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Mechanism of Crumb Toughening in Bread-like Products by Microwave Reheating

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Comparing breads reheated in conventional and microwave ovens revealed that the latter considerably toughens the crumb texture when internal boiling is induced. Moisture loss in itself has a relatively minor toughening effect. The major changes, caused by boiling, occur only in systems with starch concentration in excess of a threshold level of about 37% (wet basis). Substantially greater amounts of amylose are leached out of the granules in the case of sustained boiling during microwave heating, as compared to conventional oven heating. The free amylose solution is being “pushed” by the generated steam pressure toward the air−cell wall interface. A rich amylose phase is accumulated at that interface and over the granules. Upon cooling, the amylose undergoes rapid phase changes; thus, toughening is apparent in a relatively short time after heating. Minimizing the textural deleterious effects in microwave reheating of bread-like products should entail (a) preventing or minimizing internal boiling, (b) diluting of the starch concentration below the threshold level, (c) interfering with the amylose phase change by using complex forming agents.

KEYWORDS: **Microwave; reheating; bread; crumb; foam; starch; amylose; boiling; texture**

INTRODUCTION

Microwave reheating of baked dough-based products was reported to produce an undesirable leathery tough texture. Ways have been suggested as to how to characterize the extent of toughness (*1*) and how to solve this problem in practice (*2*−*9*). However, the mechanism responsible for this toughening is not clear. Loss of moisture, due to a high rate of heat transfer in microwave heating, is not the main cause of this toughness (*1*, *10*). Nevertheless, a decrease in bound water was observed in microwave heating (*11*), and the “loosely bound” fraction was implicated in this process but without indicating which components are involved or how (*12*). Moreover, rapidly generated gas (steam) was suggested as a possible reason for quality changes in microwave-baked breads (*13*). In a more direct approach, a number of studies analyzed the effect of microwave heating on the behavior of the two main components of dough-based products, namely, gluten and starch. The gluten may toughen the texture by excessive disulfide cross-linking (*10*). However, due to its rapidity, microwave heating was found to produce less cross-linking in gluten both in the pure state and in breads, as compared to conventional heating. On the other hand, the starch seems to cause the toughening process, but due to its complex behavior, it is unclear how. Gelatinization and swelling of the starch granules depend on the moisture content and the time−temperature history. The pattern of the temperature gradients and the heating time is much different in microwave heating when compared with conventional hot-air ovens. All of these factors, and the nonuniform nature of microwave heating, produced chalky regions in starch suspensions (*14*−*16*). However, the structure of the swollen granules did not differ after either microwave or conventional heating (*17*). The toughening process may be attributed to the degree of gelatinization and the shape, the size, and the extractability of starch granules (*18*, *19*). In addition, other factors were reported to differ in the starch fraction when microwave and conventional heating were compared (*19*−*24*). These factors were reductions in bound water and extractable lipids as well as an increase in extractable amylose.

Two other nonspecific processes are reported to have had an impact on the texture during microwave heating, but only if internal boiling was induced. The first is the disruption of a dense gel-like structure at hotspot loci due to the formation of relatively high steam pressure. This process introduces defects in the structure that weaken the texture (*25*). Obviously, this effect cannot be evaluated in a system where the net result is a tougher texture. The second process is the shrinkage of a product due to the collapse of voids (*26*). This takes place when steam is venting out the air from small voids and then, upon cooling, condenses and creates vacuum. This vacuum provides the driving force for the voids to collapse, resulting in product shrinkage. This phenomenon, which was observed in imitation

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shrimp made of surimi, caused textural toughening by formation of a denser and more compact structure than that of the original product.

It is clear that rapid heating by microwave, its temperature gradient pattern, and its nonuniform nature may affect the texture differently from conventional heating. However, the mechanism of how the mode of heating affects the texture needs to be elucidated, especially because of the complicated structure of the dough-based products. The aim of this work is to evaluate the physicochemical processes that contribute to the toughening of the texture of bread-like products, using breads as well as a model system of protein−starch foams.

MATERIALS AND METHODS

Bread Preparation. Constant volume (1260 mL) bread loaves were baked according to a straight dough method with 90 min of fermentation (*27*). The constant volume was obtained by using a bread pan (9 × 14.5 cm at the base, 10.5 × 16 cm at the top, height = 8.5 cm) that was covered with a rigid wire net. The bread formula consisted of wheat flour having 11% gluten and 72% starch (Stiebel, Haifa, Israel), with the addition of (on the basis of unit weight of the flour) 64.3% water, 2% dry yeast, 2% salt, and 5% sucrose. The dough was mixed in a mixer for 3 min (Hobart, A-200) and then underwent a fermentation period of 45 min at 30 °C, kneading, and a second fermentation of 45 min at 30 °C. A weighed portion of dough was introduced into the bread pan, which was then covered with the rigid wire net. Additional fermentation in the pan (up to 30 min) was done when full volume was not obtained during baking. The bread was baked for 35 min in a rotating baking oven [Mini-Combo, Zucchelli-Forni, Trevenzuolo (VR), Italy] at a temperature of 215 °C. After the bread had been cooled, it was weighed and placed in polyethylene bags and stored at 4 °C for 7 days. The specific volume of the bread was calculated by dividing its volume (1260 mL) by the weight of the baked loaf.

Protein−Starch Model System Preparation. The model system consisted of pasteurized liquid egg albumen (Cham, Myron, Israel) and native wheat starch (S-5127, Sigma, St. Louis, MO). The concentration levels of the starch were 16.6, 25.9, 37.5, and 42.9% (egg protein was the rest, correspondingly). The first step of the procedure was the formation of the egg albumin foam in a mixer (Kenwood Chef, A-701, Hampshire, U.K.) at high speed (no. 8) for 6 min. In the second step, the starch was added slowly into the protein foam and mixed for another minute at the lowest speed. The mixture was then poured (filled to the top) into tin cans (diameter = 83 mm, height = 114 mm, Lageen, Yagur, Israel) and subsequently sealed and submerged in boiling water for 60 min. The thermally stabilized foam was left in the can for 7 days at 4 °C before testing.

Microwave Reheating. After 7 days of storage, the loaves of bread were removed from the polyethylene bags and heated, one by one, in a microwave oven at full power. Chronologically, an Amana (RS560A, 700 W) was used first. This oven was equipped with a single temperature-sensitive fiber optics (NAS-2, Luxtron, CA) that was connected to a monitor (Luxtron, model-755). To obtain temperature profiles, a Chromex (WP 700L17, 750 W) microwave oven was purchased at a later stage. This Chromex was equipped with multichannel temperature sensing probes (OSR, FISO Technologies Inc., Quebec, Canada).

The two ovens were tested for their output with a 900 g water load in a covered 1000 mL glass. The measured power outputs were 635 and 707 W for the Amana and Chromex ovens, respectively.

Cylindrical blocks of protein−starch foam were removed from the cans after 7 days of storage and reheated in a microwave oven (Chromex).

After reheating, each bread loaf or foam was placed in a polyethylene bag and allowed to cool to room temperature prior to the mechanical analysis. The cooling time was 4 h for the loaves and 2 h for the foams.

Energy Absorption by Boiling. The energy absorption by bread loaves during boiling was measured by monitoring their weight loss. Each tested loaf was placed inside the oven on an 80 mm glass plate that was connected to a balance (Ohaus, Galaxy 400D, Pine Brook, NJ) via a 6 mm glass rod through a hole in the oven bottom. Weight readings were collected during oven operation at full power and transferred to a computer via an RS-232 serial port. Boiling rate data were obtained when both the recorded loaf-center temperature was at the boiling point and the rate of weight loss reached a steady state. The latter rate of moisture loss in grams per second multiplied by the boiling enthalpy (2257 J/g) is the rate of energy absorption by boiling in watts.

Toughness Analysis. The method used is similar in principle to that of Miller and Hoseney (*1*), where the force of cutting a slice of bread by a wire was measured. In our study, cutting was done by a Guillotine, using a flattened edge “knife” (3 mm thick, 50 mm wide) that was connected to a universal testing machine (LLOYD, TA 500), equipped with a 50 or 100 N load cell. The knife moved downward at a speed of 10 mm/min. Bread slices of 15 mm thick and 40 mm wide were cut from the bread center and clamped onto a supporting plate (50 mm wide, 80 mm long), having at its center a 13 mm slit, through which the slice was cut. This supporting metal plate was prepared from a 50 × 50 mm stainless steel square pipe (wall thickness of 2 mm), in which a 13 mm slit was cut through three sides, to allow the knife to travel.

The same procedure was used for slices of protein foam, but their thickness was only 10 mm. The mechanical data were recorded in terms of force and deformation. The work of tearing was calculated by measuring the area under the graph of force versus deformation and expressed in millijoules. In cases when breads of different specific volumes were compared, relative toughness was used. The latter is calculated, for bread loaves of the same initial specific volume, as the ratio between the work of tearing when heated by microwave and that when heated by conventional oven to a center temperature of 90 °C.

Microscopic Methods. Cubes, 5 × 5 × 5 mm, were cut from the center of the bread loaves and the protein−starch foams. The cubes were carefully placed, in order to avoid deformation of the structure, in a bag made of aluminum foil and frozen by dipping in liquid nitrogen. Following this procedure, the frozen samples were handled as follows.

Light Microscopy. The frozen samples were embedded into OCT medium for cryosectioning (Optimal Cutting Temperature medium, Tissue-Tek Sakura). Sections of 5 μm were prepared by cryotome (Leica, Jung-Frigocut 288N), placed on microscope glass slides, stained with 1% lugol solution (I_2 and KI, 1:2 mass ratio), and covered with cover slide 30 s later. The samples were analyzed by using a light microscope. The bread samples were observed with a Zeiss Axioscope and the foam ones with an Olympus BH2 microscope.

Cryo-SEM. Frozen samples were freeze-dried (Martin Christ Alpha 1−4, Osterode, Germany). The dry samples were gold-coated in a Polaron SC515 sputtering device (Fisons Instruments, Ipswich, U.K.). The microstructure was analyzed by a scanning electron microscope (SEM) (JSM-5400, JEOL, Tokyo, Japan) with an accelerating voltage of 15 kV.

Moisture Content. Moisture content was determined by drying the samples, overnight, in a vacuum oven (60 °C, 28 in Hg).

Extractable Amylose. The method described by Kim and D’Appolonia (*28*) was essentially used to determine the amount of extractable amylose. A slice of bread was frozen in liquid nitrogen and freeze-dried (Martin Christ Alpha 1−4). The dry sample was ground in a hammer mill (Culatti AG, Zurich, Switzerland). Two grams of the pulverized bread was extracted by 30 mL of water in a 100 mL Erlenmeyer flask using a magnetic stirrer for 2 h and then centrifuged for 10 min at 5000 rpm. Three volumes of methanol waswere added to the supernatant and heated on steam bath for 1 h. After standing overnight at 4 °C, the flocculated soluble starch was collected and freeze-dried. The amylose content was determined by a colorimetric method using iodine, as described by Williams et al. (*29*).

RESULTS AND DISCUSSION

Microwave reheating can indeed toughen the bread crumb much more than conventional heating, but only if boiling is induced (**Figure 1**). The data in this figure, representing relative toughness as a ratio between microwave and conventional heating, clearly indicate that as long as the product is heated to a temperature below boiling, the heating method has little effect

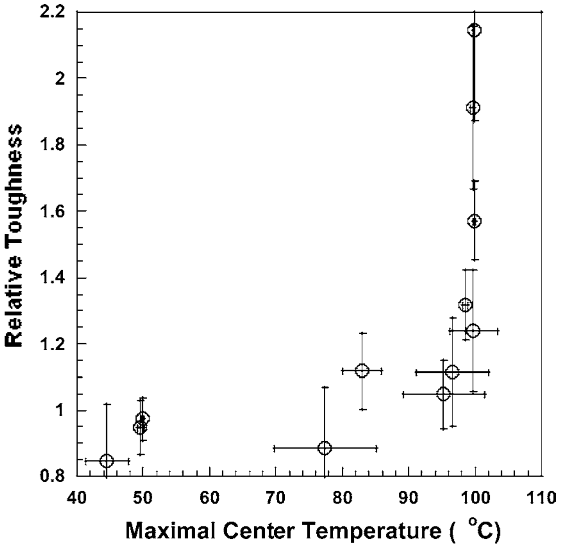

Figure 1. Effect of inducing boiling at the bread loaf center on the relative toughness of the crumb.

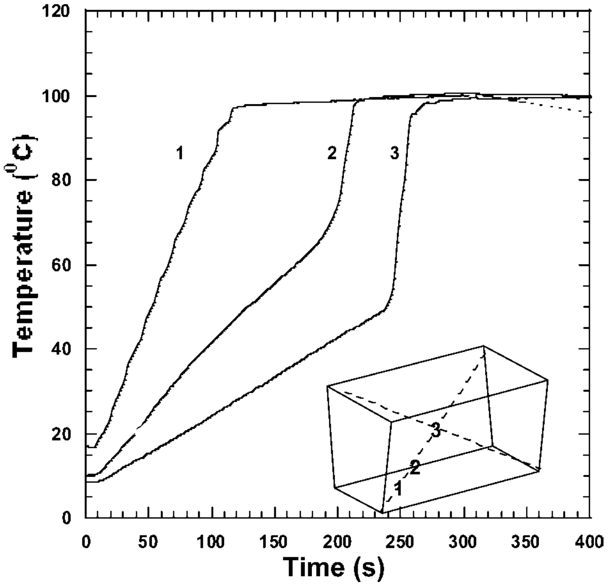

Figure 2. Temperature profile during microwave heating of bread loaf (sensor locations are indicated in the loaf scheme).

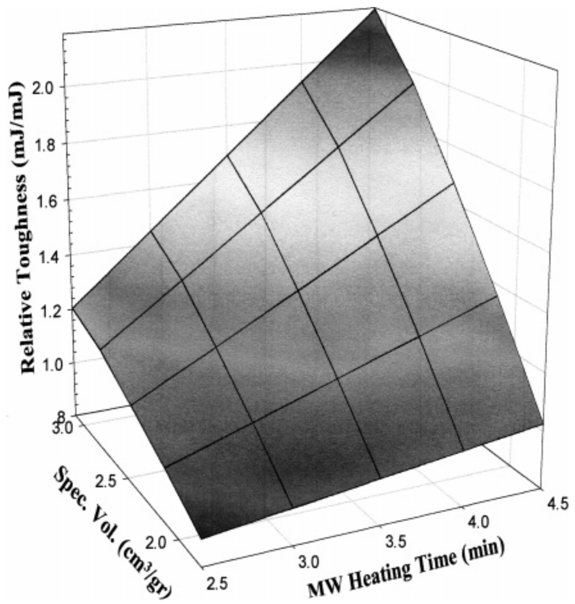

Figure 3. Surface response (41 experimental points) of the relative toughness of microwave-reheated bread loaves as a function of their initial specific volume and heating time (the relative toughness is the ratio between the work of tearing of the microwave-heated and conventionally heated breads of the same initial specific volume).

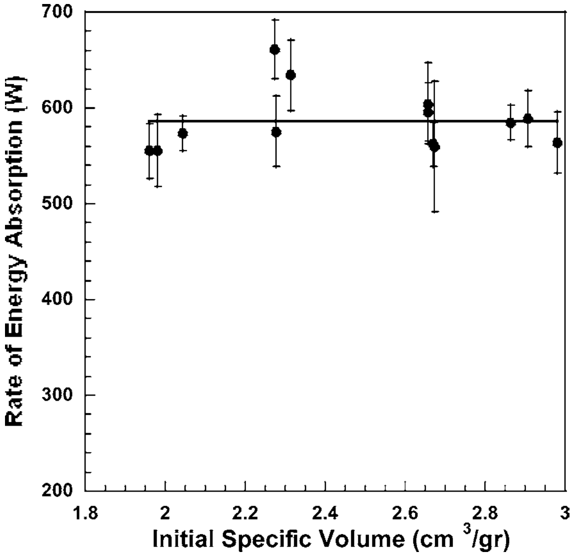

Figure 4. Rate of energy absorbed by boiling of bread loaves reheated in a microwave oven as a function of their initial specific volume.

on the crumb texture. Boiling, which can be easily produced by microwave heating, is required to cause a significant toughening of the bread crumb. As expected, the readily absorbed high input of microwave energy heats the product rapidly to its moisture boiling point (**Figure 2**). The temperature profile inside the bread shows that boiling starts first at the layers closer to the surface and a relatively short time later at the center. At that time, the entire bread crumb undergoes a boiling process, as long as energy is absorbed. When reheating of bread loaves of the same size in a microwave oven at a constant (maximal) energy output, one can see that the increase in their relative crumb toughness is apparently a function of time and of their specific volume (**Figure 3**). The longer the time and the higher the specific volume of the bread, the greater is the increase in toughness. At constant energy input, time is linearly correlated with the total energy absorbed by the product, thus also with the moisture loss by boiling. Specific volume, on the other hand, determines the loaf mass. For bread loaves of equal volume, higher specific volume means lower mass. In a situation of constant rate of energy absorption, lower mass loaves will heat more quickly, boil within a shorter time frame, and lose more of their moisture content (dry basis) than loaves of higher mass. Therefore, the combination of longer heating time and higher specific volume results in a product with lower moisture content. This conclusion is further confirmed by eliminating the possibility that the energy absorption by the boiling process may be dependent on the bread specific volume (**Figure 4**). The rate of energy absorption shows some scattering that should be expected for microwave oven operation, but it is independent of specific volume and can be considered to be practically the same for the loaves tested. Therefore, as already discussed, the main effect of the heating time and the bread specific volume is on the moisture content of the microwave-heated product.

A decrease in the moisture content of a bread loaf can by itself change the crumb texture. However, Rogers et al. (*10*) as well as Miller and Hoseney (*1*) showed that loss of moisture, by microwave heating, is not the main cause of toughness in

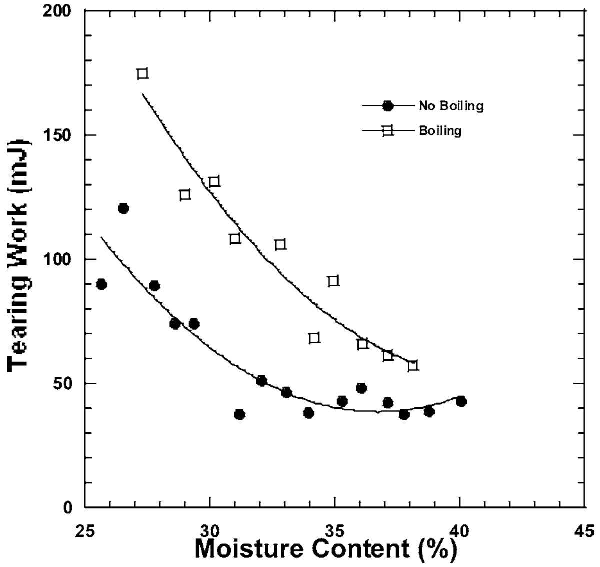

Figure 5. Effect of moisture content on the crumb tearing work when boiling is induced by microwave reheating as compared to microwave intermittent heating while maintaining temperature below 85 °C (no boiling).

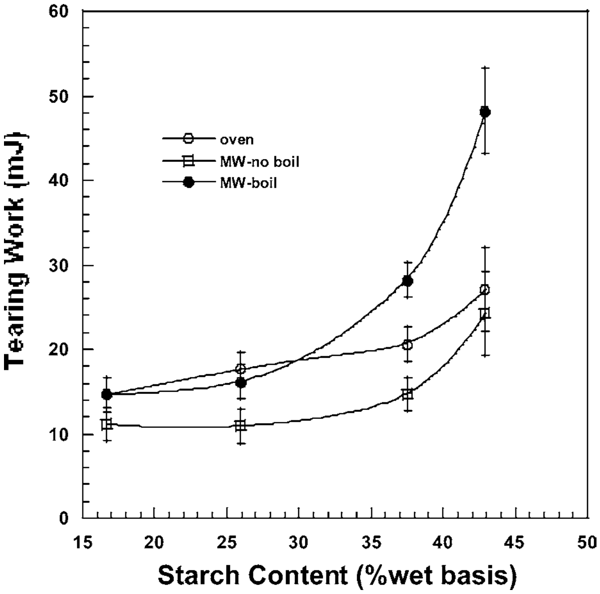

Figure 6. Tearing work of starch–protein foam as affected by starch content.

breads. The same is demonstrated in our data (**Figure 5**). The moisture content of breads, heated in a microwave oven, changed either by boiling at full power or by a long enough intermittent operation while the temperature was maintained below 85 °C. In the latter case, one observes some toughening of the texture when the moisture content decreases. However, this toughening is small compared with that obtained under boiling at the same moisture content (**Figure 5**). The toughening therefore is not a function of just the decrease in moisture content per se, but mainly of how much of it is lost by boiling. In that respect, this information corroborates the idea that rapidly generated steam is a possible reason for quality changes in microwave-baked breads (*13*).

Toughening of the crumb of the protein−starch model system follows the same pattern as that of the bread. Again, the texture is toughened by microwave heating only when boiling takes place (**Figure 6**). Due to the flexibility of changing its composition, the model system provides a very important clue about the mechanism as significant textural changes, by microwave heating, occur only when the starch content exceeds a threshold level. Above this level of about 37% (wet basis), toughness increases very steeply with concentration. On the other hand, no extra toughening by microwave heating is observed below that level. These findings imply that the starch fraction plays a major role in changing the crumb texture of the model system. It seems to happen when the starch becomes a dominant factor in affecting the product structure. Hug-Iten et al. (*30*) reported that on baking, starch was gelatinized and led to the formation of a continuous starch network. It is reasonable to assume that such a phenomenon can happen only when the starch occupies a large enough volume. Therefore, one may eliminate toughening by microwave heating just by preventing the starch from becoming a major structural element of the crumb, namely, by maintaining starch content below the threshold level. It should be noted that the starch content in the tested bread dough formula was about 41.5%. This value is calculated on the basis of diluting the 72% starch in the flour used for the bread preparation by adding 73.3 g of the combined weight of water, yeast, salt, and sugar to 100 g of that flour.

The information obtained so far indicates two important possible general approaches to alleviate or prevent toughening of bread crumb due to microwave heating. The first approach is simply to avoid, or at least to minimize, internal boiling either by proper operation of the microwave oven or by decreasing the energy input into the internal part of the bread. The latter can be achieved by using a metalized film susceptor (*8*). The susceptor absorbs part of the microwave energy and dissipates it at the product's surface, thus leaving much less energy available for internal heating and boiling. This way one can obtain a soft crumb as well as a crispy crust. The second approach to prevent toughening is by reducing the concentration of the starch fraction below a critical threshold. Shukla (*9*) suggests dilution of starch by incorporation of an effective amount of small starch granules (*3*), long-grain rice flour (*2*), or chemically modified starches (*5*) into the baked goods. The main effect of these practical solutions is, most probably, through the reduction in the volume and the connectivity of the starch fraction. Starch dilution can be achieved also by adding other biopolymers and fibers (*1*, *6*). Such biopolymers may also entail additional accompanied moisture, thus further diluting the starch fraction.

Although it is clear that starch has to be a dominating structural component to become the major player in causing toughness in microwave-heated bread, the question remains as to what the mechanism is. During boiling, two key factors should be considered, namely, the high gelatinization temperature and the generated steam. The most striking effect of inducing boiling by microwave heating is a considerable increase in extractable amylose (**Figure 7**). Such a phenomenon was also reported by Higo et al. (*19*) for microwave heating. Seyhun et al. (*31*) showed that more amylose was leached in cakes during microwave baking than in conventionally baked ones. Similar results were obtained by Patel et al. (*32*), who obtained higher amylose content in breads baked at higher heating rates than in breads baked at lower rates. The highest heating rates in the latter study were obtained in a hybrid oven combining hot air and microwave power. Considering the fact that boiling is required to create toughness in microwave heating, it is interesting to note that the release of amylose and its deposition on the granules were also reported by Langton and Hermansson (*33*) for high-temperature gelatinization. Obviously, when boiling is involved, this high gelatinization temperature involves

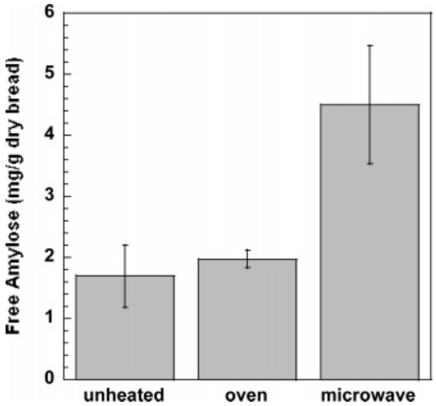

Figure 7. Extractability of amylose from bread after microwave reheating with boiling as compared to conventional oven and nonheated control breads.

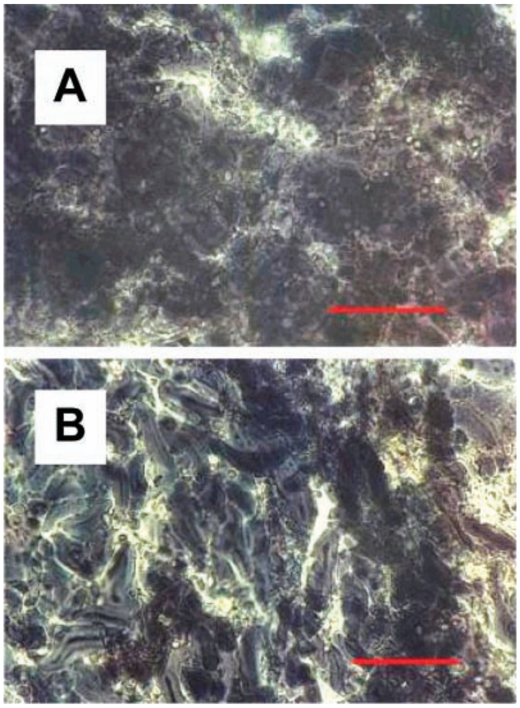

Figure 8. Cryosections of bread crumb stained with iodine solution after heating in microwave (**A**) and conventional (**B**) ovens (magnification ×40, bar size = 50 μm).

also generated steam, which might be of some help in the leaching process. However, this steam must be vented through the air-cell voids by building enough pressure and pushing its way out through the interstitial spacing, occupied by the solution of the leached free amylose. This should cause a redistribution of the amylose over the granules as well as carry the solution toward the cell wall. The expected result should not only be the spreading of amylose over the granules but also the formation of a reach phase at the cell wall−air interface. Examination of iodine-stained cryosections of bread by light microscopy indeed supports this idea of what is happening during boiling. The micrographs first show visible differences between samples heated by microwave (with boiling) and those heated by conventional oven (**Figure 8**). In conventional heating, amylose, selectively stained by the iodine solution, can be clearly observed inside the starch granules. In contrast, microwave heating causes the amylose to spread outside the granules with a considerable accumulation at the air−cell wall interface (**Figure 9**). The same picture is obtained for the protein−starch foam model system (**Figure 10**). Here, too, an amylose-rich phase is observed at the cell wall interface, as well as on the starch granules. SEM micrographs of the air−cell wall cross section of bread seem to verify this observation (**Figures 11** and **12**). The microwave-heated samples show a dense interface as compared with a more porous one that is formed by conventional heating. The porous structure should be attributed to the process of preparation of the samples for the SEM analysis, namely, the freeze-drying process. Evaporated ice crystals left the pores in the conventionally heated samples. The fact that they were absent in the microwave-heated samples indicates that water did not freeze in the amylose-rich phase probably due to low moisture content or unfreezeable water, which is what one expects to find in a crystalline phase of amylose.

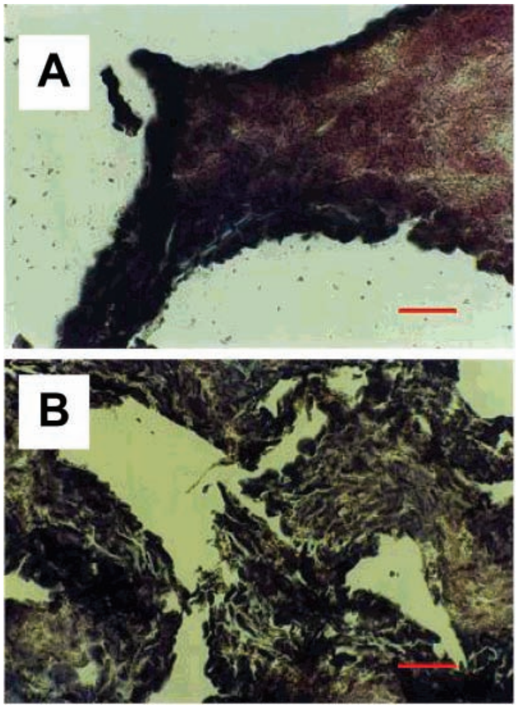

Figure 9. Cryosections of bread crumb stained with iodine solution after heating in microwave (**A**) and conventional (**B**) ovens (magnification ×10, bar size = 100 μm).

The SEM micrographs (**Figures 11** and **12**) suggest also that the microwave heating does not cause disintegration of the starch granules. It seems that one can exclude changes in granule structure as a major cause for crumb toughness. Theoretically, one may consider a possible role of amylopectin, which is known to affect bread toughness by retrogradation. The latter involves two kinetically distinct steps (*34*). The first is a rapid gelation and crystallization of amylose. The second is slow recrystallization of amylopectin. Depending on its molecular size and concentration, amylose may undergo either precipitation or gelation (*35*). On the basis of literature data, the turbidity caused by precipitation reaches half of its maximal value in only 2.5 min (*36*). In the case of gelation, half of the maximal rigidity is obtained after about 40 min (*35*, *37*). In contrast, the development of rigidity in high amylopectin waxy maze gel at room temperature shows a lag period of about 3 h and half of the maximal rigidity value only after 9 h (*37*). In fact, the literature data indicate that the bread crumb toughens very shortly after microwave reheating. Merabet (*12*) reported that the test panels observed this phenomenon 15 and 25 min after heating. Miller and Hoseney (*1*) were able to detect changes in toughness 4 min after microwave reheating. In the present study,

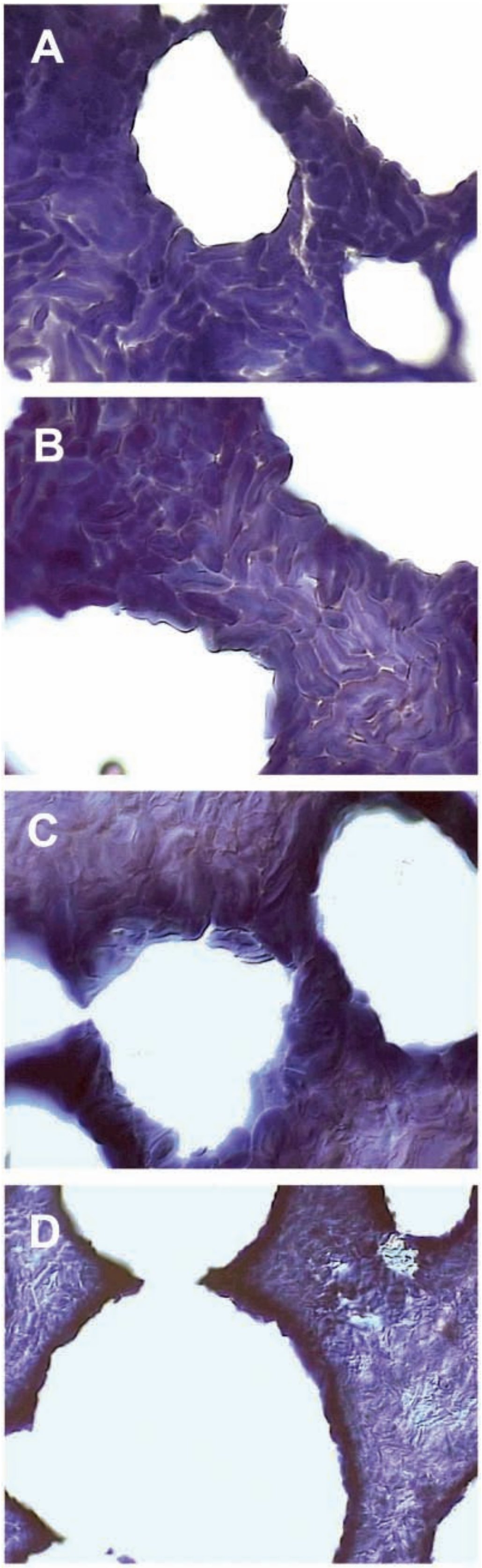

Figure 10. Cryosections of starch–protein foam stained with iodine solution after heating in a conventional oven (**A**) and in a microwave oven without boiling (**B**) and with boiling (**C**, **D**). (**A**–**C**, magnification ×20; and **D**, ×10.)

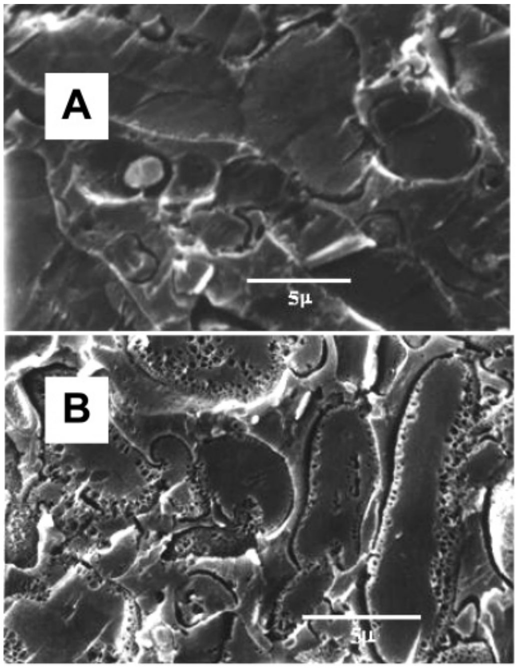

Figure 11. SEM micrographs of cross sections of air cell wall of bread crumb after heating by microwave (**A**) and conventional (**B**) ovens.

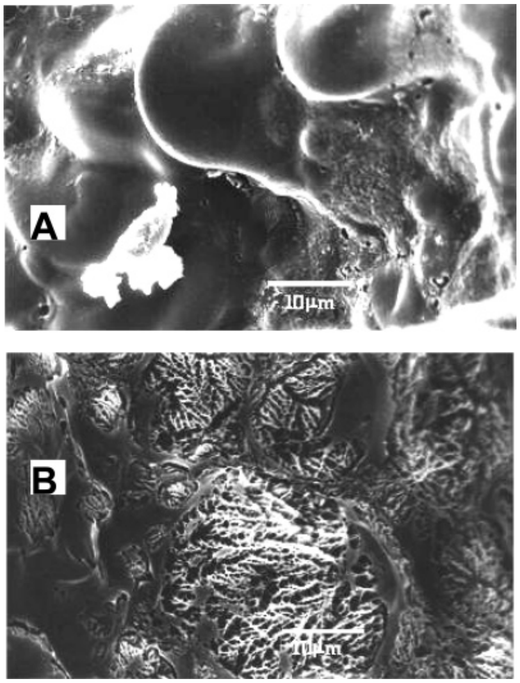

Figure 12. SEM micrographs of the surface of air cell wall of bread crumb after heating by microwave (**A**) and conventional (**B**) ovens.

testing of the mechanical properties was carried out 4 and 2 h after reheating of bread and the model system, respectively. That length of time was required only to ensure testing at room temperature. Taking into account this information and the 1 order of magnitude difference between the fast kinetics of the phase change of amylose and that of amylopectin, amylose must be responsible for the toughening process. Therefore, the release and redistribution of amylose over the cell wall matrix and interface seems to be a major important process with respect to textural changes in microwave heating. One practical solution to alleviate the deleterious effect of microwave heating is based on the addition of emulsifiers (*1*). These authors (Miller and Hoseney) state that the emulsifiers' effect was not due to the addition of more fat into the system. Therefore, one can assume that the main effect of the emulsifiers is due to the formation of complexes with amylose.

In conclusion, microwave heating or reheating may toughen the texture of bread-like products solely if internal boiling is induced. The higher the moisture loss by boiling, the tougher the crumb becomes. Therefore, the most effective way to eliminate the problem of crumb toughening in bread-like products is to avoid reaching the boiling point during reheating in a microwave oven.

When boiling does occur, the starch fraction is responsible for the major part of the toughening but only if its concentration in the product is above a threshold level. This level in a model system of protein−starch foams was found to be at a concentration of about 37% (wet basis), above which the toughening effect increases steeply. This threshold level is in the range of the starch concentration in bread. Therefore, one practical solution to reduce toughening is by diluting the starch fraction to a level below the threshold. This has been done in the industry by adding starches of modified properties or other biopolymers that reduce the starch content not only by their own concentration but also by their accompanied moisture content.

In the starch fraction, amylose is the component that is mainly responsible for the textural changes by microwave heating. During boiling, amylose is leached out from the starch granules and is spread and deposited on them as well as on the cell wall−air interface. The textural changes that follow the microwave heating are most probably due to the rapid phase changes of this amylose, affecting key structural elements of the crumb matrix. Formation of complexes with amylose is being used by the industry to alleviate some of the toughening problem.

LITERATURE CITED

(1) Miller, R. A.; Hoseney, R. C. Methods to measure microwave-induced toughness of bread. *J. Food Sci.* **1997**, *62*, 1202−1204.

(2) Ottenberg, R. Yeast-raisable wheat-based food products that exhibit reduced deterioration in palatability upon exposure to microwave energy. U.S. Patent 4463020, 1984.

(3) Ottenberg, R. Yeast-raisable wheat-based food products that exhibit reduced deterioration in palatability upon exposure to microwave energy. U.S. Patent 4560559, 1985.

(4) Anderson, K. H.; Lorence, M. W.; DeVay, G. E. Method of microwave heating of starch-based products. U.S. Patent 4842876, 1989.

(5) Cochran, S. A.; Benjamin, E. J.; Crocker, M. E.; Seidel, W. C.; Cipriano, V. L. Microwaveable baked goods. U.S. Patent 4885180, 1989.

(6) Engelbrecht, D. A.; Spies, R. D. Microwaveable bread products. U.S. Patent 5164216, 1991.

(7) Huang, V. T.; Hoseney, R. C.; Graf, E.; Ghiasi, K.; Miller, L.; Weber, J. L.; Gaertner, K. C.; Matson, K. L.; Hunstinger, A. M.; Antoinette, M.; Roger, D. K.; Saguy, I. A. Starch-based products for microwave cooking or heating. U.S. Patent 5035904, 1991.

(8) Saari, A. L.; Langler, J. E.; Dechaine, R. C.; Monroe, E. R.; Bergstrom, J. P.; Kusske, W. P. Method of preparing microwave bread. U.S. Patent 5049398, 1991.

(9) Shulka, T. P. Bread and bread-like dough formulations for the microwave. *Cereal Foods World* **1995**, *38* (2), 95−96.

(10) Rogers, D. E.; Doescher, L. C.; Hoseney, R. C. Texture characteristics of reheated bread. *Cereal Chem.* **1990**, *67* (2), 188−191.

(11) Higo, A.; Shimazaki, M.; Noguchi, S.; Nakazwa, F. Hardening of food texture induced by microwave irradiation. X. Changes in bound water contents of bread after irradiation. *Kaseigaku Zasshi* **1983**, *34* (8), 474−479.

(12) Merabet, M. Water behavior in baked dough-based products and relation to textural changes induced by microwave reheating. In *Water Science for Food, Health, Agriculture, and Environment*; Berk, Z., Leslie, R. B., Lillford, P. J., Mizrahi, S., Eds.; Technomic Publishing: Lancaster, PA, 2001; pp 207−222.

(13) Yin, Y.; Walker, C. E. A quality comparison of breads baked by conventional versus nonconventional ones: a review. *J. Sci. Food Agric.* **1995**, *67*, 283−291.

(14) Goebel, N. K.; Grider, J. A.; Davis, E. A.; Gordon, J. The effects of microwave energy and convection heating on wheat starch granule transformation. *Food Microstruct.* **1984**, *3*, 73−82.

(15) Zylema, B. J.; Grider, J. A.; Gordon, J.; and Davis, E. A. Model wheat starch systems heated by microwave irradiation and conduction with equalized heating times. *Cereal Chem.* **1985**, *62* (6), 447−453.

(16) Ndife, M.; Sumnu, G.; Bayindirh, L. Differential scanning calorimetry determination of gelatinization rates in different starches due to microwave heating. *Food Sci. Technol. (Lebensm.-Wiss. -Technol.)* **1998**, *31* (5), 484−488.

(17) Huang, J.; Hess, W. M.; Weber, D. J.; Purcell, A. E.; Huber, C. S. Scanning electron microscopy: tissue characteristics and starch granule variations of potatoes after microwave and conductive heating. *Food Microstruct.* **1990**, *9*, 13−122.

(18) Higo, A. Hardening of food texture induced by microwave irradiation. III. Changes in properties of starch granules under water limited conditions. *Kaseigaku Zasshi* **1981**, *32* (3), 185−191.

(19) Higo, A.; Okubo, M.; Shimazaki, M. Hardening of food texture induced by microwave irradiation. II. Changes in properties of starch in bread accompanied by hardening. *Kaseigaku Zasshi* **1981**, *32* (3), 178−184.

(20) Higo, A.; Okubo, M.; Shimazaki, M. Hardening of food texture induced by microwave irradiation. IV. Decrease lipid extractability caused by irradiation and food texture. *Kaseigaku Zasshi* **1982**, *33* (4), 173−178.

(21) Higo, A.; Shimazaki, M.; Noguchi, S. Hardening of food texture induced by microwave irradiation. V. Differences in lipid extractability of some model systems with regard to water content. *Kaseigaku Zasshi* **1982**, *33* (5), 221−227.

(22) Higo, A.; Shimazaki, M.; Noguchi, S. Hardening of food texture induced by microwave irradiation. VI. Formation of starch fatty acid methyl ester complex. *Kaseigaku Zasshi* **1982**, *33* (6), 297−303.

(23) Higo, A.; Noguchi, S.; Nakazwa, F.; Shimazaki, M. Hardening of food texture induced by microwave irradiation. VII. Effect of starch-gel formation on hardening of bread. *Kaseigaku Zasshi* **1983**, *34* (2), 83−88.

(24) Higo, A.; Noguchi, S.; Shimazaki, M. Hardening of food texture induced by microwave irradiation. IX. Study of the specific effects of microwave. *Kaseigaku Zasshi* **1983**, *34* (5), 251−257.

(25) Gropper, M.; Ramon, O.; Kopelman, I. J.; Mizrahi, S. Effects of microwave reheating on surimi gel texture. *Food Res. Int.* 1**997**, *30*, 761−768.

(26) Uzzan, M.; Kesselman, E.; Ramon, O.; Kopelman, I. J.; Mizrahi, S. Mechanism of textural changes induced by microwave reheating of a surimi shrimp imitation. *J. Food Eng.* **2006**, *74*, 279−284.

(27) AACC. *Approved Methods of the American Association of Cereal Chemists*; American Association of Cereal Chemists: St. Paul, MN, 1969; Method 10-10.

(28) Kim, S. K.; D'Appolonia, B. L. Bread staling studies: I. Effect of protein content on staling rate and bread pasting properties. *Cereal Chem.* **1977**, *54* (2), 207−215.

(29) Williams, P. C.; Kuzina, F. D.; Hlynka, I. A rapid colorimetric procedure for estimating the amylose content of starches and flours. *Cereal Chem.* **1970**, *47*, 411−420.

(30) Hug-Iten, S.; Handschin, S.; BeH atrice Conde-Petit, B.; Escher, F. Changes in starch microstructure on baking and staling of wheat bread. *Food Sci. Technol.* **1999**, *32*, 255−260.

(31) Seyhun, N.; Sumnu, G.; Sahin, S. Effects of different starch types on retardation of staling of microwave-baked cakes. *Food Bioprod. Process.* **2005**, *83* (C1), 1−5.

(32) Patel, B. K.; Waniska, R. D.; Seetharaman, K. Impact of different baking processes on bread firmness and starch properties in breadcrumb. *J. Cereal Sci.* **2005**, *42*, 173−184.

(33) Langton, M.; Hermansson, A. M. Microstructural changes in wheat-starch dispersions during heating and cooling. *Food Microstruct.* **1989**, *8* (1), 29−39.

(34) Miles, M. J.; Morris, V. J.; Orford, P. D.; Ring, S. G. The role of amylose and amylopectin in the gelation and retrogradation of starch. *Carbohydr. Res.* **1985**, *135* (2), 271−281.

(35) Clark, A. H.; Gidley, M. J.; Richardson, R. K.; Ross-Murphy, S. B. Rheological studies of aqueous amylose gels: the effect of chain length and concentration on gel modulus. *Macromolecules* **1989**, *22*, 356−351.

(36) Gidley, M. J.; Bulpin, P. V. Aggregation of amylose in aqueous systems: the effect of chain length on phase behavior and aggregation kinetics. *Macromolecules* **1989**, *22*, 341−346.

(37) Billiaderis, C. G. Structures and phase transitions of starch in food systems. *Food Technol.* **1992**, *46* (6), 98−109.

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