A Rapid Single-Kernel Wheat Hardness Tester[1]

S. R. ECKHOFF,[2,4] W. A. SUPAK,[2] and A. B. DAVIS[3,5]

Cereal Chem. 65(6):503–508

ABSTRACT

The design of an instrument to differentiate hard from soft wheat on an individual kernel basis and its initial evaluation are presented. The unit is an automated system capable of sampling rates up to 200 kernels per minute. Hardness evaluation is achieved by shearing individual kernels and recording the associated force breakage curves. The tester was found to have an 80% classification accuracy for the five hard and five soft varieties tested. Initial testing showed that a discriminant model combining peak force, peak sharpness, and a Fourier transformation of data collected produced a useful classification system. However, peak force as a single criterion was almost as effective. A sharp cutting edge supplied the greatest differentiation between brittle and ductile materials when compared with square-edged and radius blades. Peak force readings collected were affected by variations in kernel moisture content, size, and orientation during cutting.

There is a need for a rapid, objective means of determining wheat hardness to classify wheat according to its end-use functionality. Current classification procedures rely upon subjective determination of wheat hardness based upon visual observation of the wheat size, shape, and color. The advent of new cultivars that do not conform to current visual classification characteristics but which have desirable insect or disease resistance, drought resistance, and acceptable end-use qualities has confounded the current classification method.

Several bulk sampling methods have been tested for wheat hardness evaluation. Near-infrared analysis (Williams and Sobering 1986), measurement of the effects of hard and soft wheat on grinding (Williams et al 1987), the particle size index method (Cutler and Brinson 1935), and pearling resistance (Chesterfield 1971) are all means for determining hardness properties of bulk samples. Although these methods are suitable when homogeneous lots of wheat are tested, they are not discriminating enough for identification of mixtures of hard and soft wheat varieties. Mixing of wheat classes can be a problem in grain trading, especially when a sizable price difference exists between hard and soft wheat. Mixing also affects wheat milling characteristics when more than 5% of one wheat class is mixed with another.

Research on hardness of single kernels has focused primarily on penetration tests. Grosh and Milner (1959) used the Miag microhardness tester for kernel hardness evaluation in a study on wheat adsorption of water. The Miag tester consists of a diamond point upon which a 1,000-g weight is placed. To determine wheat hardness, individual kernels are punctured with the point, and the indentation is measured with a dissecting binocular. In a similar test, Katz et al (1959) adapted a Barcol impressor to measure the deflection of a diamond stylus during kernel testing. Gasiorowski and Poliszko (1977) attempted to develop a wheat endosperm microhardness index based on the hardness of vitreous and floury structure constituents. These methods were seen as having potential for classification if the wheat preparation and analysis time could be reduced.

A recent study by Gaines (1986) examined wheat discrimination by individual kernel texture analysis. His work indicated the possibility for a 90–95% accuracy in wheat classification, but also noted the need for a high-speed testing procedure. Gaines indicated that to judge a 50:50 mixture of hard and soft wheat, a sample size of nearly 2,500 kernels would be required, and this number would be appropriate only if there were no intrinsic overlap between wheat classes. The Federal Grain Inspection Service (FGIS) has expressed a desire for a single-kernel sampling rate for wheat hardness of 400 kernels in 5 min (G. Jackson, *personal communication,* National Wheat Classification Committee Meeting, Kansas City, MO, May 20, 1987). This rate and sample size would correspond to the FGIS current visual classification procedure.

Mattern (1988) crushes individual kernels of wheat and then views the kernels through a microscope to classify them on a hardness scale from 1 to 10. He uses the physical characteristics of the fracture surfaces to determine hardness. This method appears to be the most accurate one available and will be used as a standard for individual kernel testers, but it is labor intensive and time-consuming.

One recent effort to analyze wheat samples on an individual kernel basis used a continuous, automated single-kernel hardness tester (Lai et al 1985). The device tested hardness by recording the stress-strain relationships encountered when crushing kernels. A sampling rate of 15 kernels per minute was achieved with this system at a reported accuracy of 90%.

An instrument has been developed (K. Norris, *personal communication,* National Wheat Classification Committee Meeting, Kansas City, MO, May 20, 1987) that distinguishes hard from soft wheat based upon sounds generated as kernels are individually ground in an Udy mill. Each kernel is given a hardness score ranging from 0 to 100; the scale is partitioned into four ranges for classification. Sample percentages in these ranges determine the wheat hardness class. The instrument is capable of analyzing approximately 20 kernels per minute.

C. R. Martin (*personal communication,* National Wheat Classification Committee Meeting, Kansas City, MO, May 20, 1987) developed a wheat characterization tester that measures both hardness and individual kernel moisture. Kernels are dropped into a roller-crusher with one surface a roller and the second surface crescent-shaped and electrically insulated. The crescent is cantilevered with a load cell capable of measuring the forces experienced by the crescent as each kernel is crushed. The moisture content is measured by correlating moisture to the electrical conductance across the roll gap in a fashion similar to the Tag-Heppenstahl moisture meter.

An instrument developed at Kansas State University (Eckhoff et al 1986) was designed to be rapid enough for FGIS inspection requirements and to compensate for kernel factors affecting the hardness test. This article reports on the design, development, and initial evaluation of this Kansas State individual kernel wheat hardness tester.

MATERIALS AND METHODS

Instrument Design and Operation

Figure 1 shows the basic components of the KSU wheat hardness tester. The instrument is designed to position individual wheat kernels so that they can be sliced by a rotary knife. The force experienced by the knife in cutting a kernel is measured by a load cell. This recorded breakage event is analyzed to determine if a

[1]Contribution no. 88-138, Agricultural Experiment Station, Kansas State University, Manhattan 66506.
[2]Department of Agricultural Engineering, Kansas State University.
[3]Department of Grain Science and Industry, Kansas State University.
[4]Current address: Department of Agricultural Engineering, University of Illinois, Urbana 61801.
[5]Current address: Entenmann's Inc., Bayshore, NY 11706.

© 1988 American Association of Cereal Chemists, Inc.

kernel is hard or soft.

The initial design premise of the instrument assumed that hard wheat kernels are more brittle than soft kernels (MacRitchie 1980). This concept can be expanded beyond a maximum breakage force criterion to include an evaluation of other breakage event features for their discriminating ability.

Individual sorting of kernels is achieved using a Syntron vibrating feeder (FMC, model EB-051), which aligns the kernels for transport to a drop tube. Kernels fall to a rotating plate revolving at approximately 8 rpm. The plate contains 48 closely aligned holes, each having a 45° beveled entrance. A cross-sectional diagram of a hole is shown in Figure 2. The beveled area acts as a funnel to catch the kernels. About half of the kernels drop directly into the holes. The other half either lie crosswise in the beveled funnel area or are only partially in the hole. A blast of air from an air tube moves any kernel not correctly positioned and directs it into a hole.

A knife groove shown in Figure 2 extends around the plate and beyond the back of the holes. A rotary knife sits in this groove. As the plate containing the kernels is rotated, the knife slices through the kernels. To allow for the deflection required to induce load cell readings, the knife is free-spinning, with its support mounted on bearings. Based on initial Instron tests, we chose a sharp cutting edge (5° taper) over a blunt cut or a crushing action.

After slicing, kernels are removed from the holes by gravity. The stationary plate does not completely cover the bottom of the rotating plate in the clean-out area and kernels fall out. A second cleaning by compressed air removes particles from the hole and knife groove. The groove is also cleaned with a metal scraper.

During cutting, force readings are collected from a 50-lb load cell (Alphatron, model SL50) connected through a Tecmar data-acquisition board (Scientific Solutions, Tecmar Labmaster) to a Zenith 150 computer. Although the load cell is continuously monitored, no data are collected until a preset force level is reached. When that threshold is reached, a specified number of force readings (typically 300–500 per kernel) are collected at 0.5-msec intervals. Direct memory addressing is used for data collection and storage.

Upon completion of sample processing, recorded data are written to a floppy disk. Off-line processing is currently used to ensure a record of the data and to facilitate the appropriate statistical analysis for studying the discriminating factors of the individual breakage curves.

A 12-bit encoder (BEI, M25D-X-HSS4096N) is mounted for kernel diameter measurements. Capable of reading approximately 4,100 positions on a circle, the encoder first records the positions of the backs of the 48 holes on the rotating plate. Then, a position reading is taken for each kernel when the threshold force level is reached. Kernel size can be estimated by subtracting the hole position from the kernel position. In this study, the encoder was not used, because the effects of kernel size on forces generated with a shearing cut were not known.

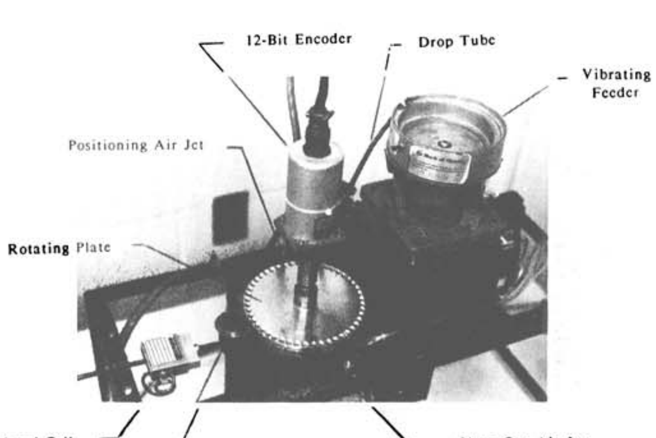

Fig. 1. Kansas State University wheat hardness tester.

Analysis of Breakage Curves

Experimental analysis focused on determining which features of the breakage curve (Fig. 3) gave the best differentiation of hard and soft wheat cultivars. Criteria considered were peak force, peak sharpness, backslope, area under the breakage curve, and Fourier transformations of the data using various time windows.

Digital determination of peak sharpness was done by summing the absolute magnitudes of the rate of change in slope (2nd derivative) between force readings falling 25 points before and 25 points after the peak force. Backslope was calculated by summing the rate of change in force with regard to time (first derivative) for 25 points following the peak force reading. Energy required to break a kernel was expressed by an area calculation of the breakage curve using the trapezoid rule (James et al 1985).

The Fourier transformation was run on all 300 points of data collected for each individual kernel. Spectral analysis of this nature has been used to determine firmness of fruits (De Baerdemaeker et al 1982). Justification for applying the parameter to wheat is the difference in starch-protein bonding (Hoseney 1986) associated with the two wheat classes.

Samples and Preparation

The following wheat samples were used in testing: hard—Mustang, Wrangler, Newton, Parker 76, and Scout 66; Soft—Hill 81, Daws, Pike, Caldwell, and Crew Club. Cultivar selection was influenced by availability and variability when tested by other

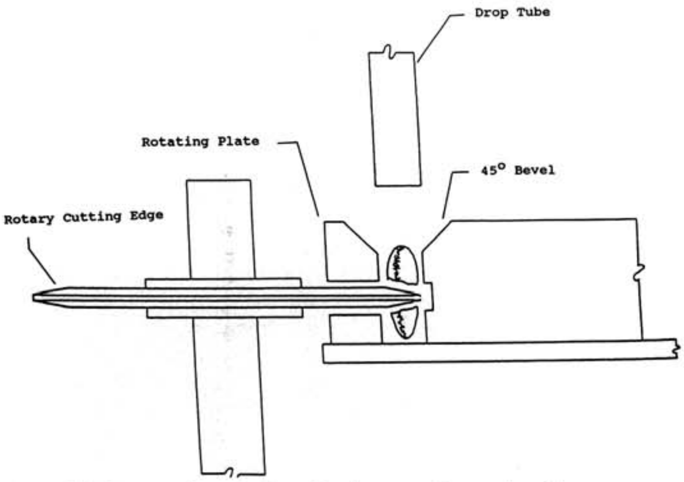

Fig. 2. Hardness testing of a kernel as it passes the cutting edge.

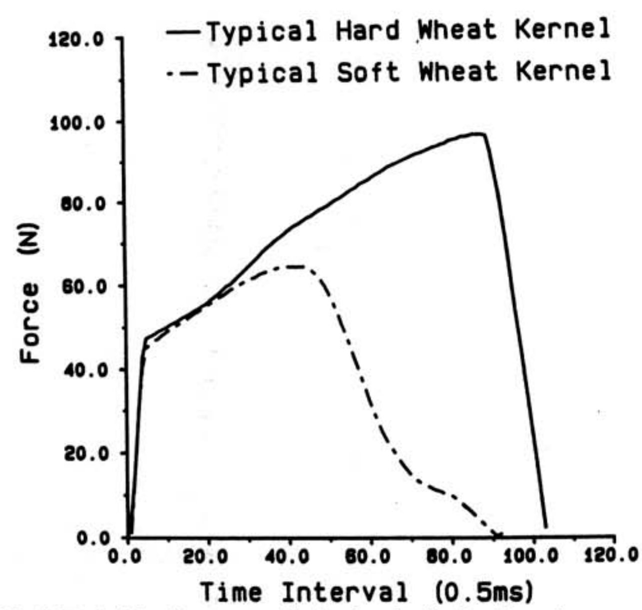

Fig. 3. Typical breakage curves for hard and soft wheat kernels.

classification means. Trouble has been encountered with near-infrared analysis in classifying Scout 66 (NIR Specialties, *personal communication*), and work by Lai et al (1985) indicated difficulties in classifying Pike with shear techniques.

All samples were sieved through a Tyler screen size no. 6 sieve and caught with nos. 7 or 8 sieves. Kernels falling in these size specifications will be referred to hereafter as nos. 7 or 8 sized kernels, respectively. Additionally, kernels were conditioned in sealed chambers with air humidity controlled by glycerin-water mixes (J. Tuite, Dept. of Plant Pathology, Purdue University, *personal communication*). Before being tested, samples were placed in the chambers for a minimum of two weeks. Moisture content of conditioned samples was checked with a Dickey-john Motomco moisture meter.

Criteria for Hard-Soft Wheat Discrimination

Initial evaluation of analysis parameters was conducted on 50-kernel samples of a hard wheat variety, Mustang, and 50-kernel samples of a soft wheat variety, Daws. The moisture content of the samples was near 9%.

Kernels were tested by manually placing individual kernels in a specified hole. A plate speed of 8 rpm was used when slicing kernels. Three hundred force readings were recorded for each kernel.

For additional analysis of the discussed criteria, 1,000 hard and 1,000 soft wheat kernels were tested. All samples were of a no. 7 sieve size and conditioned to a moisture content of approximately 10%.

TABLE I
Initial Evaluation of Wheat Classification Parameters Expressed on a Quartile Basis[a]

Parameter	Quartile 1	Quartile 2	Mean
Peak force (N)			
Mustang	93.51	121.62	102.82
Daws	64.77	83.85	74.15
FFT[b] 30 Hz (db)			
Mustang	5.646	9.945	7.130
Daws	−0.726	5.205	2.001
Area[c] (N·sec)			
Mustang	900.0	1,296.7	1,114.1
Daws	647.8	944.8	798.1
Peak sharpness			
Mustang	4.12	7.84	6.44
Daws	2.32	4.04	3.38
Blackslope (25 pts)			
Mustang	−0.433	−0.257	−0.347
Daws	−0.283	−0.150	−0.217

[a] Data represent 200 kernels each of Mustang (hard) and Daws (soft) wheat at a moisture content near 9%.
[b] Fourier transformation of the force amplitude at 30 Hz.
[c] Area under the breakage curve.

TABLE II
Variety Comparison of Peak Force Readings Collected with the Kansas State University Wheat Hardness Tester[a]

Wheat Varieties	Mean (N)	SD
Hard		
Mustang	82.94	19.78
Newton	91.57	21.16
Parker 76	87.68	18.78
Scout 66	80.09	16.76
Wrangler	93.99	21.55
Average	87.25	19.78
Soft		
Caldwell	64.43	14.74
Crew Club	69.14	14.46
Daws	65.22	14.93
Hill 81	61.50	13.69
Pike	67.45	14.85
Average	64.43	14.74

[a] All samples were tempered to a moisture content near 10%, and only kernels of a no. 7 sieve size were tested. Orientation was random.

For the automated testing, the only manual handling of the wheat was when the kernels were dropped into the vibrating feeder. Data for 25 kernels were collected per run with 300 force readings collected for each kernel tested. Plate speed was 8 rpm, and a sharp blade was used.

Kernel Moisture Analysis

The five hard and five soft wheat varieties discussed earlier were conditioned to levels of 9, 11, and 13% moisture. Five hundred hard and 500 soft kernels were tested at each moisture content. All kernels were overs of a no. 7 sieve. Testing was automated.

Kernel Size Analysis

To evaluate the effects of kernel size, kernels were separated by sieving into nos. 7 and 8 sizes. Because of difficulty in obtaining a suitable number of kernels for other sieve sizes, only those two sizes were included in this evaluation. A sample size of 625 hard and 625 soft kernels per sieve size was used with all kernels conditioned to a moisture content of approximately 10%.

Kernel Orientation Analysis

Preliminary testing with kernels of Mustang (hard) and Daws (soft) varieties indicated that kernel orientation might affect peak force readings. Kernels were hand-positioned with the crease either facing toward or away from the cutting edge. Using the 10 wheat varieties mentioned above, 375 hard and soft kernels were cut per orientation. All kernels were of the same size (no. 7) and moisture content (approximately 10%).

RESULTS AND DISCUSSION

Table I shows results from initial testing of the Mustang and Daws wheat varieties. Calculations of the classification parameters are presented in terms of quartile values. Peak force, a Fourier transformation of the force amplitude at 30 Hz, and peak sharpness values for hard and soft kernels were found to overlap less than 25% when used independently for wheat classification; quartile 1 for Mustang is greater than quartile 3 for Daws. When these parameters were combined in a discriminant model, a classification overlap near 10% was observed.

Fourier transformation of the analyzed signal yielded no frequencies peculiar to hard or soft wheat. An amplitude difference between hard and soft wheat kernels was observed at the 30 Hz frequency. The motor driving the rotating disk was identified as the

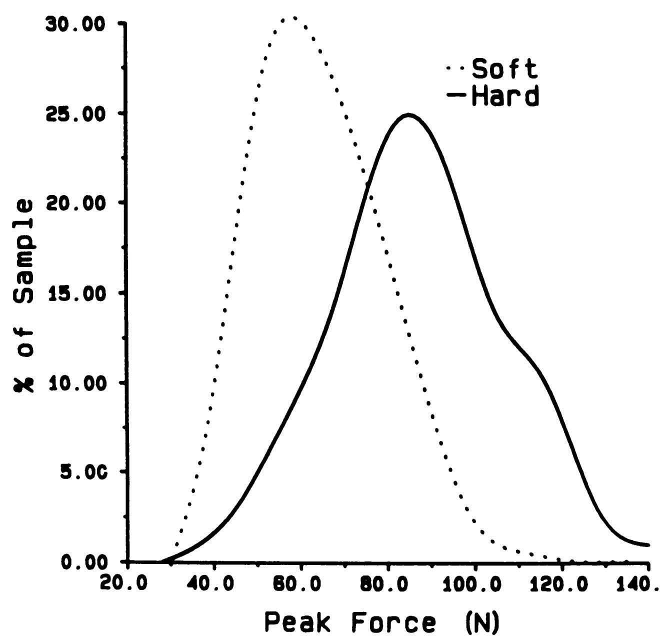

Fig. 4. Peak force distribution curves for a sample of 1,000 hard and 1,000 soft wheat kernels.

source of this vibration. Differentiation between hard and soft wheat kernels at 30 Hz was likely due to a greater dampening of the vibration by soft kernels.

Additional testing of all 10 varieties indicated peak force to be the most effective single criterion. A multiple criteria model combining peak force, the Fourier transform, and peak sharpness gave only a small improvement in discrimination. A stepwise discriminant analysis of the parameters gave R^2 correlation factors in hard-soft wheat classification of 0.6 for peak force and 0.35 for the Fourier transform and peak sharpness.

Classification accuracy was approximately 80% for the wheat kernels tested. A peak force average of 87.25 newtons (N) was observed for hard wheat kernels, whereas the soft kernels had a mean of 64.43 N (Table II). Kernels with peak breakage force above 75 N were classified as hard. Kernels below 75 N were classified as soft.

A large degree of variability was encountered between cultivars. A range in mean peak force readings of 14 N was observed for the hard varieties and 7 N for the soft varieties. As anticipated, Scout 66 was a troublesome variety among the hard wheat cultivars, with a mean peak force reading of 7 N less than the mean for all hard kernels tested. Mustang also had a peak force measurement that was substantially lower (nearly 5 N) than the average for hard varieties. Among the soft varieties, Pike and a wheat grown in the Northwest, Crew Club, showed the largest peak force readings. The coefficients of variation for the hard and soft samples were almost equal (hard 0.227, soft 0.229).

The hard wheat distribution appeared normal (Fig. 4). The soft distribution showed a skew to the right, in agreement with results reported by Gaines (1986).

Small but significant differences because of moisture were observed in peak force readings for the two wheat classes (Fig. 5). These differences between moisture content ranges were more significant for the hard wheat kernels than the soft (hard P value 0.005, soft P value 0.05). However, moisture effects on peak force readings varied with the cultivars tested (Table III), in accordance with observations by Smeets and Cleve (1956).

Since the moisture content range for marketable grain typically runs from 7 to 14%, moisture effects on kernel hardness will likely have to be considered. However, further testing of the relation of moisture to wheat hardness will be required because of the variability of hardness response to different moistures observed in the varieties analyzed.

Peak force results from the kernel size test showed a definite distribution shift between the two sieve sizes for both wheat classes (Fig. 6). Larger kernels recorded a significantly higher ($P = 0.005$) breakage force than smaller kernels. Table IV shows an overall mean peak force difference of 14 N between hard wheat kernels of no. 7 and no. 8 size and a difference of 10 N among the soft kernels. This effect of kernel size was observed previously by Gaines (1986). The magnitude of these differences indicates that a method for kernel size measurement will be necessary.

Kernel orientation also produced significant differences ($P = 0.005$) in peak force readings for the two wheat classes. Kernels with the crease oriented toward the cutting edge had a greater resistance to shearing than kernels with the crease turned away from the cutting edge (Fig. 7). A mean difference of approximately 6 N was noted for both wheat classes (Table V).

CONCLUSION

A sharp cutting edge was found to supply the greatest differentiation between peak force readings collected for hard and soft wheat kernels. Plate rpm and cutting edge depth had little effect on discrimination. Preliminary testing indicated that a

TABLE III
Analysis of Kernel Moisture Content Effects on Peak Force Readings

	9% mc		11% mc		13% mc	
Wheat Varieties	**Mean (N)**	**SD**	**Mean (N)**	**SD**	**Mean (N)**	**SD**
Hard						
Mustang	78.13	20.22	73.70	18.76	75.11	15.64
Newton	90.40	23.61	82.70	22.27	78.73	17.07
Parker	88.36	20.36	81.21	16.29	75.03	18.25
Scout 66	80.14	19.53	77.30	16.16	71.91	16.72
Wrangler	91.26	27.78	86.86	22.63	80.71	21.38
Average	85.52	23.25	80.24	20.02	76.30	18.12
Soft						
Caldwell	50.03	15.64	54.05	16.09	51.08	14.12
Crew Club	63.75	16.08	65.28	17.01	58.90	13.71
Daws	63.96	20.60	60.32	15.60	54.94	13.74
Hill 81	81.50	17.51	74.72	16.95	69.58	16.90
Pike	70.22	17.46	63.09	15.55	66.38	17.01
Average	65.80	20.31	63.41	17.62	60.18	16.62

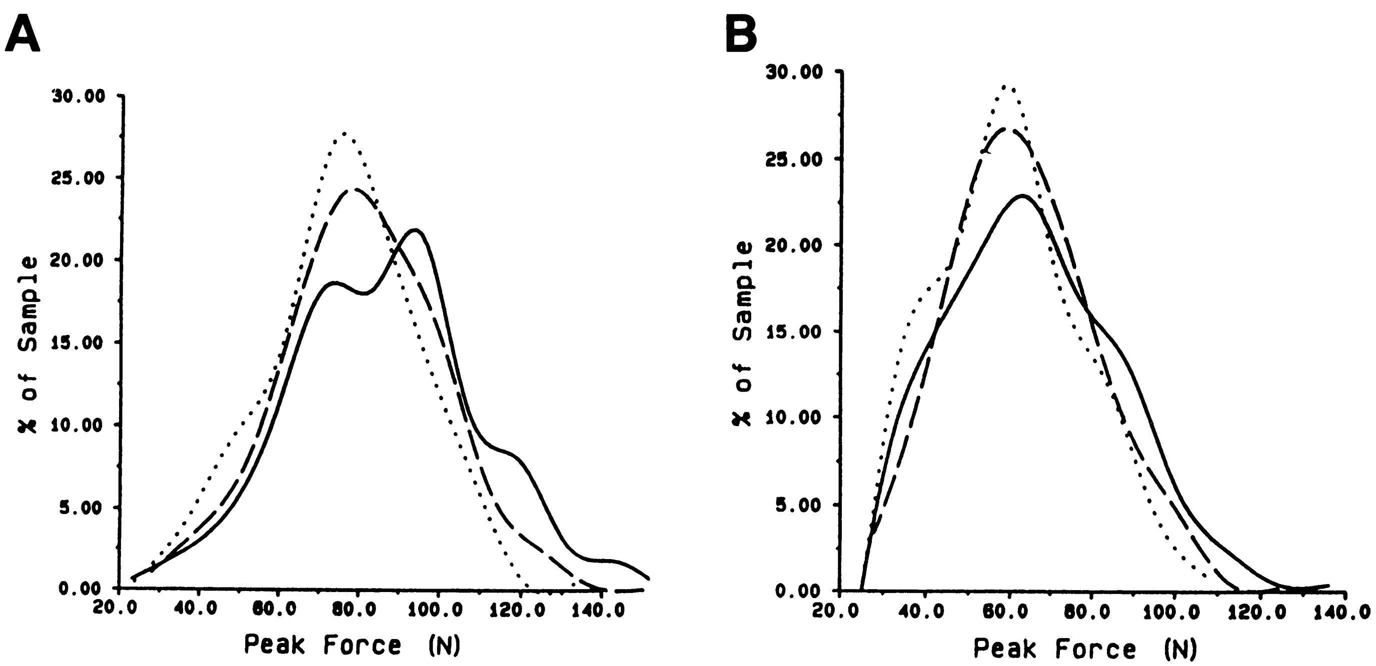

Fig. 5. Distribution curves for analysis of kernel moisture content effects on peak force measurements. **A,** hard wheat; **B,** soft wheat. Dashed line = 9%, solid line = 11%, and dotted line = 13% moisture.

TABLE IV
Analysis of Kernel Size Effects on Peak Force Readings

Wheat Varieties	No. 7 Sieve Mean (N)	No. 7 Sieve SD	No. 8 Sieve Mean (N)	No. 8 Sieve SD
Hard				
Mustang	81.14	17.54	63.58	15.59
Newton	87.98	20.29	70.16	18.04
Parker 76	79.89	20.14	72.66	16.99
Scout 66	80.44	17.61	70.54	16.19
Wrangler	87.18	23.92	60.07	17.27
Average	83.33	20.28	69.40	17.45
Soft				
Caldwell	56.88	14.55	41.26	8.49
Crew Club	65.30	14.06	54.72	13.53
Daws	60.41	14.94	48.29	12.46
Hill 81	59.86	13.15	60.91	13.54
Pike	61.78	14.01	48.30	10.76
Average	60.84	14.37	50.80	13.59

TABLE V
Analysis of Kernel Orientation Effects on Peak Force Readings

Wheat Varieties	Crease Toward Cutting Edge Mean Force (N)	Crease Toward Cutting Edge SD	Crease Away from Cutting Edge Mean Force (N)	Crease Away from Cutting Edge SD
Hard				
Mustang	91.14	18.58	85.20	13.84
Newton	93.95	18.54	91.75	16.56
Parker 76	96.04	16.32	85.20	14.39
Scout 66	80.09	17.04	77.47	15.87
Wrangler	77.47	15.87	99.78	23.58
Average	92.20	20.03	87.19	16.67
Soft				
Caldwell	62.82	15.42	57.45	14.14
Crew Club	73.05	16.54	68.39	14.21
Daws	67.35	17.80	64.19	13.16
Hill 81	69.55	13.80	62.06	12.15
Pike	77.22	16.47	68.05	9.91
Average	70.00	16.72	64.03	13.38

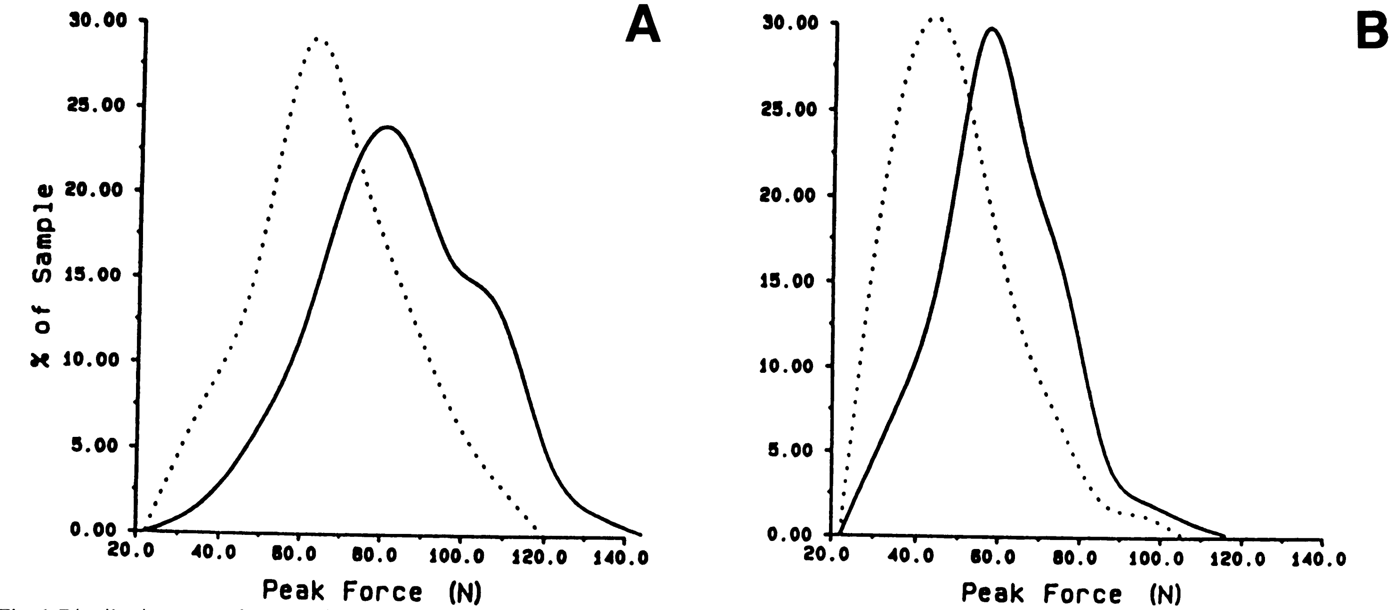

Fig. 6. Distribution curves for analysis of kernel size effects on peak force measurements. **A,** hard wheat; **B,** soft wheat. Solid line = no. 7 sieve, dotted line = no. 8 sieve.

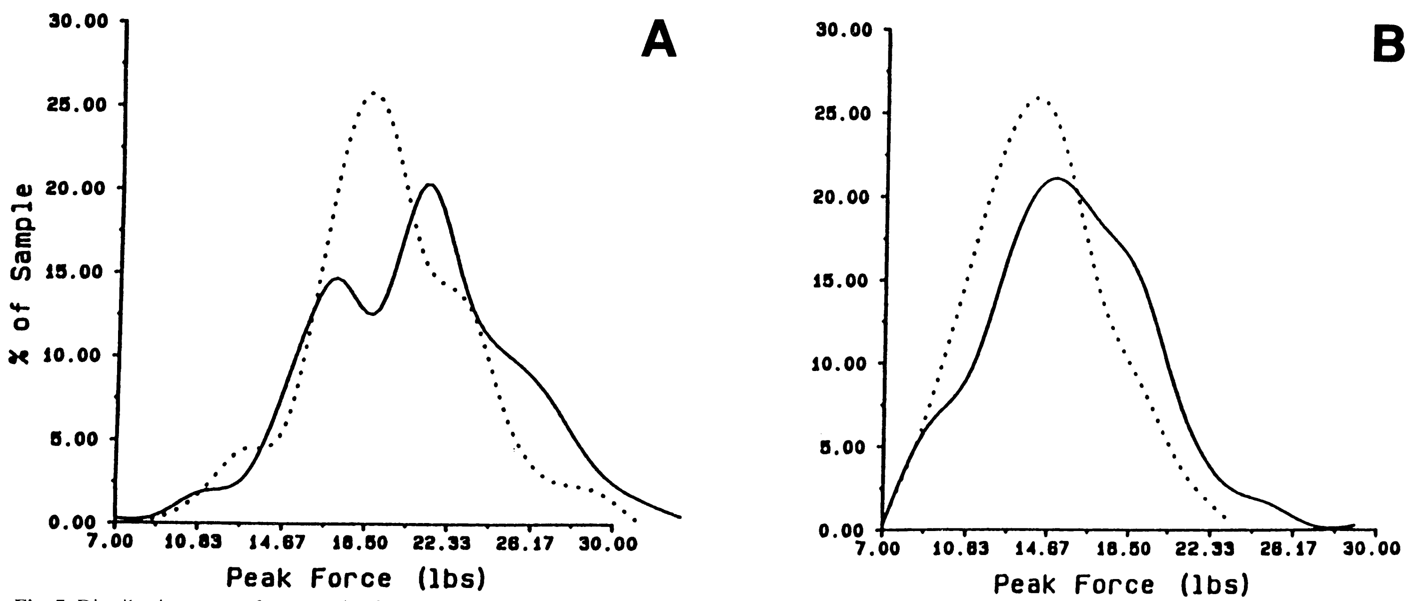

Fig. 7. Distribution curves for analysis of kernel orientation effects on peak force measurements. **A,** hard wheat; **B,** soft wheat. Solid line = kernel oriented with crease toward cutting edge, dotted line = crease away from cutting edge.

model combining peak force, peak sharpness, and a Fourier transformation of data produced the best differentiation between hard and soft wheat. Large-scale sampling using several varieties showed that peak force used independently was nearly as discriminating as the multiple criteria model. Peak force used as the sole criterion yielded a classification accuracy in the 80% range for the 10 varieties tested.

Analysis of the varieties indicated a significant difference in peak force readings associated with kernels of different sieve sizes. Kernel orientation also affected peak force values. Kernels with their crease facing the cutting edge exhibited greater resistance to shearing than kernels facing away from the cutting edge. Kernel moisture affected kernel resistance to cutting. Readings of peak force for hard wheat were more affected by changes in kernel moisture content than those for soft wheat.

LITERATURE CITED

CHESTERFIELD, R. S. 1971. A modified barley pearler for measuring hardness of Australian wheats. Aust. Inst. Agric. Sci. 37:148.

CUTLER, G. H., and BRINSON, G. A. 1935. The granulation of wholemeal and a method of expressing it numerically. Cereal Chem. 12:120.

DeBAERDEMAEKER, J. D., LEMAITRE, L., and MEIRE, R. 1982. Quality detection by frequency spectrum analysis of the fruit impact force. Trans. ASAE 25(1):175-178.

ECKHOFF, S. R., OARD, D., DAVIS, A. B., and BEHNKE, K. C. 1987. Apparatus for measuring grain hardness. U.S. patent 4,703,647. Patented Nov. 3, 1987.

GAINES, C. S. 1986. Texture (hardness and softness) variation among individual soft and hard wheat kernels. Cereal Chem. 63(6):479-484.

GASIOROWSKI, H., and POLISZKO, S. 1977. A wheat endosperm microhardness index. Acta Aliment. Acad. Sci. Hung. 6:113-117.

GROSH, G. M., and MILNER, M. 1959. Water penetration and internal cracking in tempered wheat grains. Cereal Chem. 36:260.

HOSENEY, R. C. 1986. Page 9 in: Principles of Cereal Science and Technology. Am. Assoc. Cereal Chem.: St. Paul, MN.

JAMES, M. L., SMITH, G. M., and WOLFORD, J. C. 1985. Applied Numerical Methods for Digital Computation. Harper and Row: New York. 368 p.

KATZ, R., CARDWELL, A. B., COLLINS, N. D., and HOSTETTER, A. E. 1959. A new grain hardness tester. Cereal Chem. 36:393.

LAI, F. S., ROUSSER, R., BRABEC, D., and POMERANZ, Y. 1985. Determination of hardness in wheat mixtures. II. Apparatus for automated measurement of hardness of single kernels. Cereal Chem. 62:178.

MacRITCHIE, F. 1980. Pages 271-274 in: Physiochemical aspects of some problems in wheat research. Advances in Cereal Science and Technology. Vol. 3. Am. Assoc. Cereal Chem.: St. Paul, MN.

MATTERN, P. 1988. Wheat hardness: A microscopic classification of individual grains. Cereal Chem. 65:312.

SMEETS, H. S., and CLEVE, H. 1956. Determining of conditioning by measuring softness. The Northwestern Miller, April 10, p. 3.

WILLIAMS, P. C., and SOBERING, D. C. 1986. Attempts at standardization of hardness testing in wheat II. The near-infrared reflectance method. Cereal Foods World 31:417.

WILLIAMS, P. C., KILBORN, R. H., BOISEY, P. W., and KLOEK, M. 1987. Measuring wheat hardness by revolutions per minute reduction. Cereal Chem. 64:422-427.

[Received January 13, 1988. Accepted May 26, 1988.]