried with eHT at 80°C, while a significantly higher cooking time was obtained for pasta dried with IHT at 100°C. All other drying profiles led to cooking times that were similar to that of the reference. The water uptake index was highest for the reference (55LT) and lowest for all pasta samples dried at 100°C. Pasta dried at 80°C also had a lower water uptake index than the reference, but shifting the HT phase from early to late showed a clear trend toward higher water uptake indices.

Different results are found in the literature regarding the effect of the drying temperature on water uptake of pasta during cooking. In agreement with the present study, Fang and Kahn (1996) reported decreasing water uptake indices by increasing the drying temperature from 60 to 80°C. The opposite was found in other studies (Dalbon et al 1985; Aktan and Kahn 1992). The latter authors also observed that a HT phase applied at low product moisture led to low water uptake values. The water uptake strongly depends on the cooking time; contradicting results may be due to the fact that, in the present study, the samples were compared at their respective al dente cooking times and not at a constant cooking time. The results of the cooking test in combination with microscopy suggest that a thermal treatment of pasta, as it occurs during HT drying, limits the diffusion of water into the spaghetti strand. Increased al

dente cooking times and reduced water uptake during cooking correlate with a good overcooking tolerance of pasta (Zweifel 2001).

The results of a cutting test and an adhesion test are presented in Fig. 7A and B. From the cutting test, the maximal cutting force was evaluated to obtain a measure of pasta firmness. In addition, the relative depth of penetration at 0.1 N was evaluated; this reflects the thickness of the strongly hydrated external layer of pasta (Cunin 1995). The adhesion test gives quantitative information on the stickiness of cooked pasta. Spaghetti dried at 100°C was generally firmer than spaghetti dried at LT, while no significant difference was found for spaghetti dried at 80°C. In the same manner, the relative depth of penetration was lower for pasta dried at 100°C than at 55°C, but no difference was found for drying at 80°C. Regarding the stickiness, all drying profiles reduced the stickiness compared with the reference except 80eHT. In general, IHT phases were more effective in reducing the stickiness of pasta.

HT drying leads to higher firmness and lower stickiness of cooked pasta, which is consistent with the literature (Dexter et al 1981; Akan and Khan 1992; Cunin 1995). Firmness of pasta, which primarily depends on the strength of the gluten matrix of the core, is most probably increased due to a strengthening of the protein network. The reduced relative depth penetration of HT dried pasta is due to reduced starch swelling and the presence of a continuous protein matrix as confirmed by microscopy. The stickiness is linked to the structural properties of pasta in the external layer, and extensive starch swelling and amylose leaching correlates with a sticky pasta surface. Other authors showed that the integrity of the external layer determines the amount of material that can be rinsed from cooked spaghetti, which correlates with stickiness of pasta (Dexter et al 1985; D'Egidio et al 1993).

Processing-Structure-Texture Relationships in Pasta

The present results lead to the conclusion that the structural, and thus the textural, properties of pasta are influenced by HT drying. Drying at 80°C induces smaller structural and textural changes than drying at 100°C. This is explained by the lower extent of protein denaturation at 80 than at 100°C (Fig. 3). Likewise, Zweifel (2001) showed that the molecular order of starch, as determined by the enthalpy of starch gelatinization, increases to a lesser extent during drying at 80 than at 100°C.

The properties of pasta are not only determined by the maximal drying temperature, but also by the temperature-moisture conditions during drying. In general, the structural and textural changes in pasta are less pronounced when the HT phase is applied during an early stage of the drying process (eHT), where pasta moisture is rather high. This finding was not expected because, in general, an increased reaction rate of structural transformations is found in presence of higher amounts of water, whereby water acts as plasticizer and increases polymer mobility. This was not true for the glutenin and gliadin transformation during pasta drying, because similar protein denaturation rates, as well as comparable levels of protein denaturation, were found for eHT and IHT drying. Thus, low moisture levels (13–15 g/100 g, wb) during IHT drying did not limit protein denaturation nor did they reduce the denaturation rate. Therefore, a thermal treatment of pasta at low moisture content had a favorable influence on cooking behavior and the textural properties of pasta. It has to be taken into account that in mixed starch-protein systems, the moisture content of the bulk does not reflect the water distribution in the micrometer range. Starch and protein compete for water, and the availability of water for the two fractions depends on the time-temperature conditions. A peculiarity of starch is that plasticization is time-dependent due to its granular and partly crystalline structure. The penetration of water into the starch granules presents a diffusion-controlled process. Most probably, a slight swelling of starch favored during HT drying at high product moisture (eHT) of pasta leads to a redistribution of water in favor of starch, thereby increasing the effective amount of water and further depressing T_g (Slade and Levine 1991). This

complicates the comparison of drying processes of different time lengths. Finally, it has to be considered that drying leads to moisture gradients within the product. It is conceivable that the extent of protein and starch transformation is different in the outer layer and in the core of pasta.

As already discussed in connection with the microstructure of pasta, the structural and textural properties of HT drying can not solely be explained based on the extent of protein denaturation. Changes in the starch fraction during drying are also responsible for the properties of cooked pasta. This is supported by the finding that pasta dried at 80°C presented lower stickiness with IHT drying compared with eHT drying, although similar levels of gluten denaturation were measured. The relative contribution of starch and protein to the structural and textural properties of pasta is difficult to establish because their effects on the properties of cooked pasta are superimposed. Different textural properties may not be influenced to the same extent by protein and starch transformations. It is likely that the cutting strength, which reflects the properties of the core where gluten forms the continuous phase, is primarily affected by changes in the protein fraction and that starch transformations are less important. On the other hand, the properties of the outer layer as characterized by the relative depth of penetration and the stickiness reflect the phase distribution and morphology of the mixed starch-protein system. Improved cooking and textural properties are linked to the presence of a continuous protein phase in the external zone of cooked pasta. In contrast, the formation of a continuous starch phase with extensively disrupted starch granules swollen on the pasta surface contributes to a sticky texture.

CONCLUSIONS

HT drying can control the structural properties of cooked pasta by modifying the main polymeric structuring agents, protein and starch; this is in agreement with the view that the protein phase governs the properties of pasta. The coherence of the protein network is not only determined by the properties of protein itself, but also the properties of the starch fraction, in particular by its swelling capacity. Yue et al (1999) showed that HT drying modifies the pasting characteristics of starch, but they did not find a statistical correlation between pasting properties of starch and texture of pasta. On the other hand, the crucial role of starch is confirmed by the finding that the addition of starch complexing emulsifiers improves the textural properties of pasta by limiting starch swelling and amylose leaching (Cunin 1995).

The denaturation of the wheat proteins glutenin and gliadin promote the formation of a strong gluten network that better maintains its continuity during cooking. There are indications that changes in the starch fraction during HT drying account for reduced starch granule swelling and amylose solubilization in the outer zone of the strongly hydrated pasta strand. The consequences of HT drying on the properties of cooked pasta are improved cooking properties, as revealed by higher al dente cooking times and lower water uptake indices, as well as increased firmness and lower surface stickiness. These changes of the cooking behavior and textural properties of pasta become more pronounced when the drying temperature is increased from 80 to 100°C and by shifting from an eHT to an IHT drying process where product moisture is rather low. Drying conditions determine the dispersion state and phase morphology of protein and starch in the external zone of cooked pasta, which in turn govern the cooking behavior and the textural properties of pasta. A causal connection exists between the microstructure, in particular the continuity of the protein and the starch phase, and the textural properties of pasta. Optimization of pasta drying needs to take into account structure as one fundamental variable, the benefit being the control of all properties related to structural organization, such as textural properties. However, an appraisal of HT drying processes should also take

into account other properties of pasta such as color because HT low moisture conditions may promote excessive browning of pasta.

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