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INFLUENCE OF WHEAT GRAIN MECHANICAL PROPERTIES ON GRINDING ENERGY REQUIREMENTS

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Summary. The paper presents the results concerning the influence of grain mechanical properties on wheat grinding energy requirements. The investigations were carried out on 10 wheat varieties (grain moisture was 15%). The results showed that the specific grinding energy ranged form 22 to 37 $kJ \cdot kg^{-1}$. The changes of specific grinding energy were described by using the multiple linear regression equation, where force and deformation of grain up to the rapture point and force in the end of the compression were taken as independent variables (R^2 = 0.997). The grinding efficiency index ranged form 0.215 to 0.342 $m^2 \cdot kg^{-1}$. The statistical analysis showed negative correlations between this index and such grain mechanical properties as force (r = -0.76), work (r = -0.79) and individual work (r = -0.69) determined for the end of the compression. Positive correlations were found between the grinding index K and rapture force (r = 0.64). The strongest and positive correlations were observed between K and force, work, and individual work characterized the end of the compression (0.86; 0.87 and 0.79, respectively).

Key words: wheat, grain, mechanical properties, grinding, energy requirements

INTRODUCTION

Grinding is one of the most important and energy-consuming processes in cereal industry. This process consumes from 70% of total power during the feed production up to 90% during wheat flour milling. The grinding energy requirements depend on kinematical and geometrical parameters of the grinding machine and physical properties of the ground material. Knowledge of the grinding properties of grain is essential to adjust the correct parameters of grinding and sieving machines. It is the best way to produce higher and better-quality product yields at minimum energy requirements. From among the physical properties, the mechanical ones have the greatest influence on grinding energy consumption. These properties depend mainly on a cultivar, but also form agro-climatic and agro-technical factors. Wetting or drying the grains can also modify them [Glenn and Johnston 1992, Mabille *et al.* 2001].

The mechanical properties of grain result from the endosperm properties and the bran layers (fruit and seed coat, nucellus and aleurone) properties. After wheat grain debranning (when fruit and seed coat is removed) less energy for grinding is needed [Dziki and Laskowski 2005]. Moreover, Dobraszczyk *et al.* [2002] found that mechanical properties of wheat grain, especially fracture properties, depend strongly on wheat endosperm density.

Laskowski and Różyło [2003] showed a positive correlation between wheat vitreousness and grinding energy requirements. Romański *et al.* [2003] found relationship between grain temperature and wheat compression energy requirements. As the grain temperature decreased from 40 to -20°C energy requirements increased about 12%. However Dziki [2003, 2004a] showed that grain temperature (range 0-40 °C) has no significant influence on the specific grinding energy of wheat grain, but has an influence on particle size distribution of the ground material.

Wheat hardness has the greatest influence on the grinding, especially in the wheat milling process. Millers can find real problems when they attempt to grind very soft wheat on a mill designed for harder wheat or they attempt to make hard wheat flour on a mill designed for softer wheat. The differences between soft wheat flour milling and hard wheat flour milling concern the conditioning, grinding and sifting [Posner, Hibbs 1997]. Hard wheat cultivars, especially durum wheat cultivars require more power to grind the grain than soft wheat cultivars [Kilborn *et al.* 1982, Dziki and Laskowski 2000].

Laskowski and Łysiak [1999] used a compression test of legume seeds in view of impact grinding prediction. They showed a significant relationship between the characteristics of the compression curve and the grinding energy requirement. From among the analyzed resistance parameters, the most significant relations were received between deformations up to plasticity and immediate resistance thresholds with the specific grinding energy.

The aim of the present work was to determine the influence of wheat grain mechanical properties, obtained on the basis of uniaxial compression test, on wheat grinding energy requirements.

MATERIALS AND METHODS

The investigations were carried out on 8 Polish cultivars of common wheat (Zyta, Sukces, Turnia, Rysa, Nutka, Mewa, Zorza, and Slade) and two French durum wheat (Ardente and Armet). Samples of wheat grain were tempered for 48 hours to 15% moisture level. Subsequently, individual kernels were weighed and placed on the bottom plate of universal testing machine ZWICK Z020/TN2S (the kernel crease towards the bottom plate) and compressed with a constant speed of 10 $mm \cdot min^{-1}$ until the constant distance of 0.5 mm between the plates was achieved. Changes in the loading force in relation to the kernel deformation were recorded by means of a computer kit. On the basis of the obtained compression curves (Fig. 1) the following parameters were determined: forces (F_1 and F_2), deformations (Δh_1 and Δh_2), values of work and individual work (work divided by kernel mass) for the rapture point (L_1 and L_{j1}, respectively) and in the end of the compression (L_2 and L_{j2}, respectively). For investigations the common fraction of each cultivar (2.9-3.1 mm of grain thickness) was used.

The samples were milled using SK laboratory roller mill. Four grinding stages were applied. The roll gap was 0.80 mm for the first stage, 0.4 mm for the second stage, 0.25 mm for the third stage and 0.15 mm for the fourth stage. The detailed description of laboratory mill was described by Dziki *et al.* [1997].

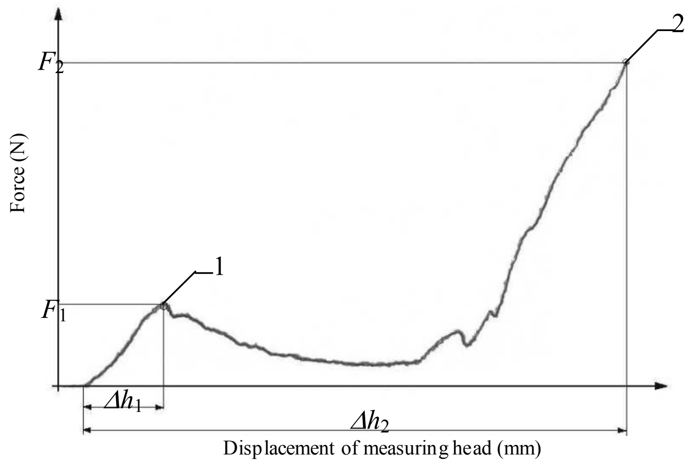

Fig. 1. Example of wheat grain compression curve: 1 – rapture point, 2 – the end of the compression (grain moisture 15%) [Dziki 2004b]

The changes of power consumption of electric current during the grinding were recorded using laboratory equipment including the grinding machine, transducer of power and a special data acquisition card connected to a PC computer. After grinding the energy consumption was calculated by using special computer software [Dziki *et al.* 1997]. It was assumed that power consumption during the grinding process is a difference between the total grinding power and loss of power transmission system during idle running [Popko 1986]. The specific grinding energy (E_r) was calculated according to the equation:

$$E_r = \frac{E_c - E_s}{m} \tag{1}$$

where:

m – the mass of ground sample, kg,
E_c – the total grinding energy consumption, J,
E_s – the idle running energy consumption, J.

The particle size distribution of the ground material was evaluated using the laboratory sieve machine Thyr 2 equipped with changeable sieves and an average particle size was calculated [Grochowicz 1996]. The grinding energy efficiency index (E_g) was determined as the ratio of grinding stock surface area (A) to grinding energy (E_w). The surface area (A) of the ground material was calculated according to the equation:

$$A = \frac{6 \cdot m}{\rho \cdot d} \tag{2}$$

where:

d – the average particle size of particles, m^2,
ρ – the density of particles (for the calculation 1300 kg/m^3 was used [Kiryluk *et al.* 1998]

The grinding index K was also calculated on the basis of the size reduction theory described by Sokołowski [1996]:

$$K = \frac{E_r}{\frac{1}{\sqrt{d}} - \frac{1}{\sqrt{D}}} \qquad (3)$$

where:

d – the average particle size of particles before grinding, m^2,

Measurements of wheat grain mechanical properties were replicated thirty times for a fraction of each variety whereas measurements of grinding energy were replicated ten times. The obtained data were statistically analyzed. The evaluations were analyzed for variance analysis. The significant differences among the means were evaluated by Tukey`s test. The Pearson's correlation coefficients and regression equations were also evaluated. All the statistical tests were carried out at the significance level of $\alpha = 0.05$.

RESULTS AND DISCUSSION

The results showed that the highest values of rapture force (F_1) and force at the end of compression (F_2) were obtained for durum wheat variety Ardente (155 N and 1716 N, respectively). The lowest values F_1 and F_2 were observed for common wheat Slade (69 N and 1023 N, respectively). The deformation of grain up to the rapture point (Δh_1) ranged from 0.20 mm (Torka variety) to 0.46 mm (Zorza variety). Dziki [2004b] showed that an increase of grain moisture content significantly decreases Δh_1. The highest values of work and individual work up to the grain rapture point (L_1 and L_{j1}) were obtained for Zorza variety (34 mJ and 0.61 J/g, respectively) and the lowest (almost three times) for Turnia and Armet varieties (12 mJ and 0.21 J/g, respectively). The individual work up to the end of grain compression ranged from 9.3 J/g (Zorza variety) to 14 J/g (durum wheat varieties). The results were presented in Tab. 1.

Table 1. Mechanical properties of wheat grain

Variety	Δh_1 mm	F_1 N	F_2 N	L_1 mJ	L_{j1} J/g	L_2 mJ	L_{j2} J/g
Ardente	0.33	155	1716	30	0.50	874	14.3
Armet	0.22	97	1583	12	0.21	794	13.7
Mewa	0.42	95	1165	27	0.50	501	9.7
Nutka	0.28	121	1206	20	0.38	617	11.8
Rysa	0.34	104	1306	23	0.44	612	11.6
Slade	0.31	69	1023	15	0.27	447	8.3
Sukces	0.28	117	1341	21	0.42	657	12.5
Turnia	0.20	103	1331	12	0.21	660	11.3
Zorza	0.46	99	1117	34	0.61	525	9.3
Zyta	0.23	102	1343	16	0.29	644	11.7

Δh_1 – deformation of grain up to the rapture point; F_1 – force caused rapture of grain, F_2 – force in the end of the compression, L_1 and L_{j1} – work and individual work compression of grain up to the rapture point, L_2 and L_{j2} – work and individual work compression of grain up to the end of compression.

The specific grinding energy (E_r) ranged form 22 kJ·kg^{-1} for common wheat variety Slade and Zorza to 37 kJ·kg^{-1} for durum wheat varieties (Fig. 2). The analysis of results showed many statistically significant ($\alpha = 0.05$) dependencies between wheat grain mechanical properties and specific grinding energy. As the F_2, L_2 and L_{j2} increased the specific grinding energy increased, too (r = 0.95; 0.97 and 0.95, respectively). Also, a positive correlation was found between the forces causing the rapture of grain (F_1) and E_r (r = 0.78).

The changes of E_r were described by using the multiple linear regression equation (backward method was used), where force and deformation of grain up to the rapture point (F_1 and Δh_1) and force in the end of the compression (F_2) were taken as independent variables:

$$E_r = 0.082F_1 - 17\Delta h_1 + 0.0162F_2 + 3.592; \ R^2 = 0.977 \quad (4)$$

Laskowski and Łysiak [1999] used the compression test of legume seeds in view of impact grinding prediction. They obtained different equations. They showed that from among the analyzed resistance parameters, the most significant relations were received between deformations up to plasticity (positive correlation) and immediate resistance thresholds (negative correlation) with the specific grinding energy. However, they used hammer mill and different raw materials.

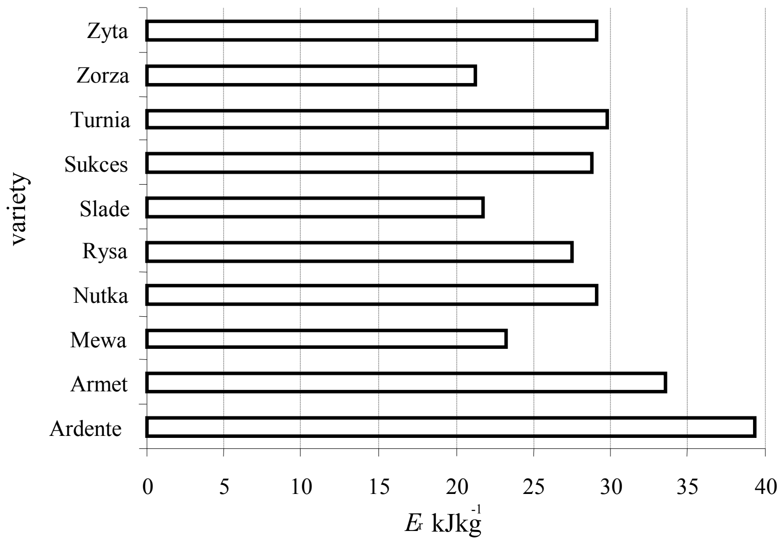

Fig. 2. Specific grinding energy of wheat grain varieties

Average particle size (*d*) ranged from 0.54 mm (Armet variety) to 0.77 mm (Slade variety) and the flour yield changed from 57% (Slade variety) to 60% (Ardente variety). From among the analyzed resistance parameters, the most significant relations were received between F_1, F_2, L_1, L_2 and average particle size (-0.65; -0.68; -0.70; -0.80, respectively). Also, a positive correlation was found between F_1 and flour yield (r = 0.70).

The results of grinding efficiency index (E_g) were presented in Figure 3. The lowest value of E_g was obtained for durum wheat variety Ardente (0.215 $m^2 \cdot kg^{-1}$) and the highest for Mewa variety (0.342 $m^2 \cdot kg^{-1}$). The analysis of relations showed negative correlations between E_g and the mechanical properties determined for the end of grain compression: F_5 (r = -0.76), L_5 (r = -0.79), L_{j5} (r = -0.69).

The changes of E_g were described by using the multiple linear regression equation (backward method was used), where average particle size (*d*) and individual work (L_{j2}) were taken as independent variables:

$$E_g = -0.479d - 0{,}028L_{j2} + 0.888; \quad R^2 = 0.781 \tag{5}$$

The grinding index *K* ranged form 28 to 45 $kJ \cdot kg^{-1} \cdot mm^{0.5}$ (Fig. 4). The highest values of K were obtained for durum wheat varieties (average 42 $kJ \cdot kg^{-1} \cdot mm^{0.5}$). The significantly lower values were obtained for common wheat varieties and the lowest ones for Zorza and Mewa variety (average 28 $kJ \cdot kg^{-1} \cdot mm^{0.5}$).

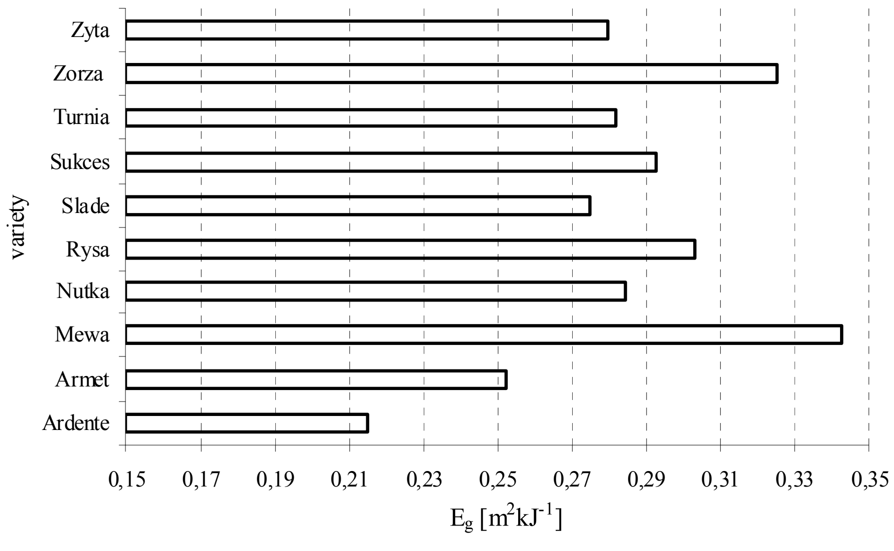

Fig. 3. Grinding efficiency index obtained for different wheat varieties

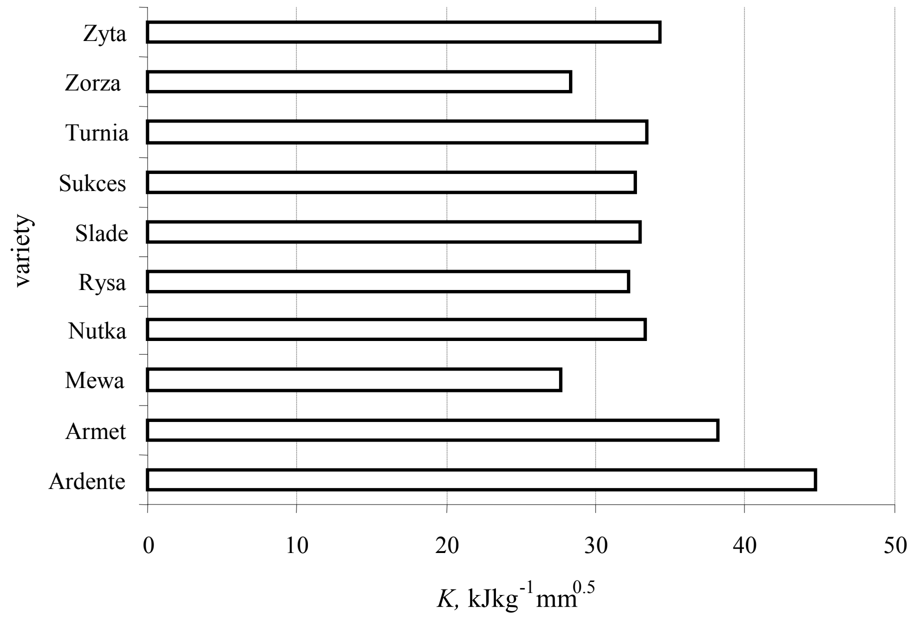

Fig. 4. Grinding index K obtained for different wheat varieties

Positive correlations were found between the grinding index *K* and rapture force (F_1). The strongest correlations were observed between *K* and force, work and individual work characterizing the end of the grain compression (0.86; 0.87 and 0.79, respectively).

CONCLUSIONS

1. The changes of specific grinding energy were described by using the multiple linear regression equation, where force and deformation of grain up to the rapture point and force in the end on the compression were taken as independent variables ($R^2 = 0.997$).
2. The grinding efficiency index ranged from 0.215 $m^2 \cdot kg^{-1}$ to 0.342 $m^2 \cdot kg^{-1}$. The analysis of relations showed negative correlations between this index and such grain mechanical properties as force (r = -0.76), work (r = -0.79) and individual work (r = -0.69) determined for the end of the compression.
3. Positive correlations were found between the grinding index *K* and rapture force (r = 0.64). The strongest and positive correlations were observed between *K* and force, work and individual work characterizing the end of the compression (0.86; 0.87 and 0.79, respectively).
4. Grain mechanical parameters obtained on the basis of uniaxial compression test show many of significant correlations with the wheat grinding energy requirements and could be a useful tool for describing the grinding process.

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