Determination of Hardness in Wheat Mixtures. II. Apparatus for Automated Measurement of Hardness of Single Kernels

F. S. LAI, R. ROUSSER, D. BRABEC, and Y. POMERANZ[1]

Cereal Chem. 62(3):178–184

ABSTRACT

A continuous automated single-kernel hardness tester (CASK-HaT) was developed to measure stress-strain relations during crushing of single wheat kernels at a rate of 15 kernels per minute. Six parameters, measured from stress-strain curves, permitted determination of hardness of hard and soft red winter wheat varieties from the 1984 crop. The single most important parameter for predicting hardness was the ratio of the first valley to the first peak in the curve. Soft wheats normally had a ratio greater than 0.4 and hard wheats less than 0.3. Computer software was developed for recording, differentiating, and determining composition of mixtures. An experienced operator could distinguish between crushing curves of single kernels of soft and hard wheats from visual observation of a digital oscilloscope. The CASK-HaT, combined with data processing software, was more than 90% accurate in determining compositions of blends of hard and soft red winter wheats.

The measurement of grain hardness has been the subject of many studies. As early as the beginning of this century, Robert (1910) described an apparatus designed to determine quantitatively, in terms of mean crushing-point of single kernels, different degrees of hardness in wheat. Hardness of wheat cultivars or selections varied with season and location, however, and plumpness and protein content of kernels were also important factors. This observation is of interest because numerous studies (see Pomeranz and Miller 1983 for review) have shown no correlation between protein content and hardness determined on bulk samples, rather than on single kernels. More recently, Simmonds (1974) and MacRitchie (1980) reviewed the morphological features of wheat grain, the role of hardness in milling, theories of grain hardness, and the mechanism of fracture of a single grain kernel.

Determinations of wheat hardness on bulk samples (time to grind, resistance to grinding, particle size index, and near-infrared reflectance) are rapid, simple, and reliable for testing pure varieties or selections in plant breeding programs or, in marketing channels, for testing samples that are known to contain no mixtures of wheat from various classes (Pomeranz et al 1985). These methods are of little value, however, for determining variability among individual kernels or for determining compositions of mixtures of various classes. In such cases, methods for testing single kernels can be employed. Testing individual kernels, however, is time consuming and affected by many factors not directly related to inherent differences in hardness. In addition, single kernel testing methods are subject to large sampling errors (and therefore require testing great numbers of individual kernels), are often difficult to interpret, and relate to the performance of bulk samples.

Several commercial instruments measure hardness of individual kernels; the Instron Universal Testing Machine (IUTM) is most widely known. The Ogawa Seiki O.S.K. grain hardness tester (Tokyo, Japan) measures the maximum force reached when a grain is compressed until fracture occurs (MacRitchie 1980). Neither instrument, however, is suited to test large numbers of kernels. None of the instruments provide computerized records of results and their interpretation.

We have now developed an instrument for automated loading, crushing, recording the stress-strain relation, and computerizing the results for single wheat kernels. We have also developed computer software for recording and interpreting the results. In this article, we describe the operation of a continuous automated single-kernel hardness tester (CASK-HaT) that was designed to determine wheat hardness on the basis of specific crushing patterns of single wheat kernels. The apparatus was used to test wheat varieties and selections from plant breeding programs and mixtures of wheats from marketing channels.

MATERIALS AND METHODS

All soft and hard wheat samples were cleaned and sieved by Carter Dockage Tester (Simon-Carter Co., Minneapolis, MN) to remove broken, shrunken, and damaged kernels. The samples were then equilibrated at 24°C and 60% RH for one week to obtain moisture contents of 12.2–13.0%.

We used three sets of materials in this study. The first set, used in preliminary tests, included soft red winter (SRW) wheat Pike and hard red winter (HRW) wheat Ram grown and harvested at Manhattan, KS, in 1983 (Table I). The second set consisted of eight hard and two soft wheat varieties. Protein contents ranged from 11.9% for Triumph to 13.3% for Vona, both HRW wheats. Bulk samples were analyzed according to four hardness assays: particle size index, Stenvert grinding resistance, Brabender grinding time, and near-infrared reflectance at 1,680 nm (Miller et al 1982). The third set of material consisted of six wheat mixtures prepared by the Federal Grain Inspection Service (FGIS), USDA, Kansas City, MO (Table II). The six samples were blends of soft (Arthur) and hard (Arkan) wheats.

Development of the Instrument

For preliminary tests we used the SRW wheat Pike and the HRW wheat Ram, harvested in 1983, to establish the feasibility of

[1]Research chemical engineer, instrument maker, engineering technician, and research chemist, respectively, U.S. Department of Agriculture, Agricultural Research Service, U.S. Grain Marketing Research Laboratory, Manhattan, KS 66502.

Mention of firm names or trade products does not constitute endorsement by the U.S. Department of Agriculture over others not mentioned.

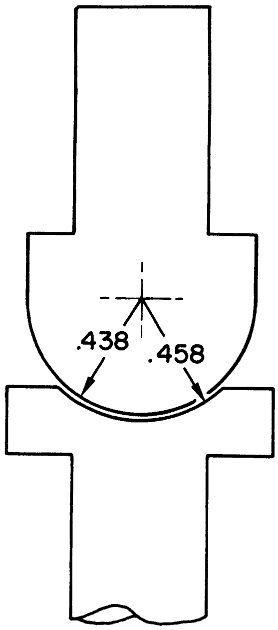

Fig. 1. Attachment for determining the force to crack or crush a single kernel.

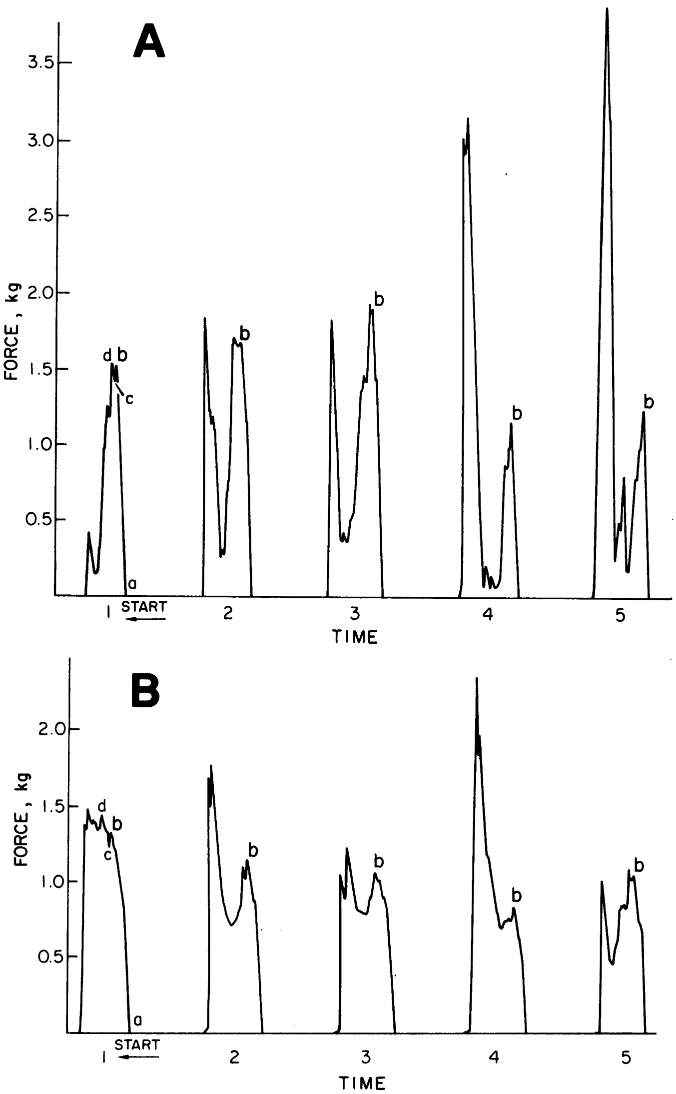

Fig. 2. Typical compression test patterns by the Instron Universal Testing Machine for kernels 1–5 of **A,** hard red winter wheat Ram and **B,** soft red winter wheat Pike. **a** = Force applied to kernel, **b** = first peak (collapse of kernel), **c** = first valley, **d** = second peak (disintegration of kernel).

using compression, shear, and puncture tests on the IUTM, model 1122 (Instron Corp., Canton, MA). For all measurements, a load cell pressure of 5 kg, a crosshead speed of 10 mm/min, and a strip chart recorder at a speed of 200 mm/min were used.

Compression Test

Compression of kernels between two flat surfaces yielded unsatisfactory results. Indentation of the surface of the lower plate with a spherical depression provided stability for a grain kernel. After a series of tests, the attachment for the final compression test, shown in Figure 1, was found to give the best results. The bottom plate was concave with a radius of 0.458 in., and the upper one was a hemisphere with a radius of 0.438 in. The gap between the upper and lower plates was adjustable. We experimented with gaps of 50, 40, 20, 15, and 10 thousandths of an inch and found that the most reproducible difference between hard and soft red winter wheat was at 15 thousandths of an inch.

The results of the test using the compression attachment (Fig. 1) on the IUTM are given in Figure 2. Note that the recording chart travels from left to right. Figure 2A shows five typical, characteristic curves of force of compression for the HRW wheat Ram as a function of time. After force is first applied to the kernel, the force increases until it reaches the first peak, at which the kernel collapses. Thereafter, the force temporarily decreases until it reaches the first valley. After the first valley, the force increases again, and eventually the head of the compression device reaches 15 thousandths of an inch from the bottom surface of the attachment. The pattern is inconsistent and difficult to interpret after the second peak, at which the kernel has disintegrated. Figure 2B shows five characteristic curves for the SRW wheat Pike.

Figures 2A and B show distinct differences in patterns. The first peak, i.e., the maximum force to collapse a kernel, was higher for the hard than for the soft wheat. An exception was the first peak of kernel no. 2 of HRW wheat Ram, which was about of the same order as kernels no. 2 and 3 of SRW wheat Pike. The patterns of collapse for the wheats from the two classes differed. The dip of the first valley in the soft wheat samples was much smaller than that in the hard wheats.

Shear Test

Shear strength is calculated from the maximum load during a shear test and depends on the original dimensions of the cross section of the specimen. The attachment we used for the shear test is shown in Figure 3. The shear bar (top of the attachment) was attached to the crosshead of the IUTM, and as the bar was lowered and the grain sheared, the force-time curve was recorded.

The results of shear tests on the IUTM using the same selections of wheats (HRW Ram and SRW Pike) as in the compression test (Fig. 2) are given in Figure 4. The shear patterns for the soft and hard wheat kernels were inconsistent. In addition, the shear test is cumbersome, because the kernel must be properly oriented and the point of the applied shearing force must be at the center of the kernel.

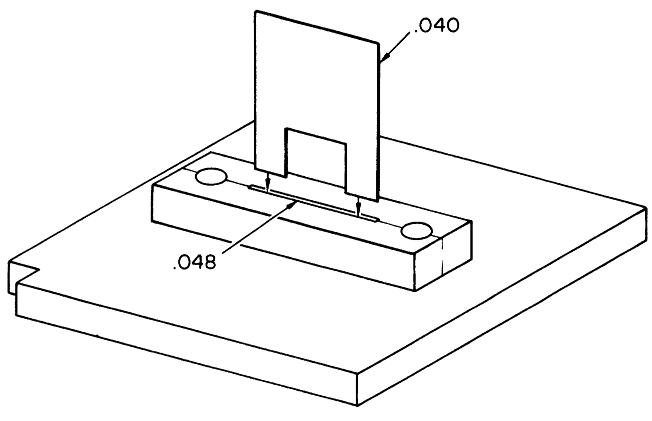

Fig. 3. Attachment for determining the force to shear a kernel. (The shear bar is at the top of the attachment.)

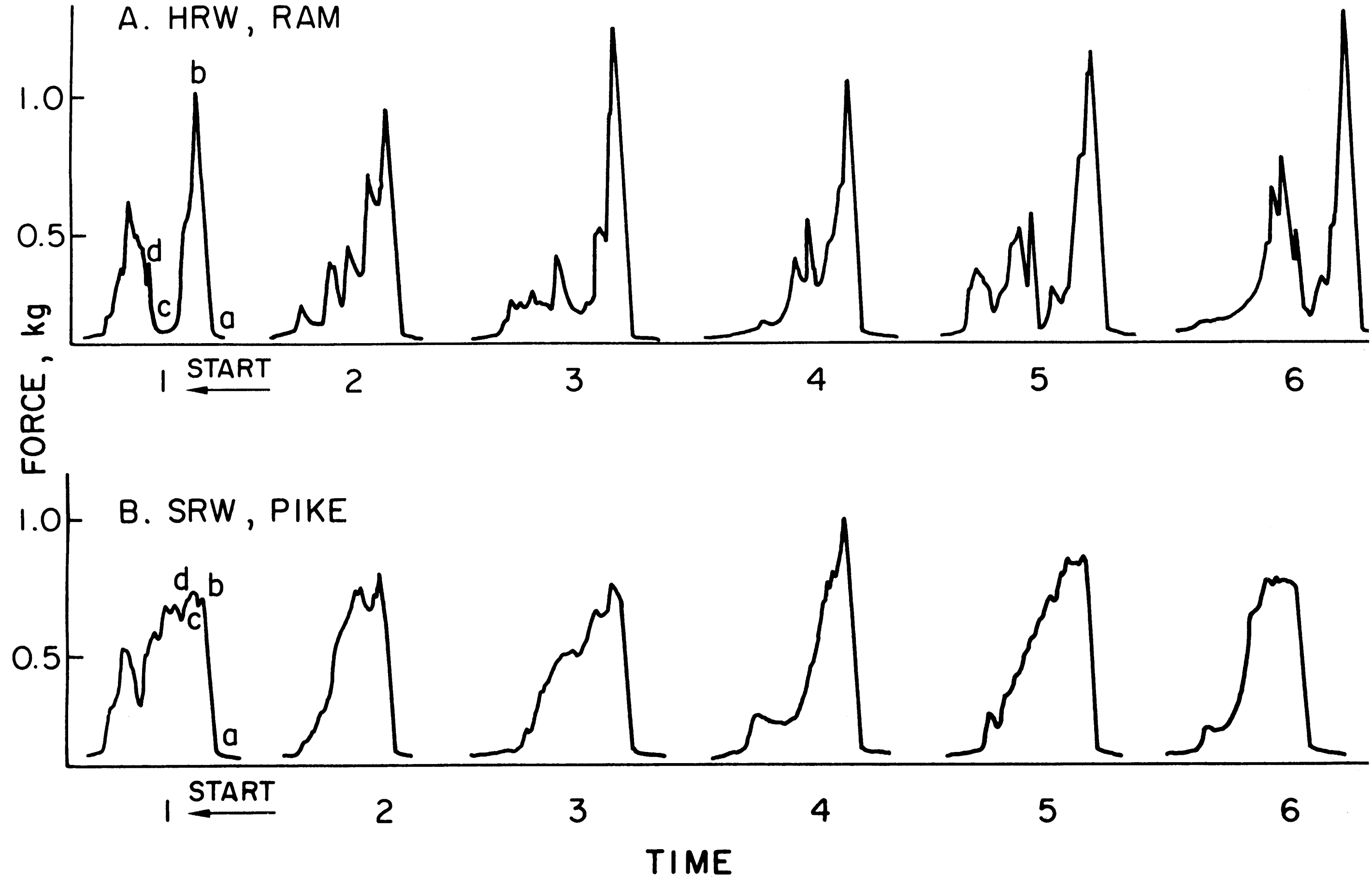

Fig. 4. Typical shear test patterns of six kernels of **A,** the hard red winter wheat Ram and **B,** the soft red winter wheat Pike, by the Instron Universal Testing Machine.

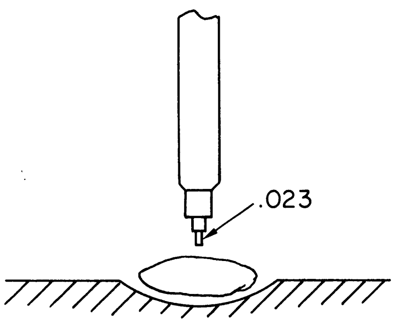

Fig. 5. Attachment for determining the force to puncture a kernel.

Puncture Test

The attachment for the puncture test is shown in Figure 5. We again used the same selections of HRW Ram and SRW Pike as in the compression and shear tests (Figs. 2 and 4). The results (Fig. 6) show a similar trend to those observed in the compression and shear tests, although there were some exceptions. The graphs produced during the puncture test were much smaller than those from the other two tests, and differences between hard and soft wheats were less pronounced.

CASK-HaT

Based on the results obtained from the IUTM, we developed the CASK-HaT (Fig. 7) to measure compression forces (stress) as a function of time (strain). The instrument can also be adapted to perform shearing and puncture tests with major changes in the feeding mechanism for proper orientation of kernels. A block diagram of the procedure is given in Figure 8. The CASK-HaT consists of the following components: vibrating feeder, vacuum line, compressed air line, kernel crushing attachment, driving cam for the crushing attachment, driving cam for the sensor, sensor amplifier, and data acquisition system. Detailed drawings of the kernel crushing attachment, its driving cam, and the driving cam for the sensor are available. The other components were from commercial sources.

A sample of grain to be tested was placed in the sample holder of a vibrating feeder (Syntron Co., Homer City, PA). The dimensions of the attachment (Fig. 1) assured, with very few exceptions, deposition of the kernels in the center of the spherical depression in the stable condition with the crease down. A line of kernels in the sample holder vibrated to a point where each was picked up by a vacuum picker controlled by a solenoid valve (Fig. 9). The vacuum line was automatically moved from the sample holder over one of the eight indentation cups in a position turntable. The turntable rotated under a fixed position angle. The cup was lifted by a driving rotating cam to meet the crushing head. The stress-strain relation during crushing was sensed by a pressure transducer (Daytronic, Miamiburg, OH) via an amplifier (Daytronic) to a data acquisition system (Nicolet, Madison, WI). After the test, the turntable advanced to where the crushed kernels were blown out of the cup by compressed air. The stress-strain relation pattern was stored in the oscilloscope, analyzed on the scope, and recorded on a floppy disk for further analysis. The data were transferred to a PDP-11 computer (Digital Equipment Corp., Boston, MA) for pattern recognition analysis. The operation was continued until the amount of stored data filled the disk. In theory, the number of tests that could be run would be limited only by the capacity of the storage disk. In our test, we stored data for 50 kernels on one side of a floppy disk. With an improvement of our triggering mechanism of the oscilloscope, it was possible to increase the storage capacity to data for 400 kernels per disk. It took about 4 sec to test each kernel.

The software we developed to establish a pattern of hard and soft wheat crushing was based on the characterization of force vs. time curves. To characterize the curve, we measured the first peak, first valley, second peak, ratio of the first valley to the first peak, maximum positive slope, and maximum of the value of the negative slope. The power of the six parameters was evaluated to differentiate curves from hard and soft wheats. In general, the predicted hardness value was determined from the combination of the ratio of the first peak to the first valley and the magnitude of each. If the ratio was less than 0.25 or greater than 0.45, the

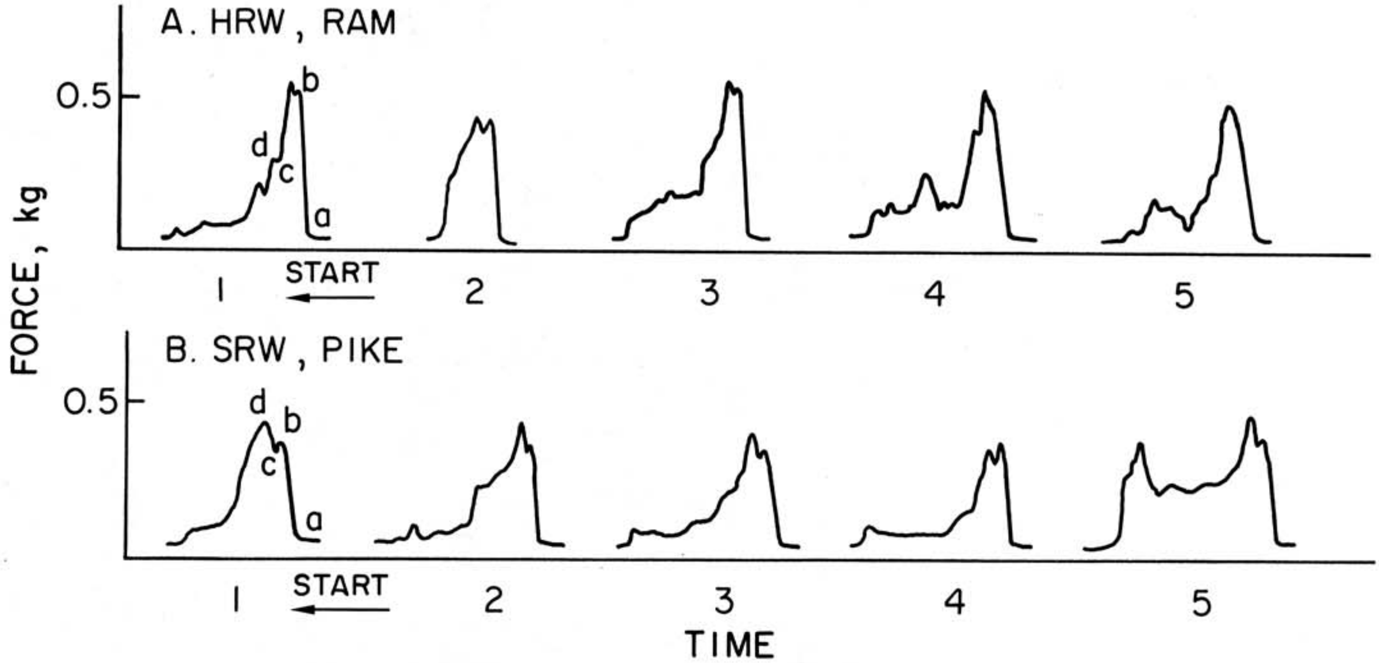

Fig. 6. Typical puncture test patterns of six kernels of **A,** the hard red winter wheat Ram and **B,** the soft red winter wheat Pike, by the Instron Universal Testing Machine.

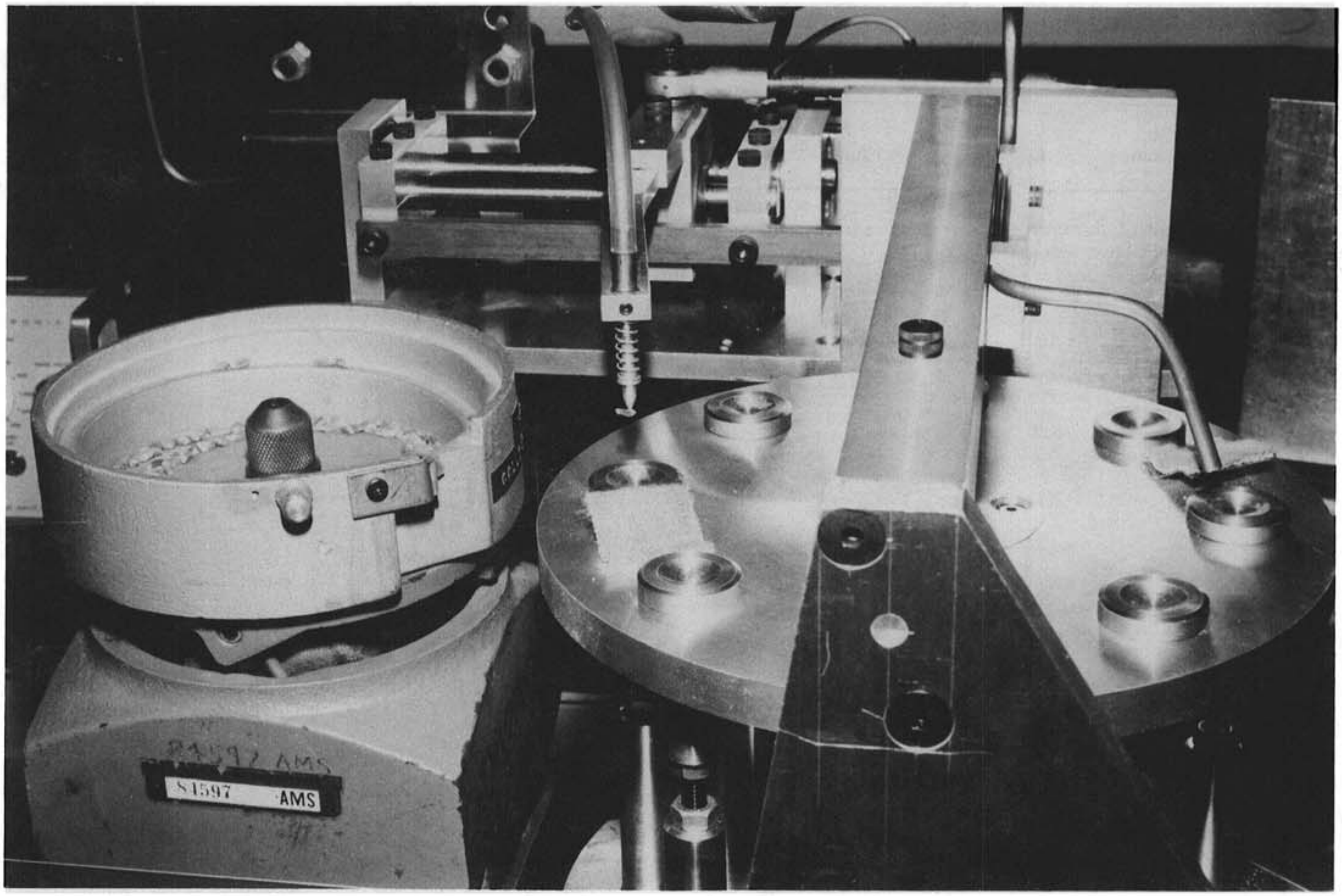

Fig. 7. Continuous automated single-kernel hardness tester.

predicted hardness value was determined as hard or soft, respectively. If the ratio was between 0.25 and 0.45, additional criteria, including the magnitude of the first peak and first valley, were considered. All soft wheats normally had a first peak to first valley ratio greater than 0.4 and hard wheats less than 0.3. An experienced operator could distinguish between the force vs. time curves of soft and hard wheats from visual observation of the digital oscilloscope.

RESULTS AND DISCUSSION

In preliminary studies, the results of crushing tests were affected by the presence of small, immature, and shrunken kernels. This is in agreement with the findings of Pomeranz and Afework (1984) in studies of hardness in bulk samples. Consequently, hardness determinations were made after separation of broken, shrunken, and small kernels by the Hart-Carter dockage tester and, if necessary, by hand. But even when such precautions were applied,

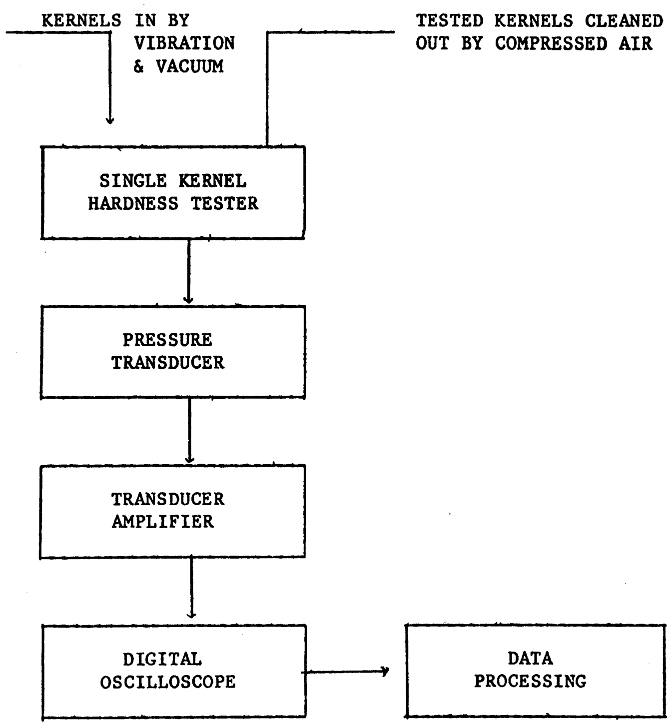

Fig. 8. Block diagram of the experimental procedures for the continuous automated single-kernel hardness tester.

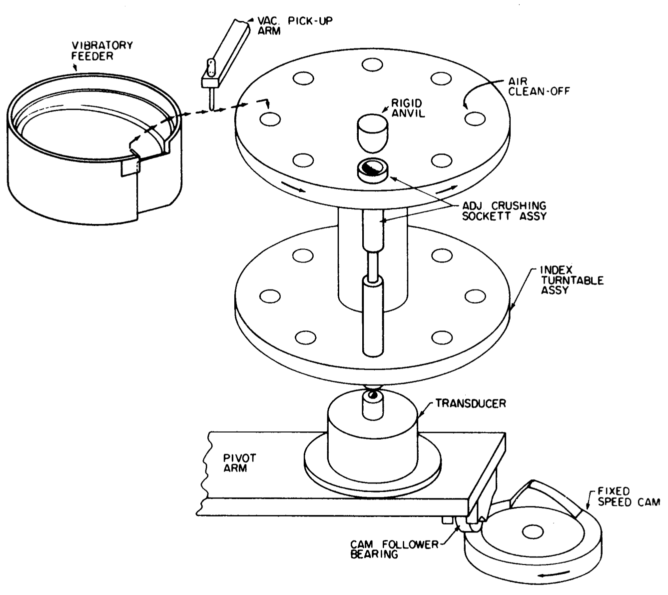

Fig. 9. Schematic diagram of the continuous automated single-kernel hardness tester.

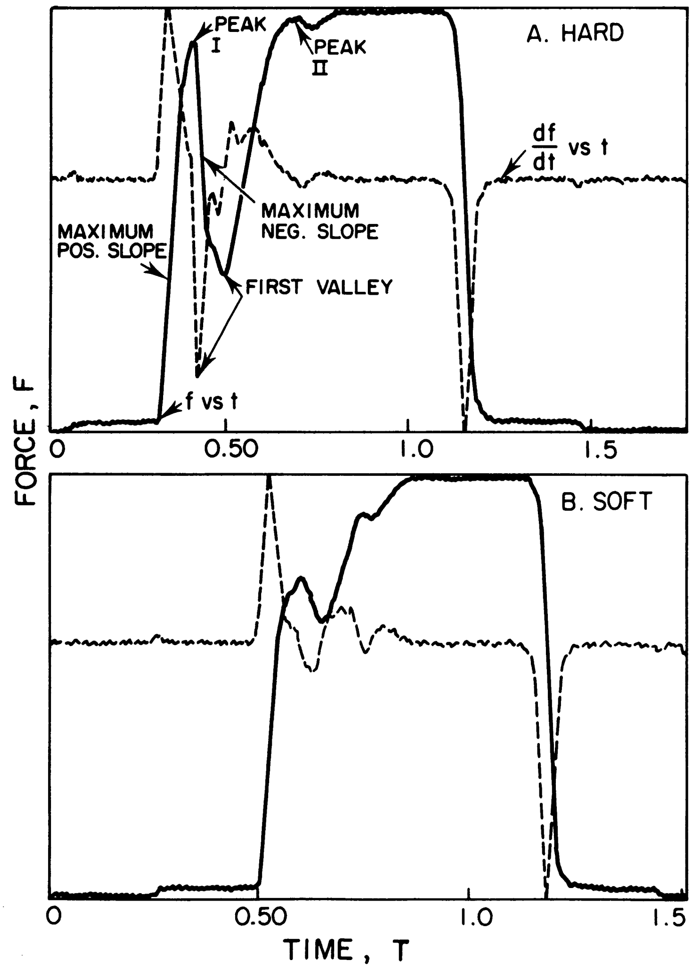

Fig. 10. Typical compression test patterns of hard and soft wheat kernels by the continuous automated single-kernel hardness tester (f = force in arbitrary instrumental units, t = time in seconds). **A,** Hard wheat, and **B,** soft wheat.

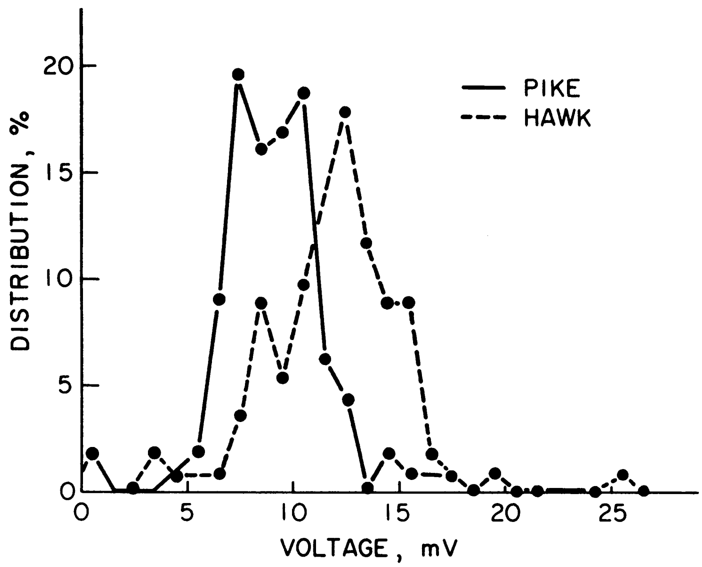

Fig. 11. Distribution curves of the first peak (at various mV values—instrumental arbitrary scale) of hard and soft wheat kernels determined by the continuous automated single-kernel hardness tester.

variations still existed among wheat kernels of a single class, in agreement with the studies of Robert (1910). As there is no reference method for determining hardness of individual kernels within a class, we assumed that the variation reflects inherent differences among kernels, genotypic or phenotypic heterogeneity or both, or a combination of those and additional unknown factors. Variability in gliadin electrophoregrams (as a criterion of purity of a variety) and hardness of individual kernels selected from Foundation Seed on the basis of grain morphology was described by Lookhart et al (1985).

Using the CASK-HaT in the compression mode, we obtained typical curves for kernels of hard and soft wheat (Fig. 10). A larger crushing force and a shorter crushing time were required to reach the first peak for a kernel of hard wheat than for a kernel of soft wheat. Figure 10 also plots the first derivative of the force vs. time curve. The curves for soft and hard wheats are distinctly different. As stated previously, several characteristics of the curves can be used to distinguish hard from soft wheat. These characteristics include the first peak, the first valley, the second peak, the calculated ratio of the first valley to the first peak, the maximum positive slope, and the maximum of the absolute value of the negative slope. We used all those characteristics to establish the crushing patterns of the eight hard and the two soft wheats (Table I). The following discussion is based on results of crushing kernels of HRW Hawk and SRW Pike wheats; similar results were recorded for the other wheats (Table I).

TABLE I
Hardness Characteristics of Hard and Soft Wheats Determined on Bulk Samples

Class and Variety	Particle Size Index	Stenvert Grinding Resistance (sec)	Grinding Time (sec)	Near Infrared Reflectance at 1,680 nm
Hard red winter				
Hawk	28.2	53.4	28.8	354
Tam 107	26.7	67.2	29.2	343
Scout	26.2	53.5	30.3	337
Newton	24.5	59.4	30.8	326
Ram	31.2	63.2	31.9	337
Arkan	30.1	52.0	32.6	317
Triumph	32.8	45.8	36.5	304
Vona	25.5	61.9	31.3	315
Mean	28.2	57.1	31.4	329
Soft red winter				
Hart	40.1	32.7	74.5	212
Pike	44.8	34.8	134.1	191
Mean	42.5	33.8	104.3	202

First Peak

The first peak is a measure of the maximum force required to crush a wheat kernel. A typical distribution curve of first peak values is shown in Figure 11. The maximum force occurred at about 12–13 mV for HRW wheat Hawk and 8–10 mV for SRW wheat Pike. Considerable overlap for the two wheat varieties occurred. Consequently, measurement of the first peak (i.e., maximum force) alone cannot be used to distinguish a hard from a soft wheat. This maximum force is frequently used as a measure of hardness of processed foods (Naewbanji et al 1983).

First Valley

A valley is the drop in force occurring as the kernel is crushed. The harder the kernel, the lower the valley. In general, the first valley of a hard wheat kernel pattern is much lower than that of a soft wheat kernel. The dip of the first valley in a soft wheat kernel was small. Typical data for Hawk and Pike are given in Figure 10; for the HRW wheat Hawk the maximum occurred at about 3–4 mV, and for SRW wheat Pike the maximum occurred at about 6–7 mV. The distribution curve (not shown) is spread widely and there is considerable overlap; consequently, this parameter alone cannot be used to identify hardness.

Second Peak

The second peak is a measure of the maximum force needed to crush the broken pieces of a kernel, affecting a second collapse of

TABLE II
Prediction of Percentage of Soft Red Winter Wheat in Hard Red Winter (HRW) Wheat Samples Provided by the Federal Grain Inspection Service (FGIS)

HRW as Determined by FGIS (%)	Hardness Tests on Bulk Samples: Grinding Time (sec)	Hardness Tests on Bulk Samples: Stenvert Grinding Resistance (sec)	HRW Determined by CASK-HaT (%)[a]
100	34.7	44.7	97.9
100	34.8	43.8	95.8
93	37.0	44.6	97.9
93	36.8	43.4	94.9
86	40.4	38.3	90.1
85	39.0	39.4	83.4

[a]Continuous automated single-kernel hardness tester.

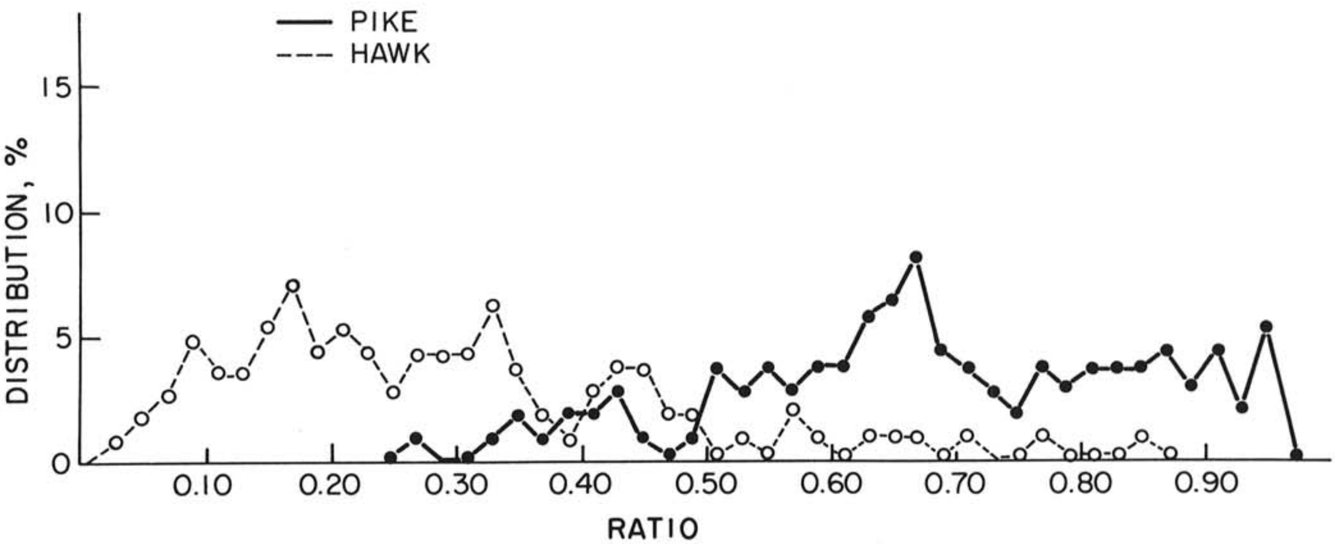

Fig. 12. Distribution curves of the ratio of the first valley to the first peak of hard and soft wheat kernels determined by the continuous automated single-kernel hardness tester.

the kernel. In general, it is rather difficult to interpret the physical meaning of the second peak. The distribution curves (not shown) of the second peak for hard and soft wheats are not as distinguishing as the first peak or the first valley.

Ratio of the First Valley to the First Peak

This ratio is a measure of the pattern of the first peak and first valley. A high ratio indicates a small dip and little breakdown of kernel structure. A small ratio (below 0.5) indicates a large dip and a pronounced collapse of kernel structure. The ratio for most HRW wheat Hawk kernels was below 0.5 and for most SRW wheat Pike kernels above 0.5 (Fig. 12). When 0.5 is used as the cut-off ratio to distinguish hard from soft wheat, 10 of 102 Hawk kernels were atypical, and 14 of 112 Pike kernels were atypical. The reasons for the atypical kernels are unknown. There may be heterogeneity within a variety or presence of kernels from other classes. Microheterogeneity is likely to affect much more the results of testing single kernels than of testing bulk samples in which the results of many kernels are compensated and averaged. Still, the ratio of the first valley over the first peak seems to be potentially the single best distinguishing characteristic to differentiate between hard and soft wheats.

Maximum Positive Slope

This slope is a measure of the maximum rate of force increase per unit time. The maximum positive slope dictates the steepness of the curve for the force vs. time relation. The distribution curves for kernels of HRW wheat and SRW wheat Pike overlapped. Maximum positive slope is therefore an unsatisfactory criterion to distinguish soft from hard wheat.

Maximum of the Absolute Value of the Negative Slope

The rate of decline in force vs. time is measured by the maximum absolute value of the negative slope, which indicates how fast the kernel collapses. Several factors (probably including kernel size and shape, resilience, and overall texture) affect this parameter, and its physical meaning is difficult to interpret. Moreover, the distribution curves (not shown) of the hard and soft wheats overlapped to such an extent that it was impossible to use this parameter as the sole criterion for determining hardness of a single kernel.

In summary, the operator-selected six methods of calculation and evaluation differed in their effectiveness in differentiating hard from soft wheats. The ratio of the first valley over the first peak was the most reliable single parameter, although no single parameter differentiated perfectly between kernels of soft and hard wheat. A combination of parameters may be needed to improve differentiation between kernels that vary in hardness and the reliability of prediction of composition of mixtures of hard and soft red winter wheats. A definitive evaluation is predicated on the availability of a reference method to determine the basis of differences in hardness characteristics among individual kernels. As stated previously, such a reference method is not available at this time. Moreover, deviations from expected hardness characteristics and polyacrylamide gel electrophoretic patterns were shown both for kernels differing in morphology and among kernels considered typical of a cultivar on the basis of grain morphology and texture (Lookhart et al 1985).

The results summarized in Table II are based on the single criterion of the ratio of the valley over the first peak. Using this single criterion, we predicted the percentage of soft wheat with more than 90% accuracy. Results of the two bulk methods showed that grinding time in the Brabender microhardness tester decreased as hardness increased, whereas the Stenvert tester, hard wheats required longer grinding time than soft wheats. The linear correlation coefficient between percentage of HRW as determined by FGIS and determined by the CASK-HaT method was 0.826. That correlation was lower than between the FGIS determination and the Brabender microhardness tester on bulk samples (0.968) and almost equal to the correlation between the FGIS determination and the Stenvert hardness test on bulk samples (0.868). A major factor in the case of the single kernel test is the large sampling error.

CONCLUSIONS

The CASK-HaT was developed to distinguish between soft and hard red winter wheats. Stress-strain relations at a rate of 15 kernels per minute were recorded for individual kernels by the tester and were used to establish patterns typical of hard and soft wheat kernels. Those patterns were the basis of a computer system, including software, that predicted with better than 90% accuracy the compositions of mixtures of hard and soft red winter wheat kernels.

ACKNOWLEDGMENT

We thank M. B. Stone, Department of Foods and Nutrition, Kansas State University, Manhattan, for counsel and for providing facilities for the Instron tests.

LITERATURE CITED

LOOKHART, G. L., LAI, F. S., and POMERANZ, Y. 1985. Variability in gliadin electrophoresis and hardness of individual kernels selected from Foundation Seed on the basis of grain morphology. Cereal Chem. 62:185.

MacRITCHIE, F. 1980. Physiochemical aspects of some problems in wheat research. Page 271 in: Advances in Cereal Science and Technology, Vol. III. Y. Pomeranz, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.

MILLER, B. S., AFEWORK, S., POMERANZ, Y., BRUINSMA, B. L., and BOOTH, G. D. 1982. A comparison of methods for measuring the hardness of wheat. Cereal Foods World 27:61.

NAEWBANJI, J. O., HARRISON, D. L., and STONE, M. B. 1983. Roasting vs. cooking in a model system: Tenderness of bull adductor muscle, conventionally chilled or electrically stimulated-hot boned. J. Food Sci. 48:337.

POMERANZ, Y., and AFEWORK, S. 1984. The effects of kernel size in plump and shrunken kernels and of sprouting on kernel hardness in wheat. J. Cereal Sci. 2:119.

POMERANZ, Y., and MILLER, B. S. 1983. Wheat hardness: Its significance and determination. Page 399 in: Developments in Food Science. 5A. Progress in Cereal Chemistry and Technology. J. Holas and J. Kratochvil, eds. Elsevier: Amsterdam.

POMERANZ, Y., AFEWORK, S., and LAI, F. S. 1985. Determination of hardness in mixtures of hard red winter and soft red winter wheats. I. Bulk samples. Cereal Chem. 62:41.

ROBERT, H. F. 1910. A quantitative method for the determination of wheat hardness. Kans. St. Agric. Coll., Exp. Stn., Bull. 67, Manhattan, KS.

SIMMONDS, D. H. 1974. Chemical basis of hardness and vitreosity in the wheat kernel. Bakers Dig. 48(5):16.

[Received November 5, 1984. Revision received January 30, 1985. Accepted January 30, 1985.]