Production of Starch with Very Low Protein Content from Soft and Hard Wheat Flours by Jet Milling and Air Classification

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ABSTRACT

Cereal Chem. 79(4):535–543

Jet milling is a fluid energy impact-milling technique generally used for the ultrafine reduction of higher value materials. The efficiency of jet milling combined with air classification appears very efficient to separate starch from other wheat flour aggregate components and to produce wheat starch with very low residual protein content. Indeed, residual protein content of the starch-rich fraction can be reduced to <2% db with a series of successive grinding and air classification operations. Lipid and pentosan contents were also reduced in the starch-rich fraction. Nevertheless, jet milling cannot eliminate grinding differences observed between different types of wheat. Wheat hardness continues to have an effect on milling and classification yields and on the composition of air classification fractions. To obtain starch-rich fraction with only 2% protein content, hard wheat flour required a series of at least five grinding steps, whereas only three steps are necessary for soft wheat flour. Under these conditions, hard wheat flours give 24% mass yield with 12% starch damage compared with 39% yield and a low starch damage content (6.4%) for soft wheat flour. These results highlight new prospects for the development of cereal flours, especially soft wheat flours.

Wheat flour contains particles of different sizes and compositions (Fig. 1). Generally, fine particles (<10 μm) contain small starch granules (type B) and protein fragments; medium-sized particles (10–40 μm) mainly contain type A starch granules; particles >40 μm are aggregates containing type A and B starch granules bound by a protein matrix (Evers and Bechtel 1988). These different-sized particles can be separated from straight-grade flours by air classification to ultimately obtain a broad range of products for various food and nonfood applications.

Many previous studies have focused on air classification (Stringfellow et al 1962; Vose 1978; Bonnet 1984). Air classification results obtained with soft and hard wheats have been reported previously (Ranhotra et al 1992; Wu and Stringfellow 1992). The fine fraction generally has high protein content (≤20–25%), along with high-damage starch, mineral, lipid, and fiber contents. The medium fraction is low in protein: ≈5% for soft wheat flours, and 8–10% for hard wheat flours. The composition of the coarse fraction generally does not markedly differ from straight-grade flour, but it is very fluid due to larger average particle size and narrow size distribution.

Air classification can be assessed by calculating the total protein-shift percentage (δ) (Gracza 1959). This parameter designates the amount (%) of protein in the parent flour that was shifted out or into the designated fraction. This parameter varies in different cereals, ranging from ≈5% for hard non-reground flours to ≈40% for barley containing normal amylose starch (Vasanthan and Bhatty 1995), and ≤40–50% for legume flours (pea, bean, etc.), and as high as 64% for oat flour (Wu and Stringfellow 1973).

Flours must be ground to enhance starch-protein separation and, thus, yields of fine and medium fractions. Pin mills are commonly used for this purpose (Bonnet 1984; Piat 1984). Pin mills use either a fixed pin disk with an intermeshed rotating pin disk or two opposite intermeshed rotating pin disks. Flours are ground by the impact of particles against the pins. Impact velocity can reach a peripheral speed up to 150 m.sec^{-1}. Flour can also be ground in an attrition mill. This grinder generally has a vertical axis with several rotors to allow the progressive reduction of the products. Grinding principle remains close to that of the pin mill, adding in more of a cavitation effect (pressure-depressure). Attrition-milled flours have lower starch damage content than those produced by pin mills (Nowakowski et al 1986; Sosulski et al 1988). Fluid energy impact, or jet milling, is another interesting option for reducing all aggregates; it produces superfine powders (Helle 1988). Particles are accelerated in a high-velocity air or gas stream, and size reduction is the result of interparticle collisions or impacts against a solid surface. There are two general types of jet mills. One is the spiral jet mill in which particles are projected at high speed by compressed gas against each other and against the walls of the grinding chamber. The slope of the nozzles causes a draught in spiral producing a dynamic separation. The largest particles remain on the periphery under the effect of the centrifugal force and are again ground, whereas the finest particles are dragged by the slackened draught. The other is an opposed jet mill with nozzles located at the periphery of the milling chamber and laid out in opposite directions. Grinding is accomplished only by interparticle collisions. This device allowed very high impact velocities between particles. This type of jet mill is associated with a dynamic "squirrel cage" classifier that allows powder of a given fineness to exit the mill, while injecting oversized particles back into the grinding chamber. Jet milling is very effective for ultrafine size reduction. The speed of the jet at the exit of the nozzles can exceed Mach 1. Even if the speed of the particles decreases considerably in the milling zone (250 m.sec^{-1}), these apparatuses achieve speeds impossible to realize by mechanical means. But, because their specific energy consumption is high, these mills are more generally used for reduction of high end-use value materials such as pharmaceutical products.

Most studies to date on air classification of flours have been aimed at obtaining ultrafine fractions with high protein concentrations. Medium starch-rich fractions have been of little interest due to the high residual protein contents (>5%). Such fractions, therefore, could not be used in as many different ways as wet-refined starch. They are often reblended with straight-grade flours to produce special flours for biscuit making. Starch-rich fractions with lower residual protein contents obtained by dry processes could benefit from new outlets in food and nonfood subsectors.

In the present study, we attempted to improve the efficiency of dry starch-protein fractionation by grinding and separating the medium fraction several times by jet milling. We assessed the grindability of hard and soft wheat flours. In addition, the different fractions obtained at each step of the process were characterized physically and chemically.

MATERIALS AND METHODS

Flour Samples

Two commercial soft and hard wheat flour samples were used in this study. The main characteristics of the two flours are reported in Tables I and II (first line of each table). Hardness values as measured by near-infrared reflectance (NIR) (Approved Method 39-70A, AACC

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Publication no. C-2002-0604-06R.

2000) were 25 and 56 for soft and hard wheat, respectively. Precipited silica (1%, w/w) (Tixosil 38, Rhodia, Collonges au Mont d'Or, France) was added to the flours as an anticaking agent to prevent aggregation related to superfine particle handling.

Air Jet Mill

Flours were ground in an Hosokawa Alpine laboratory mill (Augsburg, Germany), a general purpose installation allowing either air jet milling with the 100 AFG module (Fig. 2A), pin milling with the 50 ZPS module, or air classification with the 50 ATP module. The system is composed of a one-piece tank with three nozzles laid out horizontally, providing converging air jets in only one point. Flours are introduced in the milling chamber by a feeding system that allows a feeding rate of 5 $kg.hr^{-1}$. In the milling chamber, particles are accelerated by air jets and reduced by impact. After they have been reduced, they are classified and evacuated by a turbine. Maximum milling pressure was adjusted to 6×10^5 Pa, and the speed of the turbine was adjusted to 4,000–6,000 rpm. Trials were also conducted with the pin mill module (50 ZPS) running at maximum speed (22,000 rpm, 100 $m.sec^{-1}$) to compare performances of the two milling systems.

Air Classifier

An Hosokawa Alpine 50 ATP turboplex classifier was used to separate the particles (Fig. 2B). Particles are conveyed by air to a classifying wheel. Fine particles below the cutoff point are evacuated to the cyclone, and the finest are retained in a filter. The coarse fraction is collected in a tank under the classifying chamber. In contrast to conventional air classifiers, the classifying wheel axis of the ATP runs horizontally not vertically. All separations were made with an air flow rate of 100 $m^3.hr^{-1}$. The cutoff point was maintained between 2 and 120 µm by adjusting the turbine speed from 1,400 to 22,000 rpm.

Milling Diagram

Flours were subjected first to a cycle of air jet milling + air classification. A fine and a coarse fraction were obtained (F1 and M1, respectively). After this run, the coarse fraction was used for the subsequent milling and air-classification step. Five cycles were performed successively with increased speeds (Fig. 3). At each step, the grinding conditions became increasingly harsh, gradually increasing the selection turbine rotation rate from 4,000 to 6,000 rpm. The fines were gradually separated with each milling stage. The mill feed rates were adjusted to mill under suitable operating conditions. Due to the particle size reduction, the mean grinding rate was progressively reduced from 4 to only 2.5 $kg.hr^{-1}$ at the end of the tests.

Particle Size

Particle size of the air-classified fractions was determined with a Coulter LS laser granulometer (Beckman-Coulter, Roissy CDG, France). Results were expressed by the value of median particle diameter (d_{50}) corresponding to the size (µm) that divides the particle distribution into two equal parts.

Analysis

Moisture content of the air-classified fractions was determined according to Approved Method 44-19 (AACC 2000). Protein (N × 5.7) was measured by the combustion method of Dumas (Approved Method 46-30) with an NA2000 apparatus (ThermoFinnigan, Les Ulis, France). Damaged starch content was measured with the Megazyme kit (Megazyme, County Wicklow, Ireland) (Approved Method 76-31). Free lipid content was determined by diethyl ether extraction followed by evaporation and weighing the residue (AACC 30-20). Total water-insoluble pentosans (WIP) and water-soluble pentosans (WSP) were determined as described by Rouau and Surget (1994).

Microscopy

Flours and air-classified fractions were individually sprinkled on double-sided adhesive tapes mounted on circular aluminum stubs. The samples were then coated with a thin layer (100 Å) of ionized platinum and examined in a Jeol JSM-6300F scanning electron microscope (Jeol Europe SA, Croissy sur Seine, France).

RESULTS AND DISCUSSION

Air classification results obtained with hard and soft wheat flours after no milling, pin milling, and jet milling are presented in Table III. Clearly better starch-protein separation was obtained with the jet milling technique. Protein content of the medium-size fraction after air classification with no milling, pin milling, and jet milling were, respectively, 10.1, 9.5, and 7.7 (db) for hard wheat and 6.9, 8.1, and 6.6% (db) for soft wheat. In addition to the impressive features of jet-milled flours, this milling system was beneficial for regrinding the medium fraction. For instance, we noted that using a jet mill to regrind the medium fraction with an initial 7% residual protein content decreased the protein content of this fraction to 4.8%, compared with 6.1% when pin milling was used for this regrinding process. On the basis of these preliminary results, variations in flour composition were investigated by initially milling the flours and then successively regrinding the starch-rich coarse fraction in a jet mill. Results obtained with hard and soft wheats using the milling steps outlined in Fig. 3 are pooled in Tables I and II, respectively.

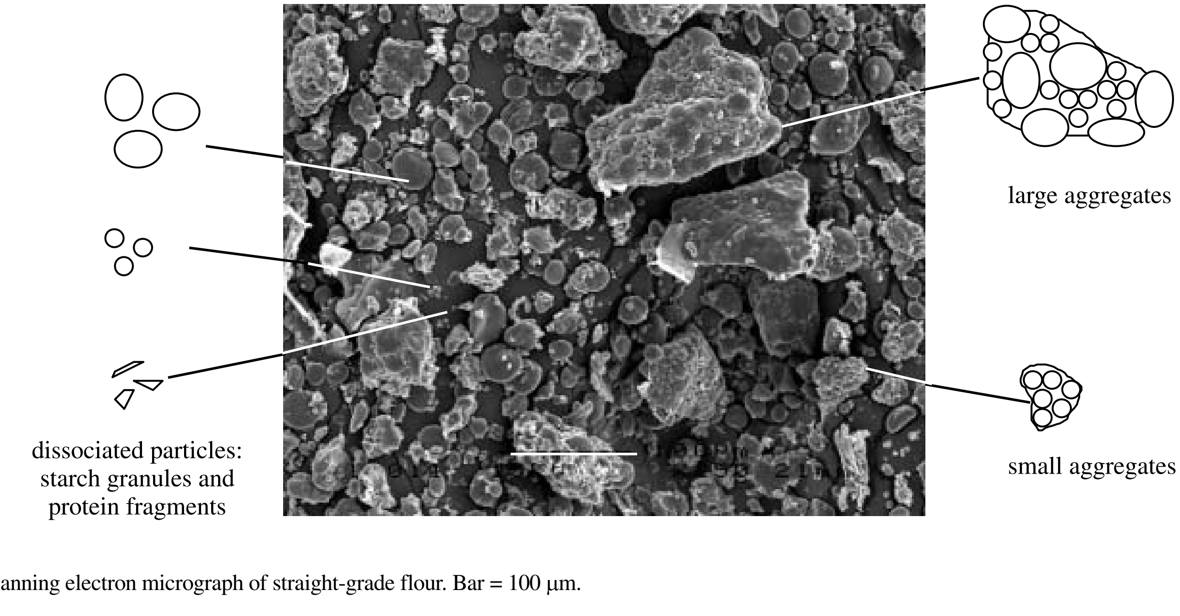

Fig. 1. Scanning electron micrograph of straight-grade flour. Bar = 100 µm.

Proteins

Protein contents were finally reduced to 1.5% (db) for soft wheat flours and to 2.5% (db) for hard wheat flours. A comparison of these results with the initial flour composition indicated that after five grinding and air classification cycles, the protein content was reduced by 87% for soft wheat flour and 80% for hard wheat flour. Proteins were substantially reduced until the 3rd milling stage, and then more moderately in the 4th and 5th stages (Fig. 4). Proteins were concentrated in the fine fractions. Fines obtained at the end of the first milling stage (fraction F1) had the highest protein concentration (20.7% for soft wheat flour and 22.9% for hard wheat flour). These results are in line with those commonly obtained for this particle size range (<15 µm) (Ranhotra et al 1992; Wu and Stringfellow 1992).

Pentosans and Lipids

Variations in pentosan and lipids (Fig. 5) were similar to the protein patterns (Fig. 4). There was a significant positive correlation between protein content and soluble and total pentosan contents (r = 0.942 and 0.940, respectively, $P < 0.001$) and between protein and free lipid contents ($r = 0.957$, $P < 0.001$). These results are in agreement with those obtained in previous studies (Ponte et al 1963; MacArthur and D'Appolonia 1977; Shogren et al 1988). The amount of pentosans and lipids eliminated from the medium fraction after three air classification runs was ≈80% and after five runs was ≈90%.

Total pentosan contents were initially ≈1.5%, and finally reduced to 0.10–0.15%. These pentosans were concentrated in the fine fractions, especially in the F1 fraction at ≈2.3%. The ratio of soluble to insoluble pentosans was generally higher in the fine fractions. Similar results were obtained for the two hard and soft wheats. However, the soluble pentosan levels seemed to be slightly higher in all hard wheat flour fractions at the 2nd milling stage.

The lipid contents for both types of flour dropped from an initial 1.30% to <0.20% after processing. The peak lipid concentration was obtained in the F1 fraction (≈1.80–1.90%). These results are similar to those previously obtained by Ranhotra et al (1992) with different hard and soft wheat flours. Moreover, according to MacArthur and D'Appolonia (1977), protein-rich fine fractions have

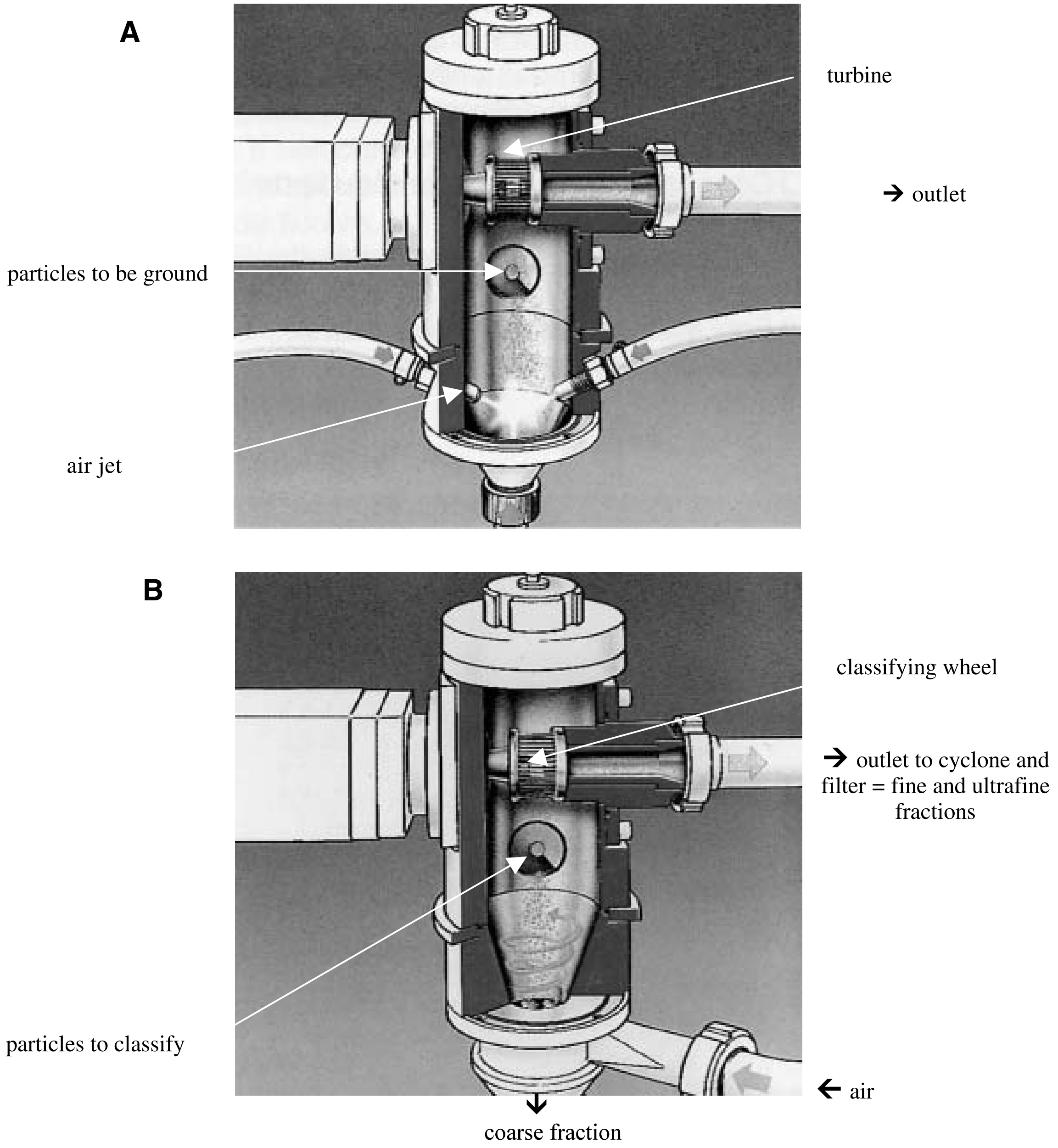

Fig. 2. Jet milling (**A**) and air classification (**B**) using Hosokawa Alpine AG laboratory mill.

a higher percentage of small starch granules than coarse fractions, and Kulp (1973) stated that small starch granules contain about two-fold more lipids than large starch granules.

Shift Rates of Different Constituents

We calculated the extent of impoverishment of the medium fraction for each constituent and each milling stream to evaluate composition and yield patterns (Table IV). The shift rate was calculated according to the formula (Gracza 1959):

$$\frac{|C_{Mi} - C_0|}{C_0} \times \eta_{Mi}$$

where: C_{Mi} = protein, pentosan or lipid content of medium fraction *i* at each step of the grinding process; C_0 = initial protein, pentosan, or lipid content; η_{Mi} = yield of medium fraction *i* at each step of the grinding process. We calculated the extent of impoverishment of the medium fraction for each constituent and each milling stream to evaluate composition and yield patterns (Table IV).

The protein shift rate was 37.6% for soft wheat flour and 29.5% for hard wheat flour, which was much higher than results generally obtained by pin milling. Vose (1978) reported a protein shift rate of 20–25% for soft wheat flours and ≈15% for hard wheat flours. Wu and Stringfellow (1992) obtained protein shifts equal to or even higher than our rates. It should be pointed out that their results were obtained after air classification of flours into five fractions instead of the two fractions used in our study. An analysis of the results revealed a decrease in the protein shift rate at the 3rd milling stage, despite the fact that the protein contents continued to significantly decline. These results should eventually be taken into account to come up with a suitable trade-off between minimum protein contents required and the cost-effectiveness of grain processing operations.

We also calculated the pentosan and lipid shift rates. Pentosan shift rates reached 34% for soft wheat flour and 28% for hard wheat flour (slightly lower than the protein shift rates of 38 and 30%, respectively). For lipids, however, the shift rate reached 40% for both types of flour. Thus, the air classification ability of the different flour components could be compared with the best results obtained for lipids, then proteins, and then pentosans.

Starch Damage

The final medium fraction after five milling stages with hard and soft wheat flours contained ≈12% damaged starch. Figure 6 shows the starch damage patterns over the milling course. For soft wheat

TABLE I
Mass Yield (%), Median Granulometry d_{50} (μm), and Chemical Composition (% db) of Air-Classified Fractions Obtained from Soft Flour

					Pentosans			
Fraction	**Mass Yield**	**d_{50}**	**Proteins**	**Damaged Starch**	**Water Soluble (WSP)[a]**	**Total (WIP)[a]**	**WSP/WIP**	**Lipids[b]**
Flour	100.0	73.0	11.4	3.6	0.41	1.42	0.29	1.30
AFG1	100.0	12.9	11.1	5.5	0.38	1.29	0.30	···
F1	34.4	6.5	20.7	7.8	0.70	2.20	0.32	1.79
M1	65.6	17.5	6.6	4.2	0.25	0.85	0.29	0.73
AFG2	65.6	12.9	6.1	6.6	0.26	0.80	0.33	···
F2	11.3	5.7	15.8	11.7	0.71	2.12	0.34	1.49
M2	54.3	15.0	3.5	5.4	0.07	0.53	0.14	0.35
AFG3	54.3	11.9	3.3	8.8	0.14	0.52	0.27	···
F3	15.7	7.8	6.6	11.8	0.36	1.08	0.33	0.50*
M3	38.6	13.4	2.2	6.4	0.06	0.25	0.23	0.29
AFG4	38.6	10.6	2.3	10.6	0.06	0.23	0.26	···
F4	5.6	4.5	5.6	13.4	0.31	0.97	0.32	0.42
M4	33.0	11.6	1.8	9.0	0.04	0.14	0.29	0.20*
AFG5	33.0	9.7	1.8	12.1	0.04	0.15	0.25	···
F5	3.5	4.7	3.9	17.2	0.23	0.69	0.34	0.35
M5	29.5	10.4	1.5	11.3	0.03	0.11	0.24	0.18

[a] Rouau and Surget (1994).
[b] * = no experimental values: calculated data.

TABLE II
Mass Yield (%), Median Granulometry d_{50} (μm), and Chemical Composition (% db) of Air-Classified Fractions Obtained from Hard Flour

					Pentosans			
Fraction	**Mass Yield**	**d_{50}**	**Proteins**	**Damaged Starch[b]**	**Water Soluble (WSP)[a]**	**Total (WIP)[a]**	**WSP/WIP**	**Lipids[b]**
Flour	100.0	95.0	12.5	6.2	0.38	1.54	0.25	1.30
AFG1	100.0	14.8	12.5	10.7	0.41	1.49	0.27	···
F1	31.2	5.9	22.9	12.2	0.74	2.35	0.32	1.86
M1	68.6	18.8	7.7	7.9	0.30	0.96	0.32	0.54
AFG2	68.6	13.2	7.4	11.0	0.34	0.99	0.34	···
F2	18.7	7.0	16.1	12.5	0.38	0.98	0.38	1.05*
M2	49.9	15.4	5.1	9.0	0.19	0.68	0.29	0.35
AFG3	49.9	12.1	4.8	12.2	0.13	0.44	0.30	···
F3	16.6	8.1	8.5	17.0*	0.32	0.77	0.41	0.46
M3	33.3	13.8	3.3	9.6	0.09	0.26	0.36	0.25
AFG4	33.3	11.0	3.4	12.3	0.10	0.28	0.36	···
F4	4.6	4.6	7.8	28.9	0.36	0.83	0.43	0.43
M4	28.8	12.0	2.9	11.6	0.07	0.24	0.30	0.22
AFG5	28.8	9.8	2.6	14.5*	0.08	0.20	0.41	···
F5	4.4	5.3	4.9	28.8	0.25	0.54	0.48	0.26
M5	24.4	10.7	2.5	12.0	0.06	0.14	0.46	0.12

[a] Rouau and Surget (1994).
[b] * = no experimental values: calculated data.

flour, the damage rate increased moderately until the 3rd milling stage (+1 point/stage, on average) and more drastically in the 4th and 5th stages (+2.5 points/stage). This pattern was steadier for hard wheat (+1.2 points/stage, on average). These starch damage levels are still quite low. From this viewpoint, the jet milling technique is, therefore, also beneficial because it provides very efficient protein-starch separation while not excessively damaging the starch component of the fraction.

Some results obtained by Wu and Stringfellow (1992) could be compared with our findings. In their study, hard and soft wheat flours were disintegrated in a pin mill and then air classified. The starch damage rate was determined in the initial flours and in the air-classified fractions. The initial flours contained very little damaged starch (≈2% for soft wheat flours and ≈3% for hard wheat flours). The soft wheat fine fraction contained 6–8% damaged starch after milling and classification, whereas the hard wheat fine fraction contained 12–15% damaged starch. In the medium fraction, the starch damage rate was ≈3% for soft wheat flour and ≈8% for hard wheat flour. These results were close to those obtained with our flours after one jet milling and air classification cycle (F1 and M1 fractions). However, the fact that our initial flours contained at least threefold more damaged starch than those used by Wu and Stringfellow (1992) indicates that the jet mill does not induce more starch damage than other milling techniques.

The extent of starch grain damage depends on the type of mechanical process that the grain has undergone (Evers and Stevens 1985). Jones (1940) considered two factors in the production of damaged starch: a surface factor that accounts for starch grain abrasion on the surface of mill rolls or other particles, and an internal factor due to forces that occur within the particles as they are processed through mill rolls. According to this author, the internal factor would account for differences in starch damage rates between hard and soft wheat. A comparison of starch damage patterns in hard and soft wheat flours according to the number of mill stages (Fig. 6) seems to confirm this hypothesis. Starch damage curves plotted for hard and soft wheat flours were parallel through the first three milling stages, followed by a marked increase in the starch damage rate in soft wheat flours. This pattern suggests that the surface factor induced mechanical breakdown of starch granules in soft wheat flours.

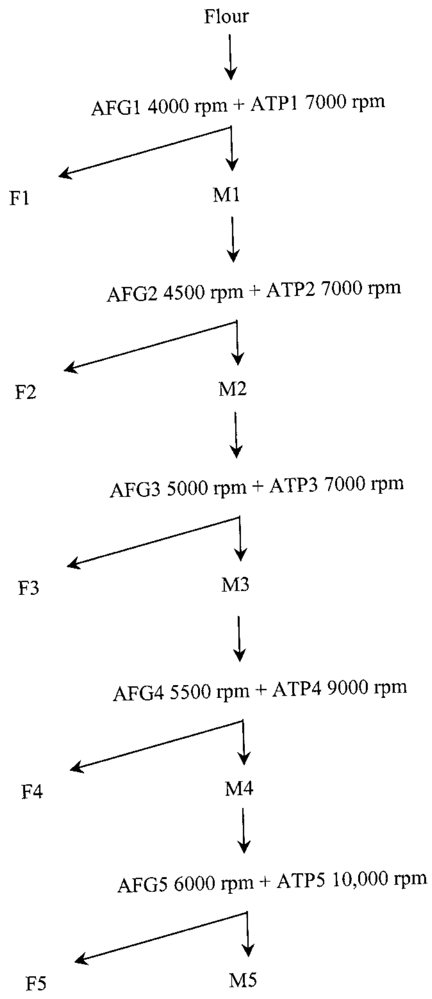

Fig. 3. Process used to prepare air-classified starch-rich fraction. AFG = air jet milling; ATP = air classification; M = medium fraction enriched in starch; F = fine fraction enriched in proteins.

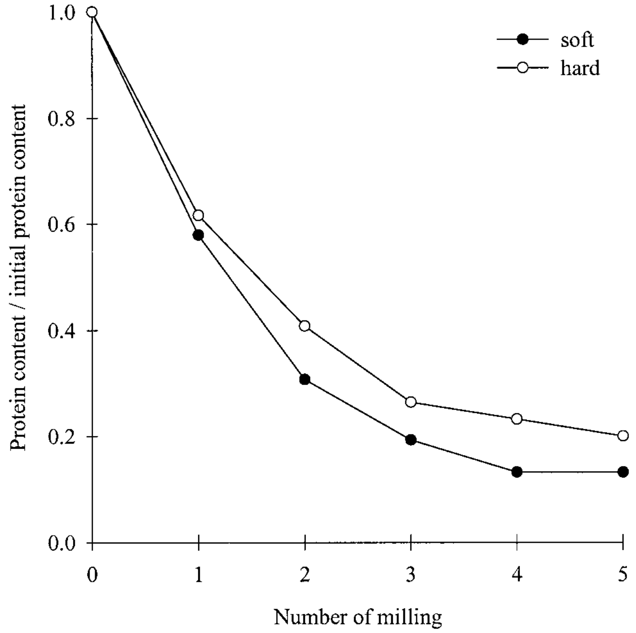

Fig. 4. Protein content to initial protein content ratio in medium fraction during five milling stages of hard and soft wheat.

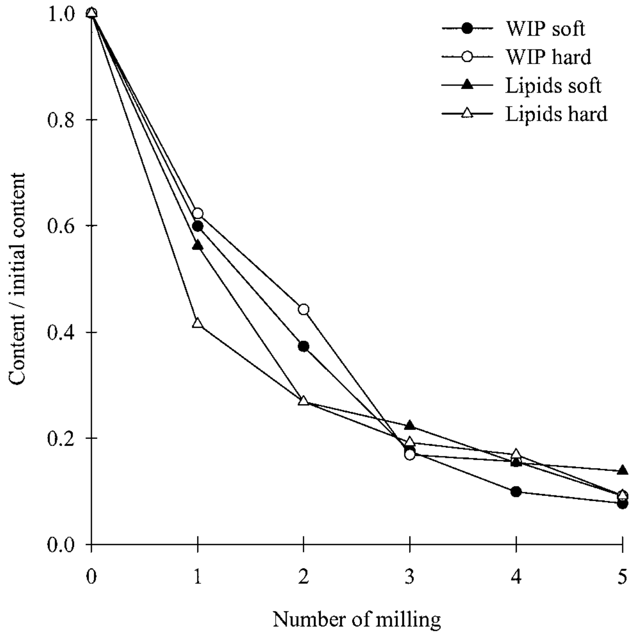

Fig. 5. Water-insoluble pentosan (WIP) content to initial WIP content ratio and lipid content to initial lipid content ratio in medium fraction during five milling stages of hard and soft wheat.

Milling Performance

Differences in milling performance between hard and soft wheat flours were assessed using jet milling. In these tests, we accurately controlled the mill load (150 g), degree of milling (pressure = 6 bar), and the grinding time in the mill (30 sec to 30 min). The curves shown in Fig. 7 give the particle reduction expressed by the evolution of the median granulometry or d_{50} kinetics of soft and hard wheat flours. For these two types of flour, there was a very substantial particle size reduction within the first few minutes of milling, but this effect faded after 5 min of milling. Hard wheat flour seemed to have greater milling resistance than soft wheat flour. Hard wheat flour showed lower particle size reduction than soft wheat flours for the same energy input. Under these experimental conditions, hard wheat flours had to be milled for ≈20 min to obtain 50% particle size reduction compared with only 5 min for soft wheat flours. These results are in line with most other previous reports on this topic (Wu et al 1990; Wang and Flores 2000). For Wu et al (1990), milling followed by air classification could be used to highlight differences between hard and soft wheat flours because there is a more substantial coarse fraction in hard wheats than in soft wheats.

Dry Starch Production Potential

The hard and soft wheat flours studied underwent the same mechanical processing. We previously showed that a more refined medium starch fraction, with a lower residual protein rate, could be obtained with soft wheat flour than with hard wheat flour. Milling yields are also better with soft wheat flour (Tables I and II). In our five-milling-stage experimental design, at the 2nd stage we noted that the soft wheat flour medium fraction yield was ≈5 points higher than the hard wheat yield. This was generally expressed by a higher protein shift rate for soft wheat flour.

Morphology of Straight-Grade Flours and Starch Granules Extracted from These Flours

Before processing, the straight-grade flours tested contained a few separated elements and many aggregates, as shown in the scanning electron microscope images (Fig. 1) and the particle size curves (Fig. 8). Soft wheat flours had 65% aggregate contents, while the hard wheat flours had 80% aggregate contents. In addition to these quantitative differences, there were qualitative differences between hard and soft wheat aggregates. In connection with the milling

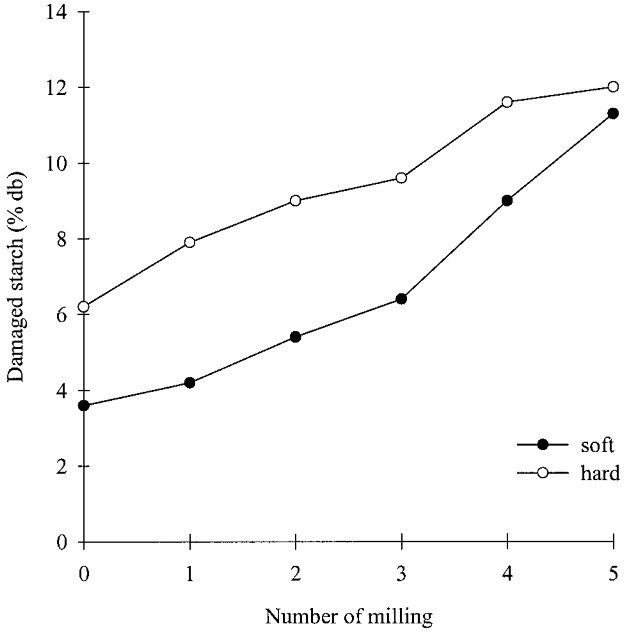

Fig. 6. Damaged starch (% db) content in medium fraction during five milling stages of hard and soft wheat.

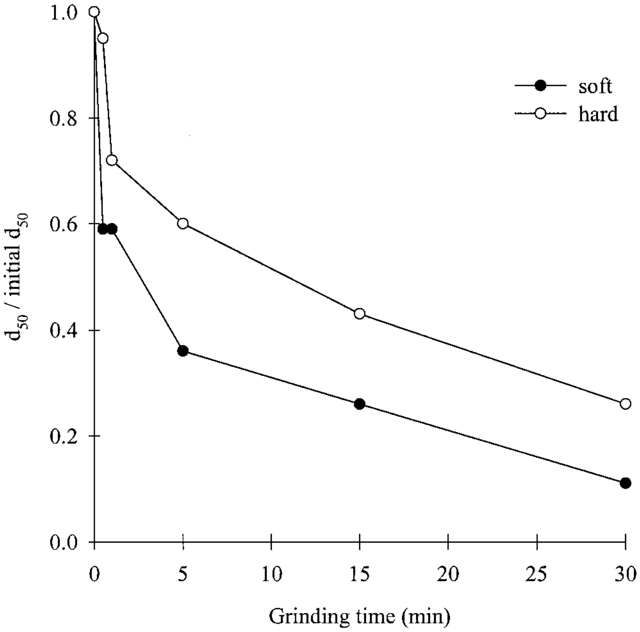

Fig. 7. Flour granulometry (d_{50}/initial d_{50}) as a function of grinding time for hard and soft wheat.

TABLE III
Effect of Air Classification After No Milling, Impact Milling, and Jet Milling[a]

	Hard Flour (initial protein content 12.5)		Soft Flour (initial protein content 11.4)	
	Mass Yield	**Protein Content**	**Mass Yield**	**Protein Content**
Air classification	15.5	10.1	27.7	6.9
Maximum impact milling (ZPS)	63.4	9.5	71.2	8.1
Maximum air jet milling (AFG)	68.6	7.7	65.6	6.6

[a] Characteristics (% db) of medium size fraction (10–40 μm) after air classification.

TABLE IV
Protein, Pentosan, and Lipid Shifts (%) After Each Step of the Grinding Process

	Soft Flour			Hard Flour		
Step	**Protein Shift**	**Pentosan Shift**	**Lipid Shift**	**Protein Shift**	**Pentosan Shift**	**Lipid Shift**
1	27.6	26.3	28.8	26.3	25.8	40.1
2	37.6	34.0	39.7	29.5	27.9	36.5
3	31.2	31.8	30.0	24.5	27.7	26.9
4	27.8	29.7	27.9	22.1	24.3	23.9
5	25.6	27.2	25.4	19.5	22.2	22.1

performance, the protein matrix of hard wheat aggregates seemed to be very compact (Fig. 9B), completely covering the starch granules, but this feature was not noted with soft wheat aggregates (Fig. 9A).

Morphological variations in the medium fraction obtained after the different milling stages with hard and soft wheat flours are shown in Fig. 10. With each successive milling stage, the product became increasingly homogeneous in terms of particle size and composition. An analysis of these photographs and the laser granulometry data (Tables I and II) revealed similar particle size variations in the two types of flour. However, the hard wheat products clearly had excess protein contents, especially after the initial air classification runs (M1 fractions).

All large aggregates (>40 µm) were eliminated during the first milling stage (Fig. 8, Fig. 10A and D). Residual proteins in the M1 fractions were then identified in two forms: small aggregates or protein fragments adhering to the surface of starch granules. The aim of successive regrinding is to separate these small aggregates and clean the surface of already separated starch granules. After regrinding the medium fraction twice (M3 products), we detected very few remaining small aggregates and the starch grain surfaces seemed cleaner.

During successive regrinding operations, the particle size range of the resulting products was narrowed and the mean particle size dropped to ≈10–15 µm compared with 15–20 µm initially (Fig. 8). The largest starch granules tended to break. In the last milling stages (M5 products), the starch granules appeared to be very broken, even in soft wheat flours. These results are in line with the already noted high increase in the starch damage rate after the 3rd milling stage.

CONCLUSIONS

Compared with standard impact milling, jet milling produces wheat flour fractions with better separation of the flour constituents. In our experimental conditions, air classification results obtained after grinding the same flour shows that the protein shift rate increased from 15 to 26 for a hard wheat flour and from 21 to 28 for a soft wheat flour between pin milling and jet milling. In fact, jet mills markedly boost the kinetic energy of flour particles, which are much more accelerated than in a pin mill. As the grinding occurs only by interparticle collisions, energy dissipated in heating is lower than in pin milling. Therefore, milling energy efficiency is higher for jet milling, even if it consumes threefold more energy than a conventional impact mill (Degant 1996). In addition to energy input, performance seems to be specifically associated with the mechanical processes involved with this type of mill. Shocks between particles disintegrate flour particles but also erode them, thus erosion milling would be more efficient for separating starch from other flour components, especially proteins.

After successive milling and air classification runs, there is a steady drop in protein, pentosan, and lipid contents in the starch-rich coarse fraction. Differences in performance between hard and soft wheats are gradually reduced with the number of successive milling stages, but differences are still noted according to the hardness of the wheats being milled.

Soft wheat flour grinds easier and has better milling yields, protein contents, and starch damage rates. A series of five grinding stages is required to obtain hard wheat flour with ≈2% protein content, whereas only three grinding stages are necessary for soft wheat flour. Under these conditions, hard wheat flours give 24% mass yields with 12% starch damage compared with 39% yields and a low 6.4% starch damage rate for soft wheat flour. For soft wheat flour, there is little advantage to continuing mechanical processing beyond the 3rd milling stage. The refinement gain levels off at the end of the grinding and classifying series, whereas there is a drop in yields and starch quality (damage rate).

Combining jet milling and air classification enhances dry separation of starch from other flour components. The results obtained in this study demonstrated that wheat starch with <2% residual protein content can be obtained by dry milling and classifying processes. These results could thus boost wheat development prospects to obtain new fractions with made-to-order composition. For more fundamental research, these new fractions could enhance analyses on the composition, and especially the nature of proteins, found on the surface of starch granules.

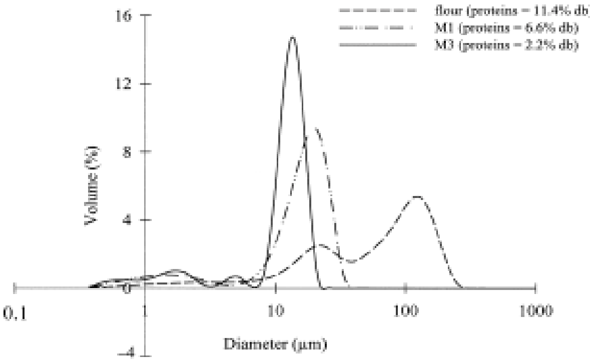

Fig. 8. Granulometric profiles obtained for straight-grade soft flour, first medium fraction (M1), and third medium fraction (M3).

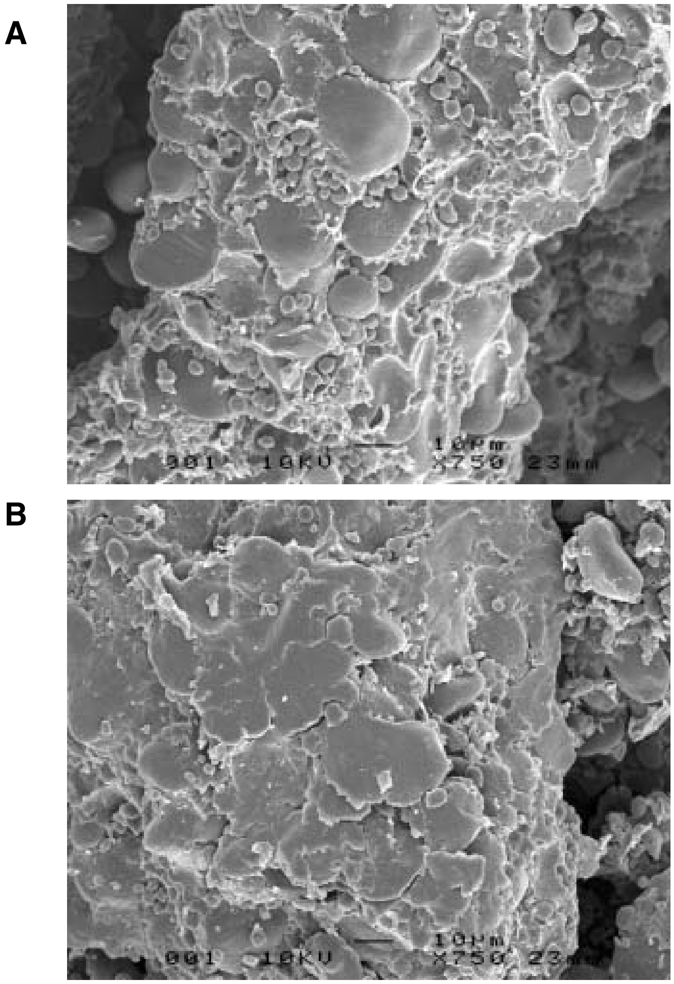

Fig. 9. Scanning electron micrographs of protein matrix of soft wheat (**A**) and hard wheat (**B**). Bar = 10 µm.

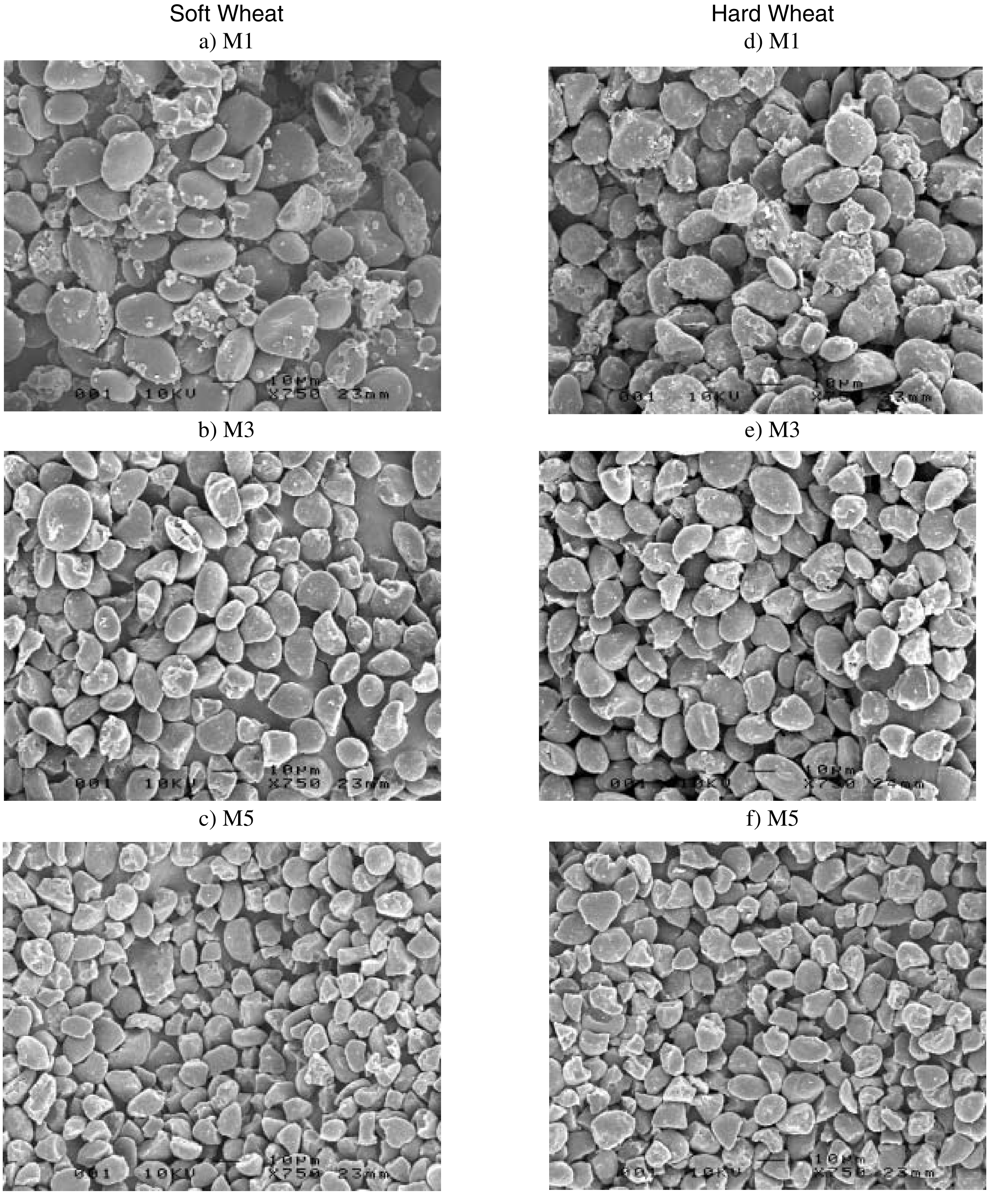

Fig. 10. Scanning electron micrographs of morphological variations in medium fraction at different milling stages of hard and soft wheat. Bar = 10 µm.

ACKNOWLEDGMENTS

This research was in part supported by the French Ministère de la Recherche et de la Technologie, under the European Program EUREKA "WIN" (Wheat for Industrial Needs) and by the French Agence de l'Environnement et de la maîtrise de l'énergie, Agrice Program.

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[Received July 30, 2001. Accepted February 23, 2002.]