MODELING THE ENERGY REQUIREMENTS OF FIRST–BREAK GRINDING

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ABSTRACT. *The influence of roller mill gap and single kernel properties of wheat on the energy requirements of first–break grinding was studied. Multiple linear regression models for energy per unit mass (E_M), new specific surface area (A_{NSS}, in log scale), and specific energy ($E_A = E_M / A_{NSS}$) were developed based on milling data from six wheat classes ground at five roll gaps with an experimental roller mill. The models, which were functions of roll gap, single kernel properties, and wheat class as a classification variable, explained most of the variability in the experimental data. Roll gap and single kernel hardness had the greatest influence on E_M, A_{NSS}, and E_A. Milling ratio, a variable that combined single kernel size and roll gap, reduced some collinearities among single kernel properties and isolated the effect of single kernel mass from that of single kernel size. The effect of single kernel mass became significant in the models based on milling ratio. Good agreement between predicted and measured values was observed from 100 validation samples. The E_A model is a potential alternative to break release as a basis for online roll gap control.*

Keywords. *Wheat, Flour milling, Roller mill, Specific energy, Single kernel properties.*

Roller mills are the workhorses of the grain milling industry. In flour milling, roller mills perform bran separation as well as size reduction. First–break, or the first roller mill operation in the milling process, performs the first bran separation by opening the wheat kernels with minimum bran breakage. Bran coming out in the form of flakes ensures ease of separation from the endosperm in succeeding stages. Mechanical energy is required to impart compressive and shear forces that break wheat kernels and reduce the size of endosperm particles.

The grinding energy and how it relates to size reduction has been a subject of considerable interest to researchers. Von Rittinger (1867) proposed the first theory of size reduction, stating that the energy required for size reduction of a material is directly proportional to the area of new surface formed. His postulate may be expressed as:

$$E_M = k\left[\frac{1}{x_2} - \frac{1}{x_1}\right] \quad (1)$$

where

E_M = breakage energy per unit mass of feed
k = the specific surface coefficient, a constant
x_1 = initial particle size
x_2 = final particle size.

Kick (1885) developed the second theory, which states that the size reduction ratio (x_1/x_2) of geometrically similar bodies is proportional to the energy required for grinding. Bond (1952) proposed the third theory of size reduction, which states that the energy required for size reduction is proportional to the square root of the ratio of the surface area to the volume of the material. These theories and their limitations have been reviewed by Rose (1967) and Guritno and Haque (1994). A theory unifying all three theories has been reported by Walker et al. (1937) and Rose (1967). However, grains, which are biological materials with varying physical and chemical properties, are unlikely to follow the classical theories that have been developed for homogenous materials such as limestone, coal, quartz, and glass (Guritno and Haque, 1994).

The study of grinding energy requirements of roller mills for flour milling is therefore a better approach. Taguida (1982) evaluated five different types of laboratory grinders (compression–shear, attrition, dynamic impact, gravity impact, and cutting action–type) based on energy consumption and particle size of the ground product. He concluded that the energy consumption increased with the capacity of grinders, and the compression–shear type grinder (roller mill) consumed the least energy among the grinders tested. Guritno and Haque (1994) studied the energy for size reduction in a patented three–roll mill using sorghum, hard red winter wheat, and corn. A mathematical model based on dimensional analysis related net specific energy consumption (in kWh/t) to feed rate, roll gaps for first and

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second reduction, geometric mean diameter of input and output material, speed ratio, and corrugation configuration. Experimental data validated the model. Net specific energy consumption increased as roll gap was reduced, decreased as fast roll speed increased, and increased with dull–to–dull corrugation.

The grinding energy is dependent on the grain physical properties and the operational parameters of the roller mill. The motivation to measure energy requirements for size reduction at specified roller mill settings led to the development of instrumented roller mills of various designs (Gehle, 1965; Kilborn et al., 1982; Fang, 1995; Pujol et al., 2000). The development of the Single Kernel Characterization System (SKCS) (Martin et al., 1993) paved the way for obtaining wheat single kernel properties and relating them to milling performance. The SKCS measures the mean and standard deviation of kernel hardness, mass, size, and moisture from a 300–kernel sample. Fang et al. (1998) used specific energy (defined in table 1) as a measure of energy efficiency of first–break grinding. They developed statistical models from response surface regression that related energy per unit mass (E_M) and energy per unit area (E_A) to roll parameters and single kernel properties of wheat. The regression models used milling data from three wheat classes (hard red spring, hard red winter, and soft red winter) tempered at three moisture levels and ground at three levels of feed rate, fast roll speed, and roll speed differential. Their suggested prediction models were:

$$E_M = 5.927 + 0.0742(H_{SK}) - 22.737(G) + 0.239(M_{SK}) + 0.709(MC) + 2.331D - 0.00785(R) \quad (2)$$

$$E_A = -6.023 + 0.0481(H_{SK}) + 10.689(G) - 0.0597(M_{SK}) + 0.564(D) \quad (3)$$

where

E_M, E_A, H_{SK}, G, and M_{SK} are defined in table 1
MC = moisture content (% wet basis)
R = fast roll speed (rpm),
D = ratio of fast roll speed to slow roll speed (unitless).

Coefficients of determination (r^2) of 0.95 and 0.88 were obtained for E_M and E_A, respectively. Among the variables in equations 2 and 3, G and H_{SK} had the highest partial correlation.

In a related study, Pasikatan et al. (1998) developed multiple linear regression models for E_M and E_A that included terms for standard deviation of single kernel properties. The study included five wheat classes and 25 hardness levels, but among roll parameters, only roll gap was varied. Wheat class, reported as having a significant effect on grinding energy (Taguida, 1982), was used as a classification variable to classify the intercepts of grinding response; it significantly influenced E_M and E_A. The models were of the form:

$$E_M = WCI - 22.439(G) + 0.0641(H_{SK}) + 6.849(S_{SK}) - 0.133(M_{SK}) + 0.499(H_{SD}) - 16.059(S_{SD}) + 0.551(M_{SD}) \quad (r^2 = 0.81) \quad (4)$$

Table 1. Definition of variables and symbols.

Variable/ Symbol	Definition	Units
A_{NS}	New surface area; the difference between total surface area of ground wheat and that of tempered whole grain sample	cm^2
A_{NSS}	New specific surface area; for a given wheat sample, the new surface area divided by the mass of the sieved sample.	cm^2/g
E_M	Energy per unit mass; amount of energy used for grinding one kg of wheat sample.	kJ/kg
E_A	Specific energy (or energy per unit area); the energy per unit mass divided by new specific surface area, or the energy required to create one unit of new surface area.	kJ/m^2
G	Roll gap; the clearance between rolls of a roller mill	mm
H_{SK}	Single kernel hardness; the mean hardness measured from a 300–kernel wheat sample by the Single Kernel Characterization System (SKCS), a number from 0–100 where 0 is softest and 100 is hardest.	index; unitless
S_{SK}	Single kernel size or diameter; the mean diameter measured from a 300–kernel wheat sample by the SKCS.	mm
M_{SK}	Single kernel mass; the mean mass measured from 300–kernel wheat sample by SKCS. The term officially used is single kernel weight.	mg
MC_{SK}	Single kernel moisture content measured from 300–kernel sample by SKCS.	%
H_{SD}	Standard deviation of single kernel hardness.	unitless
S_{SD}	Standard deviation of single kernel size.	mm
M_{SD}	Standard deviation of single kernel mass.	mg
MC_{SD}	Standard deviation of single kernel moisture content.	%
MR	Milling ratio; ratio of G to S_{SK}	unitless
WCL	Wheat class; in the U.S. wheat classification system there are 6 classes: durum, hard red spring, hard red winter, hard white, soft red winter, soft white.	—

$$E_A = WCI + 9.377(G) + 0.0850(H_{SK}) - 5.219(S_{SK}) + 0.199(M_{SK}) + 0.0669(H_{SD}) + 0.717(S_{SD}) - 0.119(M_{SD}) \quad (r^2 = 0.91) \quad (5)$$

where WCI is wheat class–specific intercept and the other single kernel properties are defined in table 1.

Other roller mill parameters that may affect grinding energy are roll differential, or the ratio of the speed of the fast roll to that of the slow roll (Wolff, 1958; Niernberger, 1966; Hsieh et al., 1980; Fang et al., 1997), roll diameter (Niernberger and Farrell, 1970), roll speed (Wolff, 1958), and roll corrugations (Kuprits, 1965; Guritno and Haque, 1994). However, for a specific roller mill these settings are fixed.

The objectives of this study were: (1) to investigate the effects of single kernel wheat properties and roll gap on grinding energy requirements of first–break; and (2) to develop and validate models for energy requirements of first–break grinding based on roll gap and single kernel properties of six wheat classes.

MATERIALS AND METHODS

WHEAT SAMPLES

One hundred forty wheat samples were used for the model development. These represented six wheat classes (durum, hard red spring, hard red winter, hard white, soft red winter, and soft white) and at least two varieties per wheat class ground at five roll gap settings. The procedure for cleaning, sampling, measurement of physical properties, and the measured properties of the wheat samples used in the experiments were described by Pasikatan et al. (2001). The wheat samples covered the H_{SK}, S_{SK}, and M_{SK} ranges of 19.7–97.6 hardness index, 2.3–3.0 mm, and 27.8–43.5 mg, respectively.

EXPERIMENTAL ROLLER MILL

An experimental first–break roller mill (ERM) equipped with a computerized data acquisition system to measure torque, roll speed, and power was used for the milling tests. The specifications of the ERM are described in Fang et al. (1997) and Fang et al. (1998). The updated data acquisition system of the ERM was described in Pasikatan et al. (2001).

The fixed settings of the ERM and their justifications were reported in Pasikatan et al. (2001). Wheat samples were ground using five roll gaps (0.38, 0.51, 0.63, 0.75 and 0.88 mm) set using a feeler gauge. The roll gaps used in this study deliberately exceeded the typical settings that could be expected from first–break grinding in order to identify the optimum roll gap setting for the models that would be developed.

GRINDING AND SIFTING PROCEDURE

The 440–g grinding samples were tempered to 15.5% and 16% for 10 and 15 hours for soft and hard wheats, respectively. Details of tempering procedure, grinding, and sampling of ground wheat samples were described in Pasikatan et al. (2001). The Gamet precision divider (Gamet Co., Minneapolis, Minn.) was used to obtain two 110–g subsamples for sifting. One set of 110–g ground wheat samples was sifted using a Rotap Sifter (Model RX–29, W.S. Tyler Corp., Mentor, Ohio) with 14 sieves to determine total surface area (TSA) according to ASAE Standard S319.3 (*ASAE Standards*, 1998). As determined in sieving tests, the sieving time for soft, hard, and club wheats was 20, 10, and 15 min, respectively, when a pair of rubber balls and a brush were placed in each fine sieve (U.S. Sieve no. 50 (0.3 mm opening) and smaller). A Denver digital balance (Model DI–4KD, Denver Instruments, Arvada, Colo.) with 0.01 resolution was used for weighing the sieves and the sieved fractions. The percent mass of the sieved fractions and TSA were calculated from the recorded masses.

EXPERIMENTAL DESIGN, MODEL DEVELOPMENT, AND VALIDATION

The response variables were A_{NSS}, E_M, and E_A (definitions in table 1). A randomized complete block design with two replications was used for the grinding experiments. Replication was the blocking factor. The independent variables were wheat class (6 levels) and roll gap (5 levels). The single kernel properties of tempered wheat were used as covariates for the model development, that is, independent variables used in the models but not controlled for by the experimental design.

First–order models relating first–break grinding performance (E_M, A_{NSS}, and E_A) with G and single kernel properties were developed using procedures REG and GLM in SAS (1990) software. Models were developed using hierarchical regression starting from roll gap and adding one variable at a time. The inclusion of each variable was justified by the nested F–test (Ott, 1993) and the improvement of the residual plots and statistics. The adjusted r^2 statistic was used instead of r^2 to assess the improvement of fit due to an added variable because adjusted r^2 includes a penalty for unnecessary independent variables, whereas r^2 improves with an added variable (Ramsey and Schafer, 1997). The programs based on procedures REG and GLM yielded similar coefficients for each term; only intercepts varied. The program based on PROC GLM was used for the final models because it generated the least–squares means of the response variables that were used as the specific wheat class intercepts. The rationale for use of hierarchical instead of stepwise regression was discussed in Pasikatan et al. (2001).

The first–break grinding energy models were validated using the procedure described by Pasikatan et al. (2001). One hundred wheat samples for validation consisted of 60 from two replicates of the wheats used in the model development (6 wheat classes, 1 variety per wheat class × 5 roll gaps × 2 replications), and 40 from two replicates of HRW and SRW wheats not used in the model development (2 HRW or SRW × 5 roll gaps × 2 replications). The latter samples were added to test the predictive ability of the models with varieties different from those in the model set. The wheat samples were ground and sifted using the same settings and procedures described for the model development set.

RESULTS AND DISCUSSION

FIRST–BREAK GRINDING MODELS

The variables G and H_{SK} were reported in the literature as good predictors of energy requirements (Kuprits, 1965; Fang, 1995) and were considered first in the models. These explained 90.8%–94.9% of the variation in the dependent variables as measured using adjusted r^2. Next, S_{SK} and M_{SK} were added to the models; these explained an additional 0.8%–1.3% of the variations in the dependent variables. Then the standard deviation terms (H_{SD}, S_{SD}, and M_{SD}) were added, accounting for an additional 0.9%–1.4% of the variability. Finally, the wheat class (WCL) variable was added to classify the grinding response according to each specific wheat class. The effect of WCL was expressed as intercepts of the response lines. Like the models for size properties of ground wheat (Pasikatan et al., 2001), these grinding models assumed wheat's tempering moisture content of 15.5% and 16% and similar slopes but different intercepts for each wheat class group.

The A_{NSS} data was skewed, probably because of the exponential equation used for its calculation (*ASAE Standards*, 1998). Log transformation of A_{NSS} data improved the statistics and the behavior of the residuals.

The potential of further improving the grinding models was explored by using an independent variable that combined G and S_{SK}. The variable was milling ratio (MR), which is the ratio of G to S_{SK}. The relationship of input wheat kernel size and particle size of ground wheat was shown to be critically dependent on milling ratio (Campbell et al., 1999). When substituted for G and S_{SK}, MR has the potential to reduce collinearities between variables and isolate the effects of each variable because there would be one less independent variable in the models. Two sets of models were therefore developed: the full models, which used G and S_{SK}, and the reduced models, which used MR instead of G and S_{SK}. The models have the general form:

Full model; Seven Variable

$$Y = \alpha_0 + \alpha_1(G') + \alpha_2 (H_{SK}') + \alpha_3 (S_{SK}') + \alpha_4 (M_{SK}') + \alpha_5 (H_{SD}') + \alpha_6 (S_{SD}') + \alpha_7 (M_{SD}') + \varepsilon \quad (6)$$

Reduced Model; Six Variables

$$Y = \beta_0 + \beta_1(MR') + \beta_2 (H_{SK}') + \beta_3 (M_{SK}') + \beta_4 (H_{SD}') + \beta_5 (S_{SD}') + \beta_6(M_{SD}') + \varepsilon \quad (7)$$

where

Y = response variable: A_{NSS} (cm^2/g), or E_M (kJ/kg), or E_A (kJ/m^2) (defined in table 1)

α_0 and β_0 = parameter denoting wheat class–specific intercepts (estimates in table 2)

α_i and β_i = parameter denoting regression coefficients or slopes (estimates in table 3)

ε = error, assumed to be a gaussian random variable with zero mean and common variance

The independent variables are defined in table 1. The primed sign indicates the measured independent variable of a sample minus the mean measurement of that independent variable for all samples used in the experiment. This means that when all independent variables are at their mean values, the value of the response variable is equal to the wheat class intercept.

Seven–Variable Models

Log_e (New Specific Surface Area) or L_ A_{NSS} was strongly related to WCL, G, H_{SK}, S_{SK}, M_{SK}, H_{SD}, and S_{SD} (tables 2 and 3). L_ A_{NSS} decreased as G, H_{SK}, and M_{SK} increased. Larger G, harder or heavier wheats would give a coarser grind (smaller L_ A_{NSS}). The inverse effect of G on A_{NSS} (or L_ A_{NSS}) was consistent with the results of Fang (1995). L_ A_{NSS} increased with S_{SK}. Smaller kernels are usually softer than bigger kernels (Gaines et al., 1997) and thus would be ground more than bigger kernels. For a fixed gap and specific wheat class, bigger kernels would undergo more grinding than smaller kernels. L_ A_{NSS} decreased as H_{SD} and S_{SD} increased, but increased with M_{SD}. The increased variations in hardness of the kernels resulted in a coarser grind (smaller L_ A_{NSS}) because increased H_{SD} tended towards harder and heavier wheats.

Tables 2 and 3 show that WCL, G, H_{SK}, and M_{SD} significantly influenced energy per unit mass (E_M). E_M decreased as G increased, but increased as H_{SK} increased. As G increased, the degree of grinding decreased, hence less grinding energy was required. As wheat hardness increased, grinding energy increased. The significant effect of WCL on grinding energy was consistent with the observations of Taguida (1982). The E_M–G and E_M–H_{SK} trends were similar to those obtained by Hsieh et al. (1980) and Fang (1995). E_M increased with S_{SK} and M_{SK}. Smaller kernels are softer than bigger kernels. Heavier kernels are usually harder than lighter kernels. As kernels became bigger and heavier, more grinding energy was required. E_M increased with H_{SD}, but decreased with S_{SD} and M_{SD}. In this data, H_{SD} distribution is skewed towards smaller S_{SD} corresponding to harder wheats. Therefore, as the heterogeneity of the kernel hardness increased, more grinding energy was required.

Specific energy (E_A) was significantly influenced by WCL, G, H_{SK}, H_{SD}, and M_{SD} (tables 2 and 3). E_A increased with G and H_{SK}. When G increased, grinding energy and the fineness of grinding decreased (see negative coefficients of E_M–G, L_ A_{NSS}–G in table 3). The rate of decrease in E_M was less than the rate of decrease in A_{NSS}, hence the increase in E_A with G. As H_{SK} increased, grinding energy increased and kernels broke into coarser pieces. An increasing grinding energy and a decreasing A_{NSS} gave an increasing E_A. The trends of the effect of G and H_{SK} on E_A were similar to the results of Fang (1995) and Pasikatan et al. (1998). As kernels become bigger and heavier, more grinding energy was

Table 2. Estimated wheat–class–intercepts and standard errors (in parentheses) in the log (new specific surface area) (L_ A_{NSS}), energy per unit mass (E_M), and specific energy (E_A) models.

	L_ A_{NSS} (cm^2/g)		E_M (kJ/kg)		E_A (kJ/m^2)	
Intercepts[a]	7–var[b]	MR[c]	7–var	MR	7–var	MR
Durum	5.0811 b (0.0452)	5.0590 b (0.0445)	18.0042 a (0.9069)	17.6751 a (0.9617)	1.4978 bc (0.0775)	1.5335 b (0.0814)
Hard Red Spring	5.1347 b (0.0342)	5.0867 b (0.0261)	19.8138 bc (0.6874)	19.0519 a (0.5636)	1.1769 a (0.0587)	1.2781 a (0.0477)
Hard Red Winter	4.9483 a (0.0216)	4.9430 a (0.0215)	19.7995 bc (0.4345)	19.7266 a (0.4652)	1.3709 b (0.0371)	1.3779 b (0.0394)
Hard White	5.1035 b (0.0269)	5.0982 b (0.0247)	19.5750 bc (0.5419)	19.4138 a (0.5346)	1.2229 a (0.0463)	1.2623 a (0.0452)
Soft Red Winter	5.2715 c (0.0289)	5.2987 c (0.0265)	22.0732 d (0.5817)	22.4982 b (0.5742)	1.2208 a (0.0497)	1.1672 a (0.0486)
Soft White	5.0134 ab (0.0332)	5.0396 b (0.0278)	21.1779 cd (0.6669)	21.6531 c (0.6025)	1.4297 b (0.0569)	1.3539 ab (0.0509)

[a] In a column, intercepts followed by similar letters are not significantly different by LSD ($p < 0.05$). Wheat class intercepts in these models are the values of the response variables when all independent variables are at their mean values. All wheat class intercepts for L_ A_{NSS}, E_M, and E_A are significant at the 0.001 level.

[b] Seven–variable model.

[c] six–variable model based on MR (G/S_{SK}) variable.

Table 3. Estimated regression coefficient and standard error (in parentheses) of each independent variable in the model for log (new specific surface area)(L_A_{NSS}), energy per unit mass (E_M), and specific energy (E_A).

Variables	L_A_{NSS} (cm^2/g)		E_M (kJ/kg)		E_A (kJ/m^2)	
	7–var[a]	MR[b]	7–var	MR	7–var	MR
G	–2.4528***		–28.3143***		1.2926***	
	(0.0356)	—	(0.7158)	—	(0.0612)	—
MR		–6.5761***		–75.3430***		3.3831***
	—	(0.0947)	—	(2.0490)	—	(0.1734)
H_{SK}	–0.0144***	–0.0137***	0.1305***	0.1406***	0.0221***	0.0213***
	(0.0009)	(0.0009)	(0.0193)	(0.0206)	(0.0017)	(0.0017)
S_{SK}	0.4262**		3.6353		0.2378	
	(0.1326)	—	(2.6637)	—	(0.2277)	—
M_{SK}	–0.02075**	–0.0286***	0.0304	0.1119	0.0020	0.0254***
	(0.0064)	(0.0032)	(0.1297)	(0.0685)	(0.0111)	(0.0058)
H_{SD}	–0.0120**	–0.0133**	0.1007	0.0903	0.0299***	0.0298**
	(0.0044)	(0.0044)	(0.0883)	(0.0946)	(0.0075)	(0.0080)
S_{SD}	–0.6267**	–0.6709**	–7.5551	–8.2241*	0.2599	0.3239
	(0.2013)	(0.2001)	(4.0422)	(4.3284)	(0.3455)	(0.3663)
M_{SD}	0.0268	0.0378***	–0.4285*	–0.2391	–0.0429*	–0.0713***
	(0.0111)	(0.0089)	(0.2230)	(0.1929)	(0.0191)	(0.0163)
Adjusted r^2[c]	0.98	0.98	0.93	0.92	0.95	0.95
C.V.[d]	1.44	1.43	7.25	7.77	9.66	10.26
MSE[e]	0.0054	0.0054	2.1783	2.5047	0.0159	0.0179

[a] Seven–variable model.
[b] Six–variable model based on MR (G/S_{SK}) variable.
[c] Adjusted r^2 is the same for each wheat class; only intercepts change due to wheat class coefficients.
[d] Coefficient of variation.
[e] Mean squared error.
Note: *, **, *** Significant at the 0.05, 0.01, and 0.001 levels, respectively. Variable values not followed by an asterisk are not significant at the 0.05 level.

required and kernels were ground coarser, thus the increase in E_A as S_{SK} and M_{SK} increased. Increased H_{SD} was associated with higher H_{SK} values, hence as H_{SD} increased, E_A increased as well.

Six–Variable Models: MR–based

The use of MR made M_{SK} either significant or more significant and increased its estimated coefficient for the L_A_{NSS} and E_A models (table 3). The standard errors of the M_{SK} coefficient decreased compared to those of the seven–variable models. MR did not make M_{SK} significant in the E_M model but it increased its estimated coefficient over that of the seven–variable model. This confirmed the effect of high correlation between S_{SK} and M_{SK} on the seven–variable models, that is, one variable masked the effect of the other. The use of MR isolated the effect of S_{SK} from M_{SK}. In the E_M model, the high coefficient of MR indicated that the explaining ability of other variables were reduced in favor of MR. As heavier kernels (bigger M_{SK}) were ground, more energy was required (higher E_M) and the grind became coarser (smaller L_A_{NSS}). The trend of M_{SK} effect was consistent with that of the seven–variable model. The trends of H_{SD}, S_{SD}, and M_{SD} in the seven–variable model were retained in the MR–based L_A_{NSS}, E_M, and E_A models.

Increased MR meant either G increased while S_{SK} was fixed, or S_{SK} decreased while G was fixed. In either case, increased MR meant less grinding action, thus giving a coarser grind (decreased L_A_{NSS}) and requiring less energy (reduced E_M) (table 3). The unit decrease in A_{NSS} was less than that of E_M, thus the increase in E_A. The statistics of MR–based models were comparable to those of the seven–variable model. The explaining ability of MR was comparable to that of G and S_{SK} for the E_M model (r^2 = 0.85 vs. 0.83; Pasikatan, 2000).

Validation of the First–Break Grinding Models

MR–based models yielded comparable statistics to the seven–variable models, particularly the L_A_{NSS} and E_A models (table 3). The predictive abilities of these two models were further evaluated. The seven–variable models generally had slightly better validation statistics than the MR–based models (table 4). Both models predicted the measured values well as shown in the mean and standard deviation of predicted values, the slope (or sensitivity) of nearly 1.0, and the high r^2.

Figures 1 through 3 show the plots of the predicted against measured values for the seven–variable L_A_{NSS}, E_M, and E_A models, respectively. The E_A predicted vs. measured values plot has three regions: the low E_A region (about 0.3–1.1 kJ/m^2) for the soft wheats, the middle E_A region (about 1.1–2.0 kJ/m^2) for the hard wheats, and the high E_A region (>2 kJ/m^2) for the very hard wheats (fig. 3). The clustering of predicted values according to wheat class was consistent with the literature.

Figure 4 shows the potential of the E_A model for roll gap control as an alternative to the break release model proposed by Pasikatan (2000). The E_A model is potentially a better basis for optimizing roll gap setting than break release because E_A includes both a measure of grinding energy and degree of grinding. An online SKCS would measure the single kernel properties of the wheat samples and send this information to a computer. A target E_A for a specific wheat class would be inputted by an operator to the control computer, which then would calculate the appropriate roll gap based on the single kernel properties of incoming wheat.

Table 4. Validation statistics for the first–break grinding models for log(new specific surface area) (L_A_{NSS}), energy per unit mass (E_M), and specific energy (E_A).

Indices	L_A_{NSS} (cm^2/g)	E_M (kJ/kg)	E_A (kJ/m^2)
Seven–variable models			
Measured values[a]	5.139 ±0.623	20.617 ±6.365	1.349 ±0.696
Predicted values[b]	5.094 ±0.607	20.392 ±5.644	1.316 ±0.649
Standard error	0.125	1.787	0.197
RMSD[c]	0.135	2.056	0.213
r^2	0.96	0.90	0.91
Bias	0.198	3.041	0.116
Slope	0.95	0.84	0.88
Reduced models based on milling ratio			
Predicted values	5.096 ±0.610	20.429 ±5.725	1.312 ±0.648
Standard error	0.126	1.958	0.203
RMSD	0.135	2.189	0.220
r^2	0.96	0.88	0.90
Bias	0.171	2.991	0.118
Slope	0.99	0.85	0.89

[a] Mean ± standard deviation for 100 measurements.
[b] Mean ± standard deviation for 100 predictions.
[c] Root mean squared difference between measured and predicted values for 100 measurements.

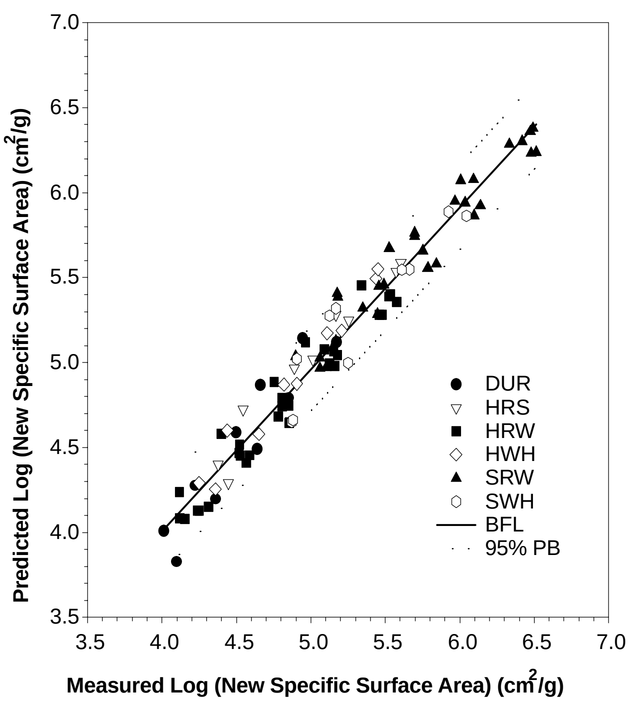

Figure 1. Relationship between measured and predicted log (new specific surface area) values for 100 validation samples. The middle line is the best–fit line (BFL); outer lines are the 95% prediction bands. DUR = durum, HRS = hard red spring, HRW = hard red winter, HWH = hard white, SRW = soft red winter, and SWH = soft white.

The computer could then send a signal to actuate a stepper motor to set the roll gap. However, more studies are needed to show the advantages of an E_A model over a break release model.

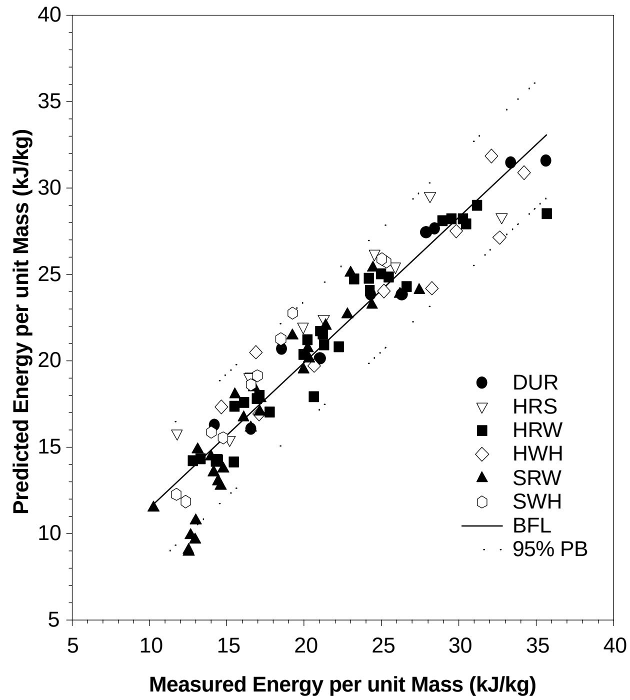

Figure 2. Relationship between measured and predicted energy per unit mass values for 100 validation samples. The middle line is the best–fit line (BFL); outer lines are the 95% prediction bands. DUR = durum, HRS = hard red spring, HRW = hard red winter, HWH = hard white, SRW = soft red winter, and SWH = soft white.

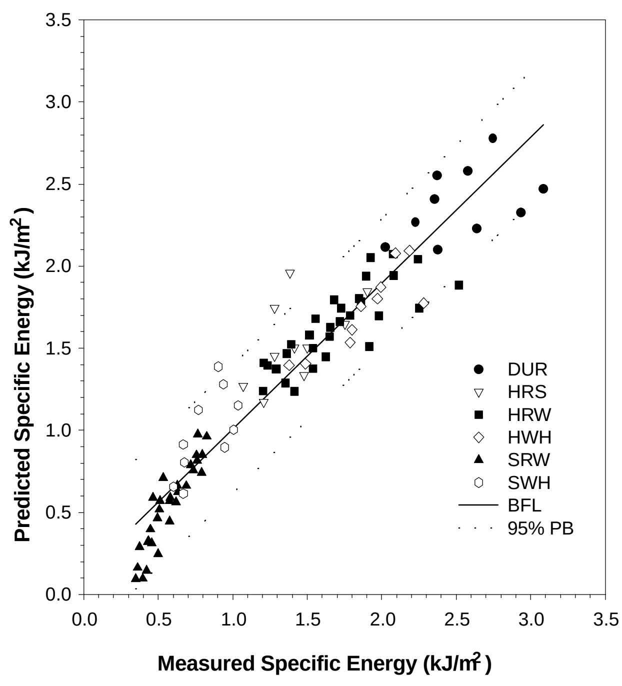

Figure 3. Relationship between measured and predicted specific energy values for 100 validation samples. The middle line is the best–fit line (BFL); outer lines are the 95% prediction bands. DUR = durum, HRS = hard red spring, HRW = hard red winter, HWH = hard white, SRW = soft red winter, and SWH = soft white.

CONCLUSIONS

1. Multiple linear regression models for energy per unit mass, new specific surface area (on a log scale), and specific energy as functions of wheat class as a classification variable, roll gap, and the single kernel properties of wheat were developed. Roll gap and single kernel hardness, in a consistent manner, had significant effects on the

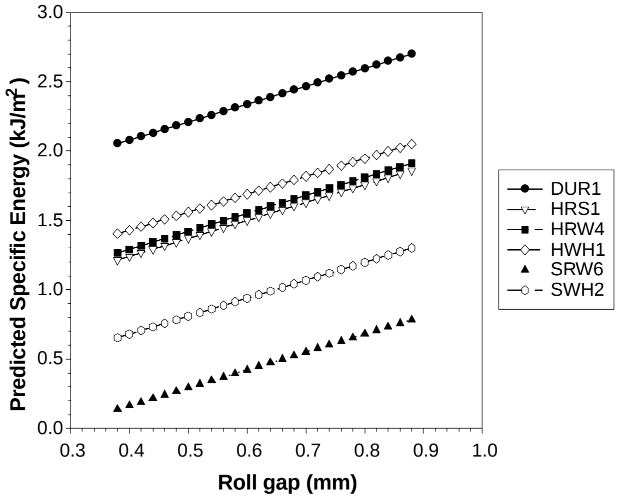

Figure 4. Prediction lines for specific energy as a function of roll gap for six of the wheat varieties used in the validation. DUR1 = 'Cando' durum, N. Dak. (1996), HRS1 = 'Butte 86' hard red spring, N. Dak. (1996), HRW4 = '2137' hard red winter, Nebr. (1999), HWH1 = 'Arlin' hard white, Colo. (1996); SRW6 = 'Jaypee', soft red winter, Ark. (1996), SWH2 = 'Tres', white club, Wash. (1993). The physical properties of these wheat samples are in Pasikatan et al. (2001).

response variables. Roll gap had an inverse effect on new specific surface area and energy per unit mass and a direct effect on specific energy. Single kernel hardness had a direct effect on energy per unit mass and specific energy, and an inverse effect on new specific surface area.

2. Models that used milling ratio, which combined single kernel size and roll gap, reduced some collinearities among single kernel properties and isolated the effect of single kernel mass from single kernel size. The effect of single kernel mass became significant in these models. Models based on milling ratio were comparable to the performance of the full models. Single kernel mass had direct effects on specific energy and inverse effects on energy per unit mass and new specific surface area.
3. Wheat class had a significant effect on the energy per unit mass, new specific area created, and specific energy. The specific energy model which accounted for the effect of wheat class could be an alternative parameter for setting roll gaps because it considered both energy and size properties. The standard deviation of single kernel properties was useful in explaining the effect of the spread (or heterogeneity) of the single kernel properties. The explaining ability of standard deviation terms was dependent on the model data set, whereas that of the mean single kernel properties could be applied beyond the model data set.
4. The models performed well in validation tests using 100 wheat samples (r^2 = 0.90 to 0.96). The consistency of the trends shown in the models with those of previous research and millers' experience was indicative of the robustness and usefulness of these models.

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