Description of a Micromill with Instrumentation for Measuring Grinding Characteristics of Wheat Grain

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ABSTRACT

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A new method for characterizing the grinding characteristics of wheat grain is described. A micromill was designed for this purpose and equipped with on-line torque transducers to obtain accurate measurements of mechanical energy consumption during milling. This micromill can be used for testing the milling performance of small quantities of grain (100 g). It can distinguish between different types of wheat grain (soft wheat, hard wheat, durum wheat) on the basis of total specific energy during milling. Wheat characterization can be enhanced by taking particle sizes of the milled products into account. A milling index based on energy consumption and particle size reduction was developed to characterize wheat behavior during milling. This index had a high discriminatory potential, ranging from 100 kJ/kg for soft wheat flour to 600 kJ/kg for durum wheat flour. This micromill directly measures the grinding resistance of wheat kernels as a function of both the kernel hardness and vitreousness, contrary to standard kernel hardness measurements obtained by particle size index and near-infrared reflectance analysis techniques that only reflect the fracture mode (fine particle reduction potential).

The mechanical properties of wheat grain have to be established to be able to predict its behavior during milling. Based on this information, millers could optimize grain preparation and mill adjustments to enhance milling yields and end product quality (particle size, purity, and starch damage). Moreover, these mechanical properties are key considerations for wheat breeding programs aimed at creating new cultivars to yield grain with high semolina or flour milling efficiency.

The mechanical properties of wheat grain are usually assessed on the basis of kernel hardness tests as described by Pomeranz and Williams (1990). Penetration tests and crush resistance tests are performed on single wheat kernels but have to be replicated with many kernels to obtain statistically representative results. Other kernel hardness tests are performed on test samples containing a few grams of wheat grain. These involve indirect measurements to determine particle sizes of break flours after grinding under standard conditions using particle size index (PSI) and near-infrared reflectance (NIR). Such tests are effective for distinguishing between different types of wheat. Unfortunately, wheat hardness has never been clearly defined, and published results are often expressed in arbitrary units that sometimes do not accurately reflect the actual physical situation.

Mechanical properties of wheat grain are difficult to measure because of morphological differences between kernels: the depth and width of the crease can be responsible for more marked differences in measurements than induced by the intrinsic properties of the endosperm. Studies have thus focused on obtaining uniform sized endosperm samples. In one of the first of these investigations, Glenn et al (1991) formed cylindrical samples with a small lathe. In addition, a new rapid method has just been developed to produce parallelepiped samples (Haddad et al 1998). The parameters measured are Young's modulus, failure stress and strain, and failure energy. It would be of considerable interest to have access to the basic mechanical properties of wheat endosperm. However, it should be kept in mind that grain is subjected to a much lower strain speed in a rheometer than between grinder rollers. Stress is induced under compression in a rheometer, whereas wheat kernels are subjected to both compression and shear stress during grinding. There is no information available in the literature on the mechanical properties of wheat grain under shear stress. Moreover, the complexity of the stress field in the reduction zone of a mill should also be noted (multiple points of application and multiple directions). Assessment of the mechanical properties of wheat grain through stress tests that accurately replicate actual grinding conditions is still probably the best way of predicting the milling behavior of wheat grain.

Perten Instruments recently marketed the SKCS (single kernel characterization system) apparatus, which has been described by Martin et al (1993). This instrument is used to determine the force required to crush a kernel between a rotating cylindrical roll and a smooth fixed crescent-shaped plate. Crushing force is measured with a strain gauge. The resulting data are generally processed with the main aim of obtaining values correlated with NIR hardness, that is, they are not really used to determine the mechanical properties of tested kernels (Gaines et al 1996).

Experimental and pilot mills can be used for direct observations of wheat grain behavior during milling. Energy consumption during milling, as measured with special instruments designed for this purpose, reflects the mechanical resistance of kernels being processed. This parameter can be assessed by measuring roll resistance during milling (torque measuring device). This type of technique is commonly implemented for assessments on cereal dough mixing apparatuses (farinograph, mixograph) but very seldom with milling apparatuses. Milling energy is often assessed indirectly on the basis of power and energy consumption measurements. Kilborn et al (1982) published a detailed description of two milling energy monitoring devices. Mechanical measurements of resistive torque can be obtained with one of these instruments; the other measures power and energy. Most of their tests were performed with the power and energy monitoring instrument. Total energy consumption for a complete milling operation ranged from 46 kJ/kg for a soft wheat cultivar to 124 kJ/kg for a durum wheat. Kilborn et al nevertheless pointed out that there was very little difference in energy consumption during passage through the first break rolls, irrespective of the wheat cultivar tested (5–6 kJ/kg). Definite differences between wheats were only noted during the subsequent reduction process. This highlights the sensitivity limitations of these instruments. This lack of sensitivity could be explained by the fact that these mills were powered with oversized motors that were able to mill grain under any conditions while ensuring a constant roll speed throughout the milling process (roll speeds can slow down as a result of load). In addition to the physical characteristics and the wheat grain preparation, energy consumption during milling depends on the mill adjustments (Scanlon and Dexter 1986, Dexter and Martin 1993).

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It is also essential to fully characterize the milling fractions produced when assessing the grindability of wheat in a roller mill. The most common particle size analyses involve sieving and laser granulometry (Hareland 1994). The created surface can be calculated on the basis of particle size distribution curves or measured by gas sorption (Shimiya and Yano 1987).

As little information has been published on the measurement of wheat milling energy, we decided to design and develop a micromill to obtain accurate measurements of mechanical energy consumed during milling. This article describes this instrument and its performances.

MATERIALS AND METHODS

Wheat Samples

Three batches of wheat with very different physical characteristics were studied: Scipion (soft wheat-floury grain), Baroudeur (hard wheat-floury and vitreous grain), and Néfer (durum wheat vitreous grain). We also present results obtained in a series of tests on 19 French common wheat cultivars harvested in 1998. The protein contents (NF V03-050) and NIR hardness values (Approved Method 39-70A, AACC 2000) were obtained for these cultivars. Grain vitreousness was also assessed by analysis of kernel cross-sections (obtained with a Pohl kernel cutter, Versuchs und Lehranstalt für Brauerei, Berlin, Germany). NIR hardness and vitreousness values ranged from 0 to 100.

Wheat samples of 100 g were used for the micromill grinding tests. A conical sample divider was used to obtain uniform batches representative of the wheat cultivar under study. The moisture content of wheat grain was generally ≈12% (percentage of total mass), and was increased to 15% for the grinding tests simply by moistening the grain samples with water. The batches were then set aside for 24 hr (including 1 hr of agitation) before milling.

Micromill

It is important to conduct tests to assess the grinding characteristics of wheat grain, which would be of interest to wheat and semolina millers, under the milling conditions encountered industrially. Our micromill design (Figs. 1 and 2) was based on the crushing roller mills used in the initial stages of cereal milling with two exceptions. First, the rolls are ≈1/20 the length of standard rolls and 1/3 the diameter. Small grain samples can be milled at this reduced scale, which is ideal for testing improved wheat cultivars developed in breeding programs. However, at constant grain size and roll gap, the reduced roll diameter decreases the grinding length. For a kernel 3 mm thick and a roll gap of 0.70 mm, the grinding zone is ≈1 cm long in the micromill as compared with 1.5–2 cm in an industrial mill. The treatment the kernel receives in the grinding zone in both cases is therefore not identical, but we verify that it is still quite comparable. Second, the micromill's instrumentation records representative levels of absorbed mechanical energy during the particle sizing process (grain, semolina, bran).

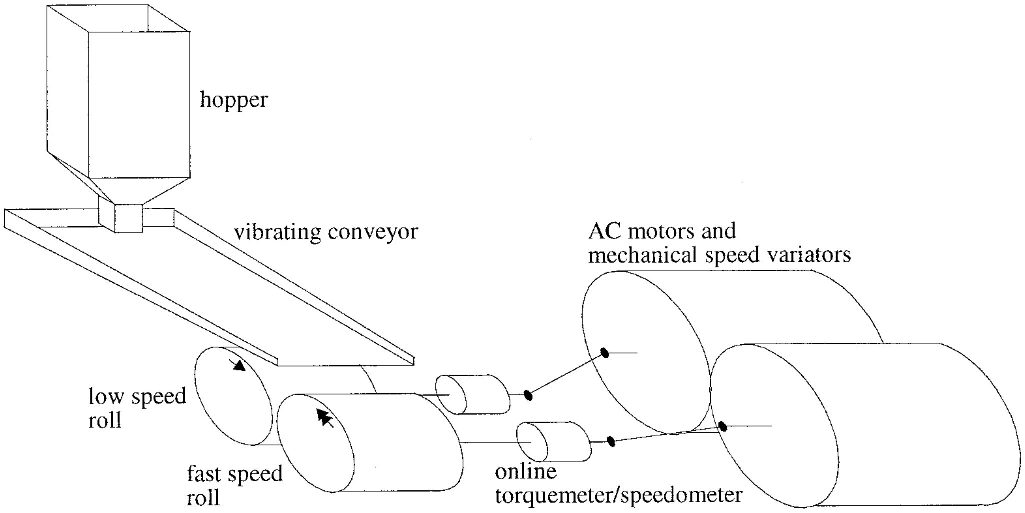

Fig. 1. Functional diagram of the INRA-UTCA micromill.

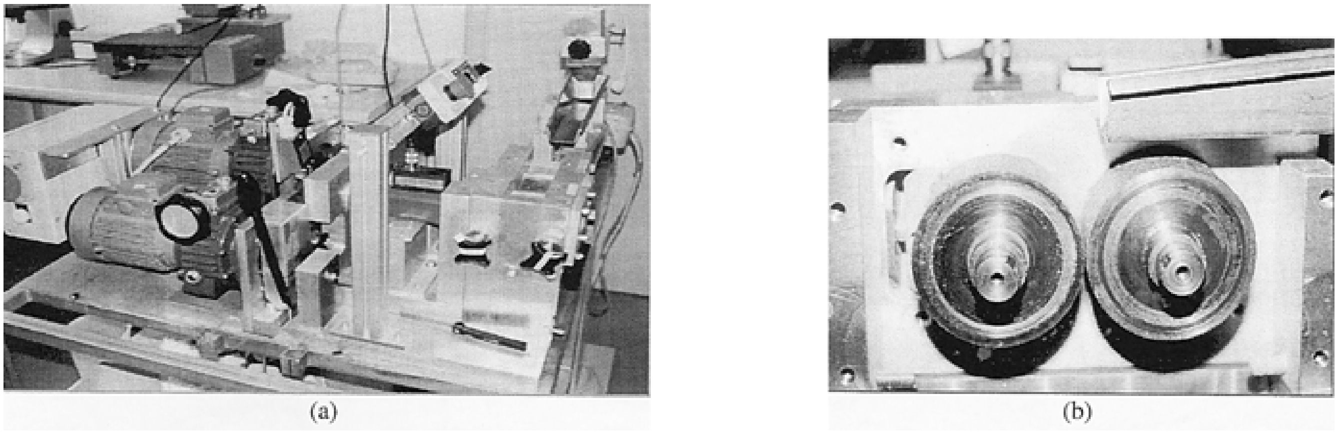

Fig. 2. INRA-UTCA micromill: (**a**) overall view (**b**) front side.

In a grinding operation, wheat grain is stressed, leading to separation of the seed coat and endosperm and subsequent reduction of the endosperm. In the micromill, as in an industrial mill, the stress is induced as the kernels are forced between metal rolls rotating in opposite directions. The maximum theoretical size of kernel particles after passage through the grinding zone is determined by the roll gap settings. On the micromill, the roll gap adjustment ranges from 0 to 3 mm and the gap is adjusted with gauge blocks. The micromill is equipped with Moulin Chopin-Dubois rolls (Tripette and Renaud, Paris, France) measuring 80 mm in diameter and 50 mm in length. The rolls are either corrugated (30°/60° profile, 8 corrugations/cm, 13% inclination) or smooth. Kernels are ground on the corrugated rolls. Roll arrangement can be varied to emphasize compressive or shear forces as a function of the roll corrugation configuration (dull-to-dull, dull-to-sharp, sharp-to-sharp, and sharp-to-dull). The smooth rolls are mainly used in the final reduction and refining steps with soft wheat semolina. We can adjust the speeds of each separate roll on the micromill, which means that particles can be subjected to a wide range of stresses. The roll speed (200–1,000 rpm) is controlled by a mechanical speed selector (Spaggiari Trasmissioni SF005, Italy) corresponding to peripheral speeds of 0.8–4.2 m/sec. When the rolls are rotating at the same speed, the particles are mainly subjected to compressive force, whereas at non-null differential speed, they are subjected to compressive and shear forces simultaneously.

In standard micromilling conditions, the corrugated roll configuration is dull-to-dull with a fast roll speed of 500 rpm, a roll differential speed of 2.5, a roll gap of 0.70 mm, and a linear mass feed rate of 290 kg/hr/m. By comparison, the main characteristics and settings of conventional rolls in a commercial first break mill are 1,000 mm in length, 250 mm in diameter, 4 corrugations/cm, 45°/65° profile, fast roll speed of 400 rpm, roll differential speed of 2.5, roll gap of 0.40 mm, and feed rate of 2500 kg/hr/m.

The reliability of the energy data partially depends on how efficiently particles to be milled are fed into the grinding zone. This efficiency depends on two main parameters: the extent of feed rate control and how uniformly the milling stock is distributed over the rolls. The stock feed system adopted for the micromill comprises a vibrating feed chute (Sinex Industrie, La Couronne, France) that receives stock to be milled through a nonvibrating infeed hopper positioned an adjustable vertical distance from the chute (relatively thick initial layer of feed stock). The feed rate is adjusted by modulating the power of the electromagnetic vibrator, thus altering the flow speed of the layer of stock to be milled, not the thickness of the stock. A weighted calibration correlates the power control component and the mass flow rate. This calibration has to be done for each type of milling product (grain, semolina, bran).

Instrumentation

During milling operations, the micromill supplies information on mechanical torque and roll speed. A torque transducer is connected to each separate roll (Staiger Mohilo 0411 model transducer, Schorndorf, Germany), placed on the kinematic chain between the motor-reducer component, the mechanical energy "producer", and the mill roll, the mechanical energy "consumer". The torque transducer thus rotates at the same speed as the roll. It is technologically designed to transmit information, through an electromagnetic field and without contact, from the mobile part of the transducer to the immobile part. Then it is relayed to a data acquisition system by an electrical connection. The transducers differ technologically from those used in standard systems, they comprise resistive strain gauges that are bonded to a proof body subjected to torque moment-induced microstrains. The transducer used in our micromill is unique because this delicate technology is absent, and it processes disturbances in magnetic lines of force between a passive rotor and a stator containing coils and detection electronics. Indeed, the transducer is highly reliable, sturdy, and cost-effective as there are no fragile components, and data are transmitted electrically between the rotor and the stator. The measurement range of this torque transducer is ±20 N•m, with ±0.5% accuracy (DIN1319), with >0.1% reproducibility (DIN1319), and a signal rising time $<3 \times 10^{-4}$ sec (i.e., 10–90% of the measuring range). The output signal ranges from –5 to +5V. The transducers have a permissible overload capacity of 130% of the measuring range and >400% before mechanical failure of the torque transducer. SEFCO R G02-0 (Colman Cuvelier, Lille, France) calibrated rolling torque limiters with an adjustment range of 8–20 N•m are connected downstream to protect these transducers.

The above-described torque transducer provides a roll speed readout. The emitted pulsed-logic signal changes logic state at a rate of 360 pulses/rotation. A Phoenix Contact MCR f/U 100K/V voltage-frequency converter (Marne la Vallée, France) harmonizes the signal (0–5V output) for the data acquisition system. The accuracy of the rotation speed readout from the voltage-frequency converter is ±0.15% of the measuring range. The response time of this converter (pulse integration time) is 18×10^{-3} sec. A graph of theoretical torque variations for each roll during milling (without speed differential) is shown in Fig. 3.

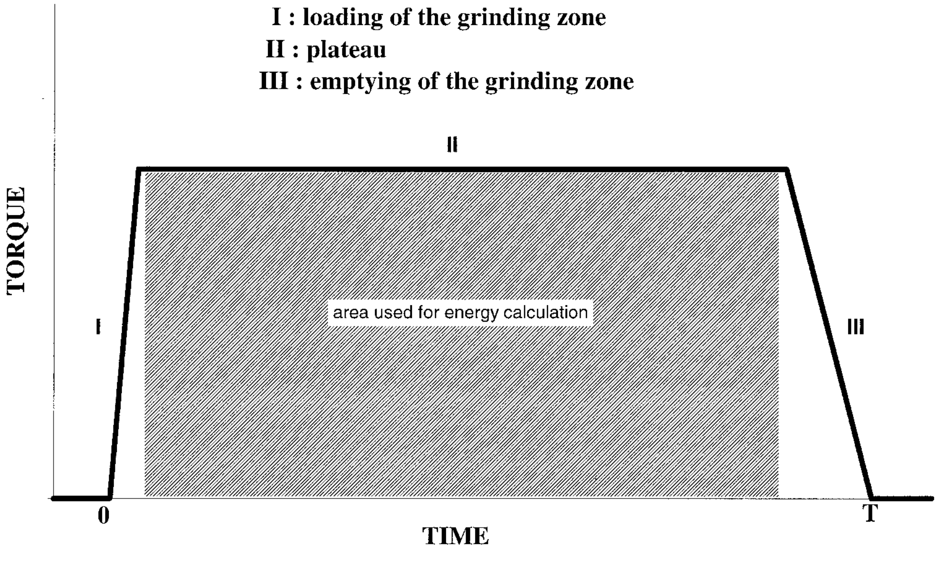

Fig. 3. Theoretical torque variations on the micromill.

There are three distinct phases. Gradual rise is the transient stabilization of the feed rate (involving the vibrating feed chute and the grinding zone). Plateau is the "stable" phase with some slight fluctuations due mainly to feed rate variations. Gradual decline is the emptying of the infeed hopper, feed chute, and grinding zone.

Online Data Acquisition

Four signals are acquired in real time, a torque measurement and a rotational speed measurement for each roll. These signals are captured by an Advantech PCL818L data acquisition card (Advantech Co., Ltd. 4F, No. 108-3, Ming-Chuan Road, Shing-Tien City, Taipei, Taiwan, R.O.C.) connected to a PC computer, and managed with a software program developed in our laboratory. With this card, 8 analogic signals (–5 to +5V, in this case) can be captured with 12-bit resolution (least significant bit = 2.44 × 10^{-3}V), and >0.1% accuracy relative to the measuring range. The program can handle a signal polling frequency as high as 100 Hz (100 measurements/sec). Tests conducted to optimize the data acquisition frequency indicated that the signal processing efficiency declines if the polling frequency drops <50 Hz. Based on these test results, the data acquisition frequency was set at 100 Hz, which is the maximum level for the data acquisition sequence used. This frequency is reconciled with the approximate kernel passage time through the grinding zone (10^{-2} sec under standard milling conditions that is the minimal data acquisition time). With a roll differential of 2.5, the same kernel will be subjected to 10–20 sharp impacts on the corrugated roll. The number of impacts depends on the size of the kernel and its location in the reduction zone.

Grain Size and Particle Size Analysis of Milling Streams

The wheat grain samples were graded first by sieving (screening with an oblong-meshed sieve; mesh size 20 mm × 3.5, 2.9, 2.4, 2.2, and 2 mm). Milling stream fractions were also sized and quantified by sieving. The milled fraction was poured into the top of a series of eight square-meshed sieves (5, 4, 3.15, 2, 1, 0.71, 0.45, and 0.2 mm). Sieving was performed for 5 min on a rotary screen (ROTEX, Tripette and Renaud, Paris). The oversized fractions were

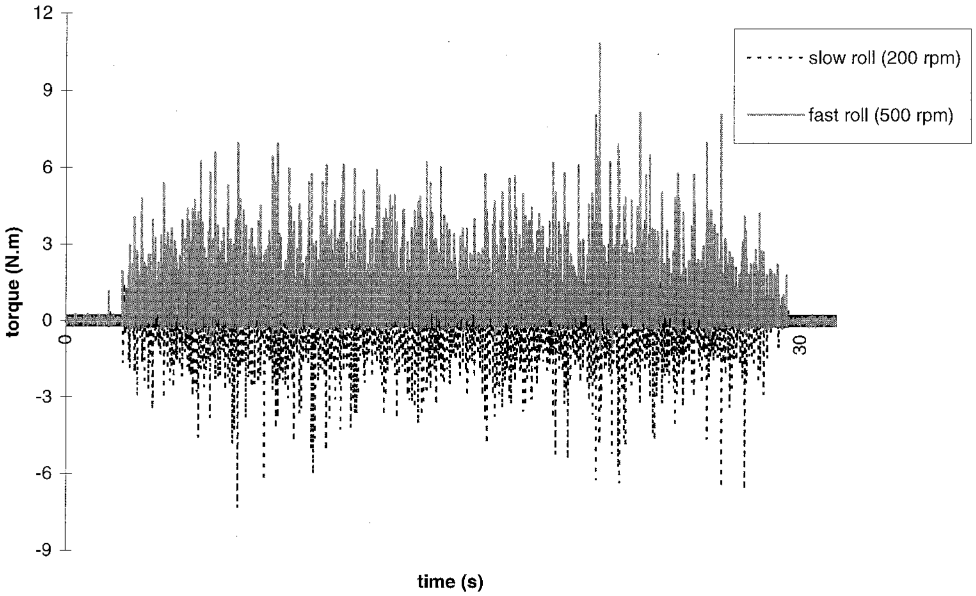

Fig. 4. Micromill torque measurements, raw signals (100 measurements per second).

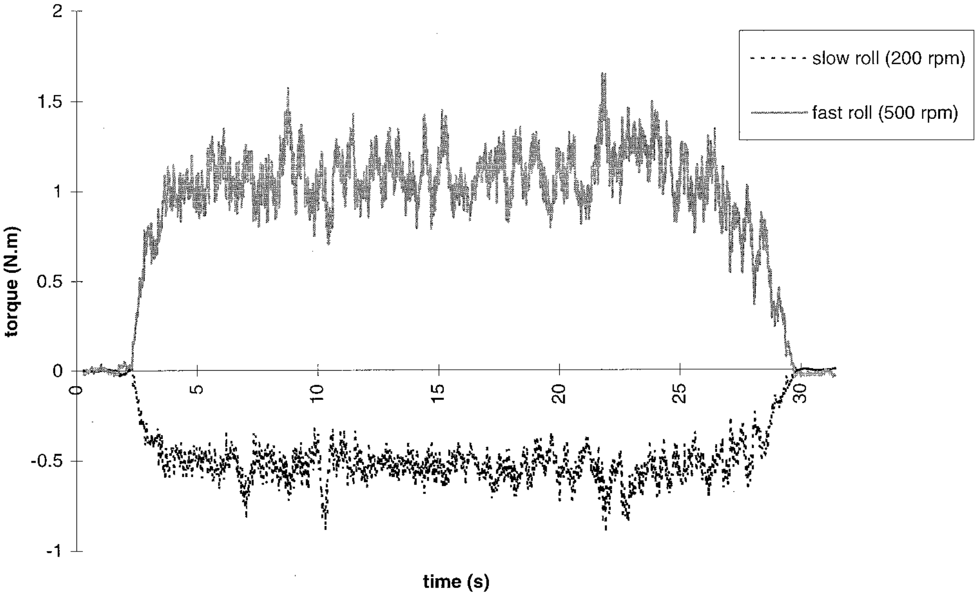

Fig. 5. Micromill torque measurements, processed signals (100 measurements per second).

then weighed. The finest fraction (flour particles <200 µm) was analyzed in a laser beam particle size analyzer (Coulter Co., Miami, FL).

RESULTS AND DISCUSSION

Data Processing

In the present study, milling products were characterized with the above-described instrumentation on the basis of the total specific milling energy (kJ/kg, db), the energy absorbed by the breaking process relative to the milled mass fraction. With the motor torque, roll speed, and feed rate known, data processing steps were followed to determine specific milling energy.

Filtering the Raw Torque Signal

The torque signal is acquired through $C = f(t)$ recordings, where C corresponds to mechanical torque measured on a roll (N•m) and t represents time (sec). Figure 4 shows a typical recording of a raw unprocessed signal obtained under standard micromilling conditions. The torque measured on the fast roll was positive, while that measured on the slow roll was negative. The fast roll actually modifies the speed of the slow cylinder (and vice versa) as the feed stock transits through the grinding zone. The extremely disturbed aspect of the signals could be explained by the vibrations produced when kernels are crushed under the impact of nipping points on the corrugated roller during passage through the grinding zone. These raw signals are hard to process. To gradually eliminate this signal noise and take only the slow underlying variations into consideration, we apply a running mean to the raw signal with the following sequence: (Y1+Y2+...+YN)/N, (Y2+Y3+...+YN+1)/N, (Y3+Y4+...+YN+2)/N,... where N represents the period, determined in numbers of points, selected for filtering the signal. Considering the conditions of acquisition that were used, 30-points seemed to be a suitable tradeoff between efficiently eliminating all signal noise and preserving the highest amount of pertinent information transmitted by the signal. Figure 5 shows the results of applying the running mean to the raw signal recording presented in Fig. 4.

Specific Milling Energy Requirements

The torque curves highlight three distinct phases: gradual increase, plateau, and gradual decline. These three phases are bordered by two short intervals when torque was close to zero. These intervals serve a dual purpose: compensating for transducer-related offset, and checking the stability of the baseline data and then compensating for any potential drift. In the calculations that follow, index 1 refers to the slow roll and index 2 to the fast roll. The energy requirements for each roll (E_1 and E_2) are calculated by integrating the areas under the torque curves (C_1, C_2):

$$E_1 = \frac{\omega_1}{M}\int_0^T C_1(t)\,dt \quad \text{and} \quad E_2 = \frac{\omega_2}{M}\int_0^T C_2(t)\,dt \tag{1}$$

The roll speeds (ω_1, ω_2) were almost constant throughout the grinding period (T) in these milling tests. M represents the mass of the milled wheat fraction.

Integration was performed from 0 to T throughout the grinding period because the torque signals were almost rectangular (very short rising and falling phases) in these test conditions.

As the torque signal is digitized by the data acquisition card, the integration is actually an approximation of the real integration. The method used here did not introduce significant errors since there were many elementary integration intervals in the areas to be integrated (>3,000 for the example given in Fig. 5).

Total Specific Milling Energy

As the energy transmitted to the two rolls is known, the algebraic sum represents the total mechanical energy absorbed during the break process, hence: $E_t = E_1 + E_2$.

Reproducibility of Energy Measurements

Reproducibility of energy measurements was assessed under standard micromilling conditions. Measurements were recorded on 12 soft wheat (Scipion) samples (100 g). Between-test disassembly and assembly of the micromill were taken into consideration in the results.

The parameters considered are mean torque levels in the stable zone (C_1^{mean}, C_2^{mean}), the area under the torque curves,

$$\left(\text{area } 1 = \int_0^T C_1(t)\,dt\ ,\ \text{area } 2 = \int_0^T C_2(t)\,dt\right) \tag{2}$$

and energies E_1, E_2, and E_t.

The results are summarized in Table I.

Observed variations in C_1^{mean} and C_2^{mean} (0.07 and 0.14 N•m, respectively) were only slightly higher than the torque transducer accuracy limits (0.5% of the measuring range, or 0.05 and 0.10 N•m, respectively). This means that there was very little variability specifically related to the use of the micromill. The coefficient of variation for the total specific milling energy was <2%.

Sensitivity of Energy Measurements

The discriminatory potential of the micromill was assessed by testing three different types of wheat in standard conditions: one soft wheat (Scipion), one hard wheat (Baroudeur), and one durum wheat (Néfer). The torque measurements and energy calculation corresponding to the soft wheat are given in Table I. For the hard and durum wheats, we obtained –0.98 and –1.23 N•m for C_1^{mean}, respectively, 2.02 and 2.51 N•m for C_2^{mean}, respectively, and 18.0 and 19.6 kJ/kg, respectively, for total specific milling energy E_t.

Energy results for the first break process were higher and much more discriminatory than those reported by Kilborn et al (1982) and were also in agreement with the results of other previous studies (Godon and Willm 1991) where energy consumption in the first break rolls was >4 kJ/kg for vitreous wheats and lower for floury wheats.

The specific milling energy of hard wheat was much higher than that of soft wheat (+36%). There was also a significant but more moderate (+9%) difference in the specific milling energy results obtained for durum wheat and hard wheat. In addition to energy requirements, it would be interesting to take the division state of

TABLE I
Reproducibility of Torque and Specific Milling Energy Measurements for Soft Wheat Cultivar Scipion

	C_1^{mean} (N•m)[a]	C_2^{mean}(N•m)[a]	Area 1 (N•m•s)[b]	Area 2 (N•m•s)[b]	E_1 (kJ/kg)[c]	E_2 (kJ/kg)[c]	E_t (kJ/kg)[d]
Mean	–0.60	1.17	–14.15	27.61	–3.41	16.64	13.24
Standard deviation	0.07	0.14	0.49	0.87	0.11	0.30	0.25
Coefficient of variation (%)	11.60	12.30	3.46	3.14	3.18	1.83	1.88

[a] Mean torque levels in the stable zone of the torque curves.

[b] Area under the torque curves.

[c] Specific milling energy for each roll.

[d] Total specific milling energy.

the milled product (surface creation or particle size) into consideration to be able to better determine differences between wheat cultivars processed in the micromill.

Milling Index

Mechanical resistance to grinding can be efficiently assessed by correlating the amount of energy consumed with the particle size reduction obtained (difference between initial and final particle size distributions).

The milling index can be calculated on the basis of several size reduction theories. For instance, the classical theories of Rittinger, Kick, and Bond are described by Guritno and Haque (1994) and Sokolowski (1996). Sokolowski also proposed a general size reduction theory, which can be expressed as:

$$E_t = K\left(\frac{1}{\sqrt{d}} - \frac{1}{\sqrt{D}}\right) \tag{3}$$

where E_t = total specific milling energy, K = milling index, and D, d = represent the particle sizes of the product before and after milling and

$$D = \left(\frac{1}{\sum_j \frac{G_j}{\sqrt{D_j}}}\right)^2 \quad \text{and} \quad d = \left(\frac{1}{\sum_i \frac{g_i}{\sqrt{d_i}}}\right)^2 \tag{4}$$

G_j and g_i = mass fractions of particles of sizes D_j and d_i (mean diameters between two sieves)

Based on the assumption that the surface created is due mainly to fine particle production, a milling index can be defined by correlating energy consumption (E_t) with the quantity (Q_F) of flour produced (flour = particles <200 µm), or $K' = E_t/Q_F$.

An increase in K' (or K) values indicated that, at constant energy, there will be lower particle size reduction or, at constant particle size reduction (same quantity of flour produced), more energy will be required.

The above-defined milling indexes K and K' were calculated for the three types of wheat studied and the results are presented in Table II. Under these conditions, there were marked differences between the wheat cultivars, indicating that the micromill is quite sensitive.

The K' index is easy to evaluate and very discriminatory, it could be a very useful prediction tool for millers. Our results are therefore expressed in terms of this index.

Effects of Kernel Hardness and Vitreousness

With the aim of further assessing the micromill results, we conducted a series of milling tests with batches of grain produced from pure common wheat cultivars and harvested in France in 1998. The grain batches had a wide range of NIR hardness (12–74) and vitreousness (9–82%) levels, while the protein content was 10.3–12.3%. The specific milling energy (E_t) measured with the micromill was 11.7–16.3 kJ/kg for these wheats. The quantity of flour produced (Q_F) was 7.4–12.3%, and the K' milling index was 104–219 kJ/kg of flour. In addition, the median particle size (D_{50}) of the flour milling streams, measured with a laser beam particle size analyzer, was 61–121 µm.

Grain characteristics (hardness, protein content, and vitreousness) were correlated with those obtained in the milling tests (energy, flour quantity, milling index, and median flour particle size). The coefficients of correlation (r) are given in Table III.

Within the tested interval, there was no significant relationship between the protein content and the milling results. As expected, NIR hardness was related to the particle size of the flour milling streams. This parameter thus mainly measures the fine particle production potential of a grain sample and is cultivar-dependent (Pomeranz and Williams 1990). Note that the K' milling index results obtained with the micromill, which assesses the grinding resistance of grain, was more closely correlated with vitreousness than with hardness. Multiple correlation analysis highlighted that the milling index depends on both kernel hardness and vitreousness, which is in line with millers' practices.

For the tested wheats, the weight of the vitreousness factor (V) was about twofold greater than that of the kernel hardness factor (D): $K' = 85.3 + 0.4D + 0.8V$ ($r = 0.83$). Further tests should be conducted with other wheat batches to confirm these results.

Hardness and vitreousness are wheat kernel characteristics, while the K' milling index also depends on the mechanical properties of other grain components (aleurone layer, seed coat) and geometric factors (grain shape and size). These results nevertheless highlight the advantage of using the direct milling energy measurement techniques implemented in this study. Indeed, a wide range of useful information was obtained in this study with the micromill, more than can be obtained through NIR hardness measurements alone.

CONCLUSIONS

The micromill provides a reproducible and discriminatory method for assessing the grinding characteristics of wheat grain. This tool could be used for testing a wide range of wheats and determining the effect of different factors on these properties (genetic variability, effects of agroclimatic conditions, nitrogen input, etc.).

In addition to being suitable under model milling conditions, the micromill can be adjusted to conduct tests under milling conditions closely matching those encountered in industrial settings. Micromilling results could thus be used for investigating grain milling behavior on larger scales (wheat breeding applications) and for assessing the basic mechanical properties of wheat grain with the aim of gaining a greater understanding of grain fracture mechanisms. The final practical aim of the micromill could be to predict the milling efficiency. For this purpose, the micromill will be useful not only to perform single-break tests but also simplified milling tests in several passages.

TABLE II
Milling Indexes Measured with the Micromill on Three Different Wheat Cultivars

	Soft Wheat Scipion	Hard Wheat Baroudeur	Durum Wheat Nefer
E_t (kJ/kg)[a]	13.2	18.0	19.6
D (mm)[b]	2.88	2.85	2.65
d (mm)[b]	0.72	0.86	1.045
K (kJ/kg/mm$^{1/2}$)[b]	22	37	54
Q_f (mass %)[c]	13.2	7.8	3.2
K' (kJ/kg of flour)[c]	100	231	612

[a] Total specific milling energy.

[b] K = Sokolowski milling index. D and d = particle size of product before and after milling.

[c] $K' = E_t/Q_f$ where Q_f = quantity of flour produced.

TABLE III
Correlation Coefficients (r) Between Grain Characteristics and Milling Results Obtained with Micromill Measurements of Wheat from the 1998 French Harvest

	Protein Content	Hardness	Vitreousness	Multiple Correlation
Specific milling energy (E_t)	0.51*[a]	0.65**	0.63**	0.76**
Quantity of flour (Q_f)	–0.31	–0.50*	–0.72***	0.75**
Grinding index ($K' = E_t/Q_f$)	0.41	0.61**	0.78***	0.83***
Median granulometry of flour (D_{50})	0.29	0.93***	0.38	0.93***

[a] *, **, *** = Significant at $P < 0.05$, 0.01, and 0.001, respectively.

In terms of further development of this instrument, increasing the torque data acquisition frequency could be useful for more in-depth studies on milling phenomena (grain-by-grain trials). It should be possible to boost the data acquisition frequency to 1,000–3,300 Hz (peak level for the torque transducer used), which corresponds to >30 measurement points per grain under standard milling conditions. It would also be interesting to conduct a more detailed energy analysis with respect to the milling process by focusing on evaluating heat dissipation.

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