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M. Ambrogina Pagani

Plerpaolo Resmini

Gerardo Dalbon

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INFLUENCE OF THE EXTRUSION PROCESS ON CHARACTERISTICS AND STRUCTURE OF PASTA

M. Ambrogina Pagani*, Pierpaolo Resmini, Gerardo Dalbon[1]

Universita degli Studi, Dipartimento di Scienze e
Tecnologie Alimentari e Microbiologiche,
Sezione Industrie Agrarie,
Via Celoria 2, 20133 MILANO, Italy

[1]Centro Ricerche Societa Braibanti,
Largo Toscanini 1, 20122 MILANO, Italy

Abstract

The effects of the kneading and forming process on pasta quality have been investigated. Using the same blend of wheat flour and keeping mixing and drying conditions constant, three types of spaghetti were produced using the following three kneading and forming processes: A) kneading with a continuous press and forming by pressure-extrusion; B) kneading and forming by sheeting-rolls; C) kneading by hand and forming with sheeting-rolls. These three processes impart different mechanical work on the dough.

The three types of dried spaghetti exhibited differences in cooking requirements and in cooking quality. Spaghetti (A) absorbed water more slowly and showed poor cooking quality. Spaghetti (B) and (C) had a shorter cooking time, no stickiness and good firmness after cooking. Spaghetti compactness seems to control water absorption during cooking, i.e., the greater the compactness, the longer the cooking time. Nevertheless, compactness does not explain differences in cooking quality. On the contrary, this characteristic is clearly related to the different organization of proteins, as transmission and scanning electron microscopy images revealed. In fact, both spaghetti (B) and (C) showed a compact and continuous protein network, probably as a consequence of the mild and ordered kneading obtained by the sheeting process. Spaghetti (A), produced by dough kneading implying strong mechanical stresses, exhibited protein network breakage which may account for its poor cooking quality.

The results of the present work indicate that industrial kneading and extrusion, as performed today in the continuous press, are unsuitable for making the best use of poor quality raw materials. The pressure-extrusion process requires technological innovations which could ensure spaghetti with cooking quality comparable to that produced in the traditional sheeting process as well as high productivity.

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Direct inquiries to P. Resmini
Telephone number: 39-2-236 7181/5426

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Introduction

It is well known that pasta quality and its cooking characteristics, as far as consumer acceptability is concerned, are affected by the quality of the raw material as well as by the processing conditions. Numerous studies in this field have specified the properties of the raw material (2, 4, 6, 8, 14, 23, 36, 38) and the conditions of the drying cycle (11, 13, 25, 35) that ensure a good quality product.

On the contrary, there have been few investigations regarding the role that the first steps of the pasta-making process (kneading and extrusion) have on pasta quality. Papers published some years ago (34, 37) reported that hand-made and roll-sheeted spaghetti always exhibit higher quality compared with pasta produced from the same raw material by the usual pressure-extrusion process. This is well known by pasta-making technologists (19, 24).

Recently, some authors observed that noodles prepared by a sheeting process (10) show a higher gluten development in comparison to those obtained in a continuous industrial press (26). However, no explanation has been found for the differences in quality due to the kind of kneading and forming processes used.

Therefore, this study was designed to control the effect of various technological processes used for dough-forming on pasta quality. In particular, the continuous industrial press was compared to the more traditional working methods, such as roll-sheeting and hand-sheeting.

Materials and Methods

Spaghetti processing

A wheat flour blend (12% protein dry mass, particle size less than 100 micrometers), obtained by mixing a commercial soft wheat flour with a low protein content and a commercial hard wheat flour in the ratio of 70/30 w/w, was used.

The flour and water (at 36°C) were blended in order to produce a mixture with a final water content of 36%. Mixing was performed in a Braibanti laboratory mixer at 500 r.p.m. for 60 sec and then at 200 r.p.m. for 40 sec. After a resting period of 20 min in the mixer at room temperature, the flour/water mixture was kneaded and formed into spaghetti according to the following processes (Fig. 1):

A) Extrusion under pressure with a continuous press (Braibanti laboratory press), using the following conditions: extrusion pressure, 60 atmospheres; dough

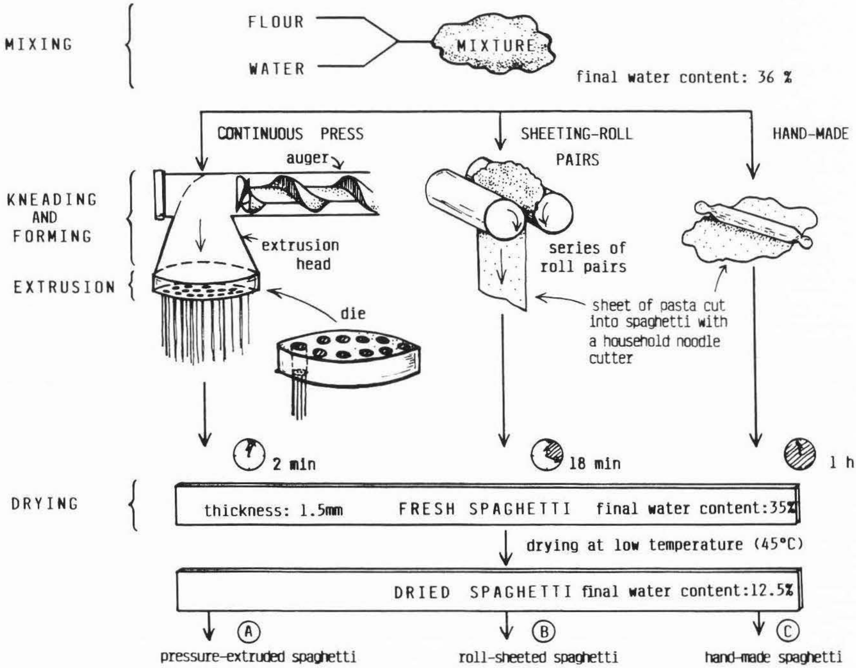


Figure 1. Diagram of spaghetti processing.

temperature, 37°C; teflon lined die with 1.5 mm square holes. The time required for passing the dough through the cylinder and the head of the extruder was 2-3 minutes.

B) Roll-sheeting by means of pairs of stainless steel cylinders (12 cm diameter). The mixture was sheeted by passing it 10 times in the same direction at a roller setting of 12 mm. The sheet was folded in half before each passage. The roll setting of 12 mm assured good kneading without tearing the surface. The dough sheeting was then completed with 1 passage at 6 mm, 1 passage at 3 mm and 2 passes at 1.5 mm. These last 4 passages were performed, without folding the sheet, in order to reduce the sheet thickness gradually. The time required for the sheeting process was about 15-18 minutes.

C) Hand-made sheeting. The dough was carefully kneaded by hand for 10 min, wrapped in aluminium foil, rested for 30 min and rolled out in a sheet with a rolling pin. It was then passed twice through the rollers used in process B) set at 1.5 mm to obtain a uniform thickness. The time required for this process was about 1 hour.

The final dough sheets obtained in processes B and C were cut into strips (1.5 mm thickness) with a home noodle cutter. The three types of fresh spaghetti, with the same shape and size ("spaghetti alla chitarra", 1.5 mm thick) were dried at the same time at low temperature (45°C for 16 hours).

A modified extrusion process was also done in the continuous press to obtain samples for ultrastructural studies. A well-kneaded dough, produced under the same conditions as reported for process B, was prepared with 10 passages through the rollers (12 mm spacing). This roll-sheeted dough was then cut into small cubes, fed into the continuous press and processed as reported above for process A. The press was stopped after 5 min of working and the die removed. The dough in the interior of the extrusion-head could be easily and carefully removed (with a sharpened lancet) prior to its extrusion.

Porosity

Porosity was evaluated with a Carlo Erba mercury intrusion porosimeter (model 2000), connected to a computer for complete automatic operation, collection and processing of data.

Mercury behaves as a non-wetting liquid. Thus, it will not flow into small cavities of a porous solid unless it is forced by pressure. The higher the pressure, the smaller the pore (18). In our test, some strands of dried spaghetti (0.5-1 g) were placed in the porosimeter vessel, evacuated, filled with mercury and then subjected to increasing pressure up to 2000 x 10^5 Pa. This pressure range allows pores with a radius from 4 to 7500 nm to be determined. The characteristics of compactness were expressed as cumulative volume (mm^3 of pores per g of solid) and as porosity % (mm^3 of pores per 100 mm^3 of solid).

Breaking strength

The breaking strength was measured with a bending test using the Instron testing machine (model 4301) equipped with a compression cell of 1000 g; the crosshead speed was fixed at 20 mm/min.

A single strand of dried spaghetti (8 cm length, 20 measurements for each type of spaghetti) was placed on two cylindrical supports (1.2 cm diameter) 3.5 cm apart. The spaghetti strand was broken in the middle by a blade made from a piece of plexiglass (1.5 mm thick with a flat cutting profile) attached to the crosshead. The breaking strength was expressed as the force (g) required for breaking the strand of spaghetti.

Evaluation of Cooking Quality

Organoleptic test. The cooking quality was determined with a standard test for durum wheat spaghetti. 100 g of spaghetti were cooked in 1000 ml of boiling mineral water for the optimal cooking time (disappearance of the central ungelatinized core, ref. 35). It was then drained for 1 min in a strainer of 169 mesh. Stickiness (spaghetti adhesiveness to teeth during mastication) and firmness (force required to compress the spaghetti between the molar teeth) were evaluated by 5 expert tasters using appropriate adjectives (5, 7). The panel also gave an overall rating of quality: 3 for the poorest, 9 for the best.

Rheological test. The instrumental evaluation of spaghetti cooking quality was obtained with the compression test proposed by Dalbon et al. (5). The Instron testing machine (model 4301) was fitted with a 10,000 g compression cell, and with a circular plunger of 3.55 cm diameter. The crosshead and chart speeds were 5 mm/min and 100 mm/min, respectively. Spaghetti was cooked at its optimal time, drained for 1 min and then placed in a Petri box. Two min after draining, 6 strands of spaghetti were placed in the center of a steel plate and compressed to a maximum pressure of 2000 g. When this value was reached, the crosshead movement was reversed and the sensitivity of the Instron machine was expanded to maximum to measure stickiness with greater precision (5, 12). Stickiness was evaluated from the negative area of the force-deformation diagram and was expressed in N x mm. The same test was repeated on 6 other strands of cooked spaghetti after fixed times of draining in order to check the increase in stickiness with time.

Water absorption during cooking

The water absorbed by dried spaghetti during cooking was determined by measuring the increase in the spaghetti weight as a function of cooking time. Cooking was performed in a small vessel provided with an appropriate strainer, divided into 4 sections. 2.5 g of spaghetti (strands 2-3 cm length) were placed in each section and plunged into the boiling water. After 2.5 min of cooking, the spaghetti in the first section was removed, drained on a filter paper for 13 min and weighed. The procedure was repeated on the spaghetti in the other sections after 5, 7.5 and 10 min of cooking. Water absorption was referred to 100 g of dried spaghetti. The material lost in the cooking water was not considered.

Transmission Electron Microscopy (TEM)

Samples were soaked in a 30% glycerol-water solution at room temperature. The imbibition times for fresh spaghetti (prior to drying) and cooked spaghetti were 20 min and 10 min, respectively. A small quantity of soaked samples was then placed on the gold specimen holders, frozen in super-cooled liquid nitrogen (LN_2) and transferred into a Balzers 301 unit. Defrosting was carried out for 20 min at -95°C. Fracturing was performed at -105°C, immediately followed by shadowing with Pt/C (film thickness: ca. 2 nm, angle: 45°) and C (film thickness 20-25 nm). Replicas were cleaned in 70% and 30% sulfuric acid solutions for at least 48 h, then washed in distilled water, acetone, and double distilled water. Replica observation was performed with a Philips EM 201 electron microscope at 60 or 80 kV.

Scanning Electron Microscopy (SEM)

Both fresh and cooked samples were immediately frozen in super-cooled LN_2 and then freeze-dried using an Edwards tissue drier (model EPD3). Freeze-drying was performed at -60°C for 24 h. Fracturing was done in two ways: 1) cryo-fracturing the samples directly in LN_2, using a pair of tweezers, and then freeze-drying. The resulting fracture plane was smooth and even. 2) dry-fracturing by fracturing the sample after freeze-drying. In this case, the fracture plane was uneven and ragged. The freeze-dried samples were mounted on stubs, sputter-coated with gold and then observed in a Cambridge Stereoscan 150 microscope at 10 or 20 kV.

Results and Discussion

Conventional production of pasta involves the fixed steps of blending flour and water into a very stiff mixture, kneading, forming by extrusion and drying. For reasons of productivity, these steps take place on line and rapidly in the modern press. The process is continuous and completely automated with a time interval of only 2 minutes from kneading to the end of extrusion. In the more traditional systems, such as roll- or hand-sheeting, the steps of kneading and forming are performed separately. Therefore, it is possible, however roughly, to isolate the effect of each technological step on final pasta quality. In this regard, kneading and forming have been studied by subjecting the same mixture of wheat flour and water (without working and dough development) to different forming processes, as shown in Fig. 1:

- kneading with a continuous press and forming by extrusion (process A);
- kneading and forming with pairs of sheeting-rolls (process B);
- kneading by hand-working and forming with pairs of sheeting-rolls (process C).

As in our previous work (35), we used only wheat flour instead of durum wheat semolina. The poor quality of this raw material makes the pasta-making process critical, and allows the effects of the three different technological processes to be more easily assessed.

An organoleptic test was first performed to evaluate the quality of the three types of spaghetti, all with the same shape and thickness and obtained

Table 1 - Cooking Quality as Evaluated by Sensory Panel

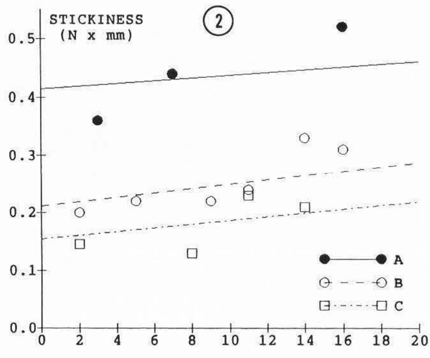
Process	Optimum Cooking Time	Stickiness	Firmness	Overall Rating*
A Pressure-extruded spaghetti	9 min	High	Weak	6.0
B Roll-sheeted spaghetti	7.5 min	Absent	Good	8.0
C Hand-made spaghetti	7.5 min	Absent	Good	8.5

*Rating scale: 3 = poorest quality; 9 = best quality

Table 2 - Characteristics of Compactness of Dried Spaghetti

Process	Cumulative Volume* (mm^3/g)	Porosity* (%)	Breaking Strength (g)
A Pressure-extruded spaghetti	26.95	3.75	88.0
B Roll-sheeted spaghetti	51.22	6.94	77.1
C Hand-made spaghetti	53.51	5.17	71.5

*See Porosity, Materials and Methods.



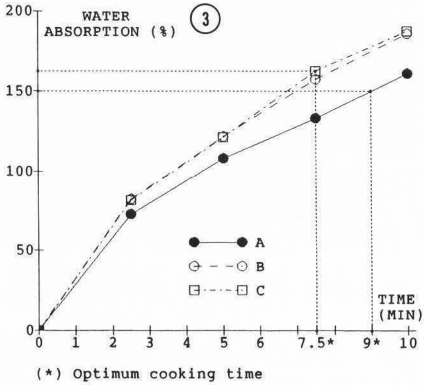


Figure 2 (at left). Stickiness of cooked spaghetti evaluated with the Instron rheological test. **A)** pressure-extruded spaghetti; **B)** roll-sheeted spaghetti; **C)** hand-made spaghetti.

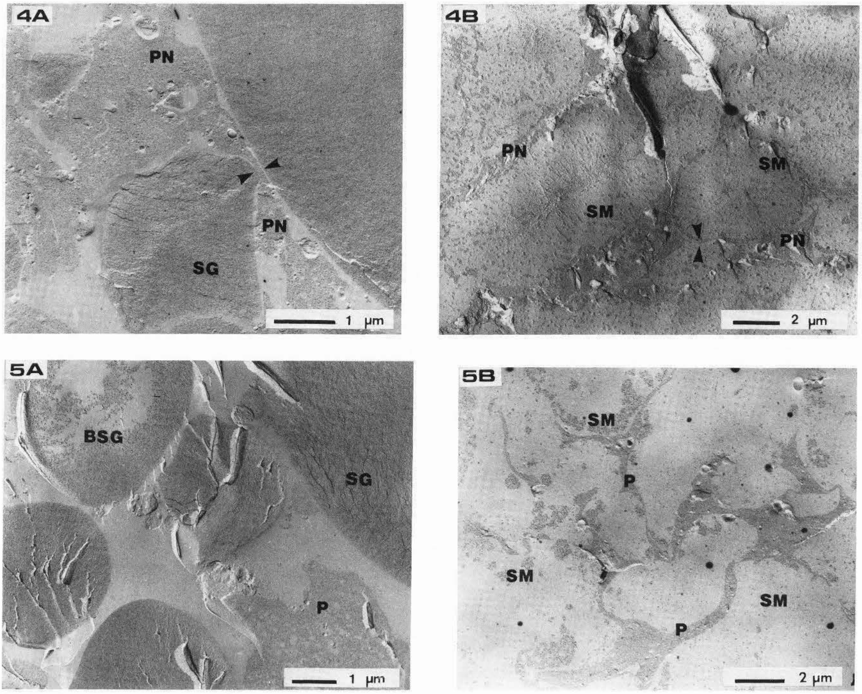
Figure 3 (at right). Water absorption during cooking (g/100 g dried spaghetti). **A)** pressure-extruded spaghetti; **B)** roll-sheeted spaghetti; **C)** hand-made spaghetti.

from the same dough. Table 1 reports noticeable differences among the three samples. The cooking quality decreases (i.e., spaghetti becomes stickier and softer) as the working time of the dough decreases and the mechanical stress of the process increases. The worst quality pasta was obtained with the continuous pressure-extrusion process, whereas the best spaghetti was produced with the hand-working process. The high quality of this last product is surprising, considering that it was obtained from the same blend of wheat flour and at the same water content (36%). No other industrial process used today produces this result, including the roll-sheeting process which is based on the same mechanical principle.

The rheological evaluation of stickiness performed with an Instron testing machine (Fig. 2) also showed the same ranking of quality for the cooked spaghetti. Process A yielded the stickiest while process C gave the least sticky spaghetti.

Certain physical characteristics of spaghetti, such as compactness and water absorption during cooking, are clearly influenced by the kind of kneading and forming. The mechanical work performed under different conditions induces a different physical stress that obviously causes a different compactness in dried spaghetti. This last parameter, evaluated by means of breaking strength and porosity (Table 2), is highest for the extruded spaghetti and lowest for the roll-sheeting product.

Porosity affects the kinetics of water



Figures 4 and 5. Freeze-fracture TEM. **All the spaghetti images were taken in the center of the strand.** **Figure 4.** Roll-sheeted spaghetti. **A)** Fresh spaghetti: the continuous protein network (PN) surrounds the starch granules (SG). **B)** Cooked spaghetti: the starch material (SM), entrapped inside the protein network (PN), is organized in fibrils and small regular aggregates. Arrows show thin protein fibrils.

Figure 5. Pressure-extruded spaghetti. **A)** Fresh spaghetti: the protein (P) forms aggregates unevenly dispersed among the starch granules (SG), some of which appear broken (BSG). **B)** Cooked spaghetti: the starch material (SM) is highly dispersed inside a weak and discontinuous protein network (P).

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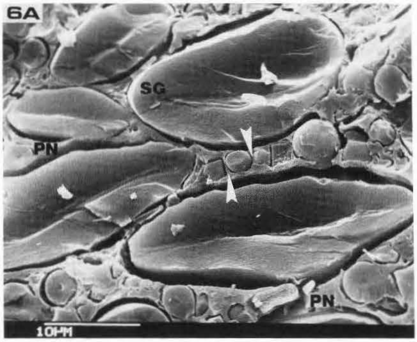
absorption during cooking (Fig. 3) and contributes to the longer cooking time needed for pasta products submitted to high pressure which are thus less porous and more compact. Contrary to what has been reported by other authors (31, 32), the compactness of the dried pasta does not appear directly related to cooking quality.

These observations emphasize that the kind of process used for kneading and forming greatly influences the macro-structure of spaghetti and its cooking behaviour. These characteristics cannot be explained on the basis of our analytical data. However, clear suggestions seem to arise from careful observations, with TEM and SEM, of the fine structure of spaghetti at various processing steps.

Some ultrastructural features seem to be related to the kind of kneading and forming. The different structures may explain the cooking behaviours of spaghetti, as reported in the literature (33, 35).

The compact and continuous protein network observed in fresh roll-sheeted pasta (Fig. 4A) is comparable to that observed in durum wheat spaghetti (35) and likely traps the starch granules which swell during cooking (Fig. 4B). Under these conditions the starch material is retained inside the spaghetti strands during cooking, thus limiting its stickiness. Owing to the reduced swelling of the granules, the starch subunits are arranged into chain-like fibrils and ordered groups. This pattern, a probable consequence of the retrogradation phenomena (15), is always observed in pasta of superior cooking quality (5, 33, 35), and is never seen in


6A
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PN
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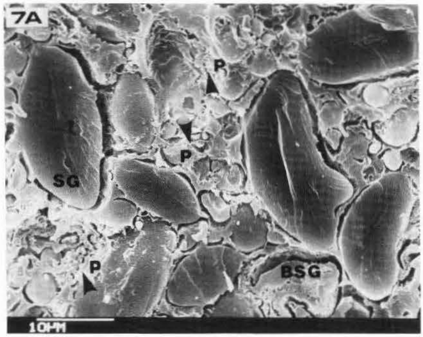
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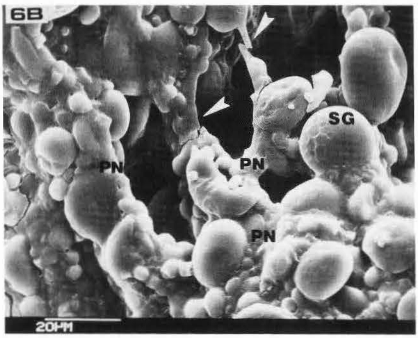
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7B
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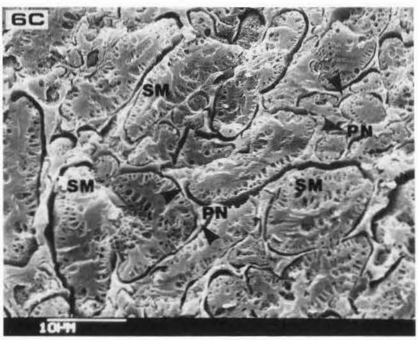
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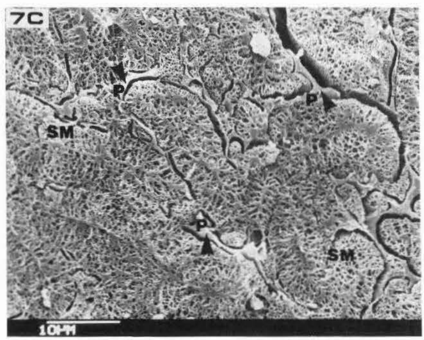
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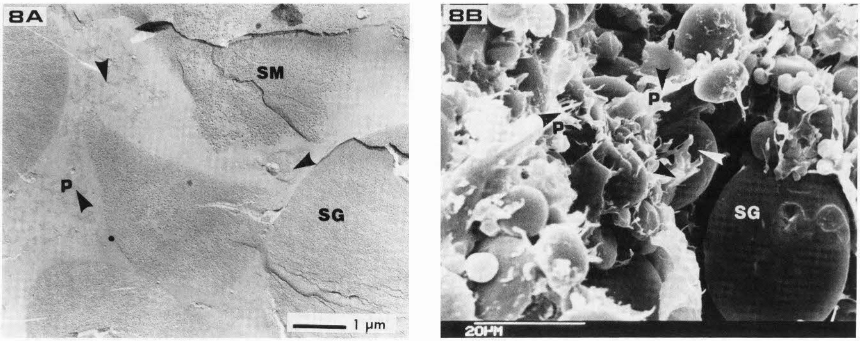

Figure 8. Ultrastructure of dough just before its extrusion through the die. **A)** Freeze-fracture TEM image; **B)** SEM image after dry-fracturing. (SG) starch granules; (SM) starch material (probably from broken starch granules); (P) and arrows indicate the broken protein fibrils.

Figure 6 (on the facing page, left panel). SEM images of roll-sheeted spaghetti. **A)** cryo-fracturing and **B)** dry-fracturing of fresh samples; **C)** cryo-fracturing of cooked spaghetti. Symbol definitions are the same as in Figure 4. Arrows show location of protein network.

Figure 7 (on the facing page, right panel). SEM images of pressure-extruded spaghetti. **A)** cryo-fracturing and **B)** dry-fracturing of fresh spaghetti; **C)** cryo-fracturing of cooked spaghetti. Symbols definitions are the same as in Figure 5. Arrows indicate the broken protein network.

products obtained with soft wheat flour processed under industrial conditions (35). Hand-made spaghetti presents the same ultrastructural features as the roll-sheeted pasta.

On the contrary, in freshly extruded spaghetti (Fig. 5A) the protein matrix looks discontinuous with protein aggregates unevenly distributed among the starch granules. During cooking (Fig. 5B), the lack of a continuous protein network causes high hydration of starch material and its marked dispersion outside the spaghetti (33, 35), resulting in stickiness (16, 29).

SEM images confirm and complement TEM results, especially when the sample is prepared by cryo-fracturing, a sectioning technique comparable to the freeze-fracturing technique. Moreover, the larger field of view of the SEM images allows the continuity of the protein framework in fresh roll-sheeted spaghetti before (Fig. 6A, 6B) and after cooking (Fig. 6C) to be more easily observed.

The presence of broken protein fibrils in freshly extruded spaghetti is just as clearly seen (Fig. 7A, 7B). A similar organization in dough taken from the press has been reported by Matsuo et al. (26). After cooking, a dramatic swelling of the starch granules can be seen. They are often so coalesced and clustered together that their individual, original edges are no longer visible (Fig. 7C). This supports the idea that during cooking, extensive starch swelling prevails, with little protein interaction. This could account for the poor cooking quality of the pressure-extruded spaghetti (35).

Since the raw material and the other technological steps of pasta-making are held constant, the results show that the processes of dough kneading and extrusion significantly affect the starch and protein macromolecular organization inside the product. This fact clearly influences spaghetti cooking quality.

The lower quality characteristics of a pressure-extruded pasta, consisting of a discontinuous protein network, can already be seen in the dough taken from the extrusion-head just before extrusion through the die holes (Fig. 8A, 8B). Therefore, the step of mere extrusion does not seem to result in ultrastructural differences between extruded and sheeted spaghetti.

By feeding the continuous press with a "worked" dough obtained by roll-sheeting, it was possible to demonstrate that dough transformation takes place before reaching the die. The "ideal" continuous protein network that this dough had when first put into the continuous press (Fig. 9A, 9B) is already lost by the time it reaches the die. The area of protein fiber breakdown is extensive in the entire field of view (Fig. 9C, 9D).

All the electron micrographs, together with the other experimental data from this work demonstrate that, in comparison with the more traditional processes, the technical step of kneading and forming carried out in the continuous press breaks down those dough structures which may affect spaghetti quality. In our case, the drop of quality is enhanced by using wheat flour whose protein, due to unsuitable gluten properties (17, 20, 21, 27) does not withstand the physical stress imposed upon it.

An explanation for protein fibril breakage could be insufficient dough development produced by auger. This phenomenon is probably related to short kneading time (28, 34) and low mechanical efficiency (10, 22) as well as the limited water content of the dough. It is well known that these factors prevent the possibility of good gluten development (9, 10, 26,

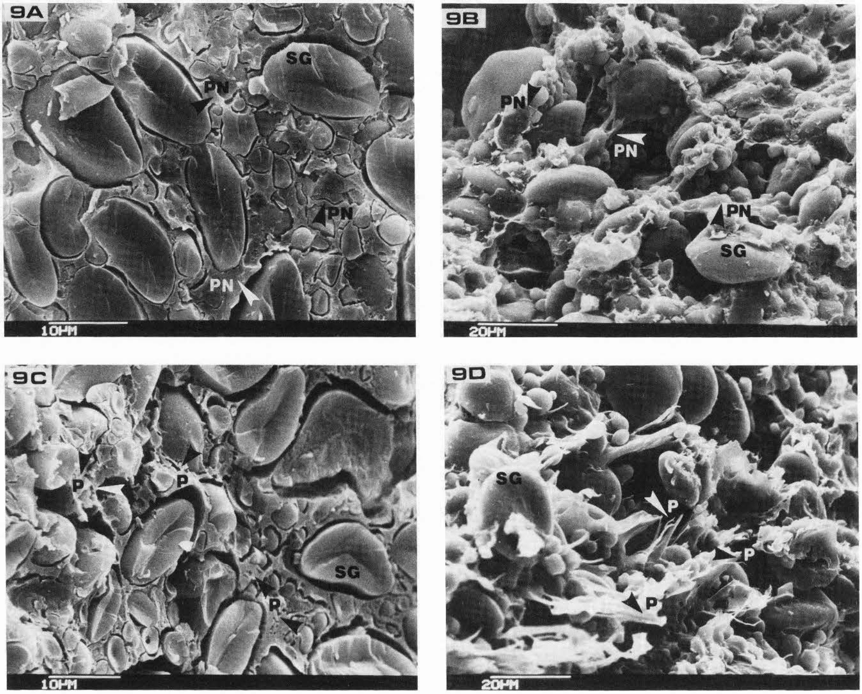

Figure 9. SEM ultrastructure of roll-sheeted dough (see text) before (A and B) and after (C and D) kneading in the continuous press by the auger. A) and C) cryo-fracturing; B) and D) dry-fracturing. The fibrils of the protein network (PN), that the dough showed after roll-sheeting, are weakened and broken (P) inside the continuous press. Arrows indicate the protein fibrils in all images.

34). In fact, the working time in a continuous press is reduced to only a few minutes in comparison with about an hour for the hand-sheeting process. The mechanical work done by the auger consists mainly in shifting the dough under pressure with coaxial rotations and laminar flow in the extrusion cylinder (26), followed, probably, by a less orderly transfer inside the extrusion-head. During sheeting, instead, the dough is formed by means of numerous passages through the rolls. As the sheet thickness is gradually reduced (by narrowing the gap between the cylinders), the dough is submitted to uni-directional and mild "stretchings" which promote an ordered and uniform gluten development. The same kind of dough structure results with the hand-working process.

The different mechanical stresses of the two kinds of dough forming could also be an explanation. Strong mechanical work takes place inside the press and induces stretching and remixing. This work is probably unsuitable for the plastic characteristics of the "developing" dough. The non-homogeneous pressure (1, 19) and the disordered movements with shearing and tearing of the dough in the last part of the machine may negatively affect the continuity of the protein matrix. It should be pointed out that, over the years, the industrial press has been improved for speed and extrusion capacity (hence for productivity - 3, 13, 34), but only somewhat improved for the regular and ordered flowing of the dough (28, 30, 34). The dough, in fact is a non-Newtonian system whose viscoelastic characteristics and behaviour during mechanical transfer are mostly unknown. On the contrary, neither the hand-working nor the roll-sheeting processes impose negative physical stress to the dough which can thus freely expand and gently form. Finally, we can presume that insufficient kneading, together with mechanical stress, may produce the micro-breakdown of the gluten network found after the continuous pressure-extrusion.

In view of the final quality of the product, kneading and forming under pressure undoubtedly represent a critical factor in the industrial process, whereas extrusion through the die, even if performed at high pressure, does not seem detrimental to pasta cooking quality. The final aim in the optimization of the kneading and forming process in the industrial press is to reach the level of spaghetti quality obtained with hand-working or, at least, with roll-sheeting, keeping all other conditions constant.

Conclusion

The results of the present investigation, obtained from cooking tests, physical-mechanical tests and ultrastructural observations, demonstrate that the kneading and forming of a pasta dough with a continuous press induces a decrease in spaghetti quality in comparison with roll-sheeting or hand-working processes. The lower quality, related to the reduced working time and to the intensity of the mechanical stress, can be explained by ultrastructure breakage of the protein matrix observed in the dough before extrusion. This finding strongly indicates that industrial pressure-extrusion used today for pasta-making is not an ideal process for making the best use of poor quality raw materials and suggests that an improvement in final product quality can be expected by improving this production step. More research is needed in order to make kneading and forming a real "biotechnological" process. In this regard, a careful examination of the ultrastructure modifications of the dough during the various steps of the process proves to be indispensable for a correct and complete evaluation of the processing conditions.

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Discussion with Reviewers

R.R. Matsuo: Why did the authors choose a blend of common wheat (T. aestivum) for their study and not durum wheat (T. turgidum var. durum)? It is particularly surprising since Italy is one of the two countries in the world that specifies 100% durum wheat for pasta products. All Italian pasta manufacturers maintain that durum wheat, especially varieties produced in Puglia, produces the best pasta with excellent texture and little surface stickiness. Therefore the obvious question is how would pasta processed by the three methods described in this paper but made with high quality durum semolina be rated?

R. Moss: Could the authors confirm that it was flour (i.e., less than 130 micrometers), and not semolina from bread wheat, that was used? Are their comments equally applicable to extruded pasta from semolina (either durum or bread wheat)? Please comment on the relative amounts of pasta made from flour versus that from the various types of semolina.

Authors: Our aim was to study the effects of different kneading and forming technologies on pasta cooking quality, the effects of which were expected to be limited. According to our experience (35), by using a raw material with poor pasta-making properties (in this case a blend of wheat flour, particle size less than 100 micrometers), it is possible to better identify the effect of a technological step on the quality of the final product. It is, however, important to emphasize that, as the production of high quality semolina is limited, the world pasta manufacture mainly consists in products obtained from durum wheat semolina of medium quality and from T. aestivum flour (21).

Presently we cannot extend our experimental results to durum wheat semolina, even if, according to reputed Italian pasta technicians (24, 34), the semolina products obtained with a sheeting process always show higher cooking quality in comparison with pressure-extruded pasta.

R. Moss: The authors conclude by stating that more work needs to be done to make the kneading and forming a real biotechnological process. They indicate that the intensity of work input in the press has an adverse effect on the protein. Have they investigated the effect of different extrusion pressures or screw design on pasta structure and porosity and hence on quality? Also, though the effect of extrusion on starch is largely ignored in the text, Figure 5A shows damaged starch granules. Does more starch get damaged during extrusion and, if so, would this not adversely influence pasta quality?

Authors: In preliminary pasta-making trials, we produced spaghetti at two different extrusion pressures: 50 and 100 atm. SEM images of both products showed a marked breakage and discontinuity in the protein network. Both types of spaghetti were judged as having poor cooking quality, even if the pasta produced at 100 atm had a little lower stickiness. In the present research, extrusion was carried out at 60 atm of pressure. This value, lower than the industrial ones (ca. 100 atm), is justified by the higher humidity of the dough we used (36% compared with 30%); that is, however, a normal humidity for sheeting processes.

The screw used in the present work had a design comparable to that of an industrial press. We have not yet investigated the effect of other screw designs on pasta quality; this aspect is related to the optimization of the press and, hence, it will be the object of future studies.

The EM images of pressure-extruded spaghetti clearly exhibit an extensive break-down of the protein network. Therefore, even if some altered starch granules have been observed, it is not possible to relate spaghetti cooking quality to these observations. We agree that starch granule damage, which can take place during extrusion [Lintas C, D'Appolonia BL (1973). Effect of spaghetti processing on semolina carbohydrates. Cereal Chem. 50, 563-570], negatively affects pasta cooking quality as the broken granules swell more quickly during cooking [Collison R (1968). Swelling and gelation of starch. In: Starch and its derivatives, JA Radley (ed.), Chapman and Hall Ltd., London, 168-193].

R. Moss: What role does increased cooking time, per se, have on pasta quality and is the time influenced by porosity? How were the number of sheeting roll passes determined, what is the influence of this factor on pasta porosity, cooking time and quality?

Authors: The optimal cooking time is evaluated as the disappearance of the central ungelatinized core of spaghetti. This factor depends on several chemical and physical characteristics of the pasta, such as protein and water content, porosity, component organization and, obviously, size of the spaghetti. For this reason we suppose that the optimal cooking time has no direct relationship with cooking quality.

The sheet of dough was fed manually into the sheeting rolls. The number of passes was chosen by visually evaluating the surface of the sheet that should appear "velvety". This aspect assures good kneading. The influence of the number of the sheeting roll passes on pasta porosity, cooking time and quality was not studied.