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RELATIONSHIPS BETWEEN RESISTANCE CHARACTERISTICS OF BARLEY KERNELS AND ENERGY CONSUMPTION DURING GRINDING ON HAMMER MILL

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Abstract. The present study undertakes evaluation of the influence of dimensional and resistance characteristics of barley kernels on the energy consumption during grinding. Resistance characteristics of barley kernels was determined using the uniaxial compression test carried out on an universal Instron tester. Studies on the grinding process were conducted with the use of a hammer mill. Study results were presented in the form of regression equations.

Keywords: biological material, physical properties, grinding

INTRODUCTION

Analyses of the phenomena accompanying the process of kernel grinding allow for the assumption the process character, and mainly its energy consumption, can be related to the resistance characteristics of the material. The above assumption was confirmed by the studies [12,13] in which energy consumption during grinding processes of non-biological materials was considered in relation to such constants as Young's modulus, or Poisson's coefficient.

Most of the studies on the resistance characteristics of kernels conducted so far aimed at the determination the effects of mechanical loading on the biological value of kernels [3,4,10,11]. Another study direction was to work out rheological models describing the studied medium and to determine material characteristics for, it such as Young's modulus and Poisson's coefficient [5,9]. In both of the above mentioned directions researchers concentrated their attention on the force range that did not exceed elastic deformation of kernels, or, on a higher levels of force range, that cause damage to the inner or outer kernel structure. Despite numerous studies on resistance characteristics there are difficulties in comparing results by different authors. An example of that can be a discrepancy as high as 2000% in determining the above mentioned Young's modulus [6]. The reason for this above is the lack of uniform methods and adequate measuring gauges on one hand, and great difficulties in describing and interpreting phenomena that take place in kernels under mechanical load.

There is still no detailed evaluation of the influence of resistance characteristics on the course of the grinding process, especially for the materials of biological origin. It induces us to carry out further systematic studies using the newest methods and measuring gauges available.

The aim of the present work is to determine the extend of influence of dimensional and resistance kernel characteristics on the energy consumption of the grinding process for some chosen kernel varieties, together with the products quality.

MATERIALS AND METHODS

Studies on the resistance characteristics and the grinding process of barley kernels were carried out using the methods worked out in the Institute of Machine Operation in Food Industry of the University of Agriculture in Lublin [7,8].

Measurements of kernel resistance characteristics

Studies were carried out on an universal testing machine Instron 4302 in the load range of 0 - 1000 N, between two parallel plates. Four barley varieties were used: Ars, Edgar, Klimek, and Kos. Determinations were carried out on the kernels from the size class of 2.7-3.1 mm. Percentage contribution of this class in the chosen barley varieties was as follows: Ars - 79%, Edgar - 73%, Klimek - 52%, and Kos - 91%. Individual barley kernels were weighed and their basic dimensional parameters were determined (thickness - h, width - b, length - c, with the accuracy of 5 x 10^{-5} m). Then they were placed with the groove facing the lower fixed plate, and compressed by means of the upper plate moving with the speed of 10^{-2} m $\min^{-1}$. The loading force was acting along kernel's thickness. Measurements were carried out until a constant distance between the plates of 5 x 10^{-4} m, was achieved according to the method described by Laskowski and Janiak [7]. Changes in the loading force in relation to kernel deformation were recorded by means of a computer kit with a measuring frequency of 200 Hz. On the basis of the so-obtained collapse curves the following parameters were determined: value of forces, deformation, work input for the characteristic points on the collapse curve, i.e.: for the proportionality threshold (1), plasticity threshold (2), biological resistance threshold (3), immediate resistance threshold (4), collapse threshold (5) (Fig. 1).

Byszewski and Haman [1] in the single-particle compression test for materials of biological origin determined three characteristic limits defined as: the limit of elasticity (linear stress-strain relation), the limit of plasticity corresponding to the value of stress above which the strain increases without the increase of the stress, and the limit of biological resistance corresponding to the beginning of macro-damages of a material. The compression process was also described in an ASAE publication and for biological materials owning the phase of plastic flaw the increase of stress after the end of this phase was observed [2]. Description more precise was presented by Laskowski and Janiak [7]. List of parameters and symbols used in present work according to above mentioned authors are presented at the end of the paper.

Studies were carried out for 5 kernel moisture levels, i.e., 10, 12, 14, 16, and 18%. The

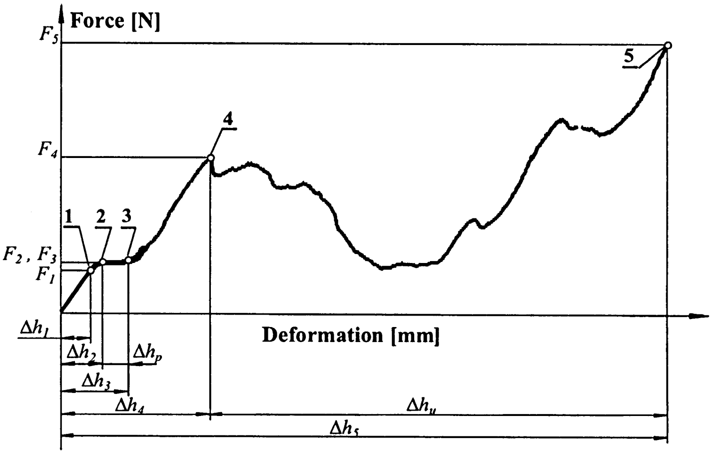

Fig. 1. Relation between the force loading kernels and upper plate travel.

above range of moisture levels is characteristic of many refining processes such as: production of flours, groats, and flakes. For each raw material and chosen moisture level measurements were taken in 50 repetitions. Numerous number of the repetitions was performed due to the large variability of results obtained in case of the compression test.

Measurements of grinding energy

Studies were carried out on a laboratory hammer mill applying methodology described by Laskowski and Łysiak [8] for 1.0 mm screen size.

Two gram kernel samples from each variety and moisture level were ground. The values of power consumption of monophase electric current with the frequency of 100 Hz was recorded. The value of energy consumption during grinding E [kWh t^{-1}] was determined using a special computer programme. Crushed material was then subjected to analysis of granulometric composition using a laboratory flat sifter. The quality of the ground material was estimated for further analyses by determining a mean particle size. Measurements of energy consumption during process were carried out in 15 repetitions (standard error less then 5%) for each of the raw materials and moisture levels.

Searching for the relations between barley kernel resistance characteristics and moisture level on one hand, and energy consumption and mean particle size of the ground material on the other hand, a method of multiple regression with the choice of the best set for independent variables was applied. An analysis of the variables describing material characteristics was carried out for two different loading ranges (up to the immediate resistance threshold, and up to the collapse threshold), and for different forms of the regression function (linear dependence, non-linear dependence) with the assumption that data analysis will allow for establishing which of the parameters, and at which conditions of kernel loading, are the most relevant for the evaluation of the grinding process.

The equations presented below based on the average values for each variety and moisture level.

RESULTS AND DISCUSSION

The results are presented in the form of regression equations, which describe relations between grinding energy and mean particle size on one hand, and kernel dimensional and resistance characteristics on the other.

Grinding energy

Linear relations

At the first stage of the present analysis a linear relation between the features considered was assumed according to the Eq. (1):

$$E = f(c, b, h, \Delta h_1, \Delta h_2, \Delta h_3, \Delta h_4, \Delta h_5, \Delta h_p, \Delta h_u, F_1, F_2, F_3, F_4, F_5, \alpha, L_1, L_4, L_5, L_p, L_u, L_{j1}, L_{j4}, L_{j5}, L_{jp}, L_{ju}). \quad (1)$$

In the above equation all the features related to kernels and the course of the crushing process were taken into consideration. The analysis of regression with the choice of the best variable set allowed for arriving at the equation of the energy consumption during crushing according to the Eq. (2):

$$E = -228.15\Delta h_2 + 46.81\Delta h_4 + 0.721F_3 + 0.16F_5 + 31.78. \quad (2)$$

The correlation coefficient for the equation was r = 0.950 at the significance level of $p<0.0000$. According to the above equation the energy consumption is a function of the following features: deformation up to the threshold of plasticity, deformation up to the threshold of immediate resistance, and the values of forces up to the threshold of biological resistance and collapse threshold. An increase in the force value and deformation up to the threshold of immediate resistance resulted in the increase in energy requirement for grinding. Calculations carried out according to the Eq. (2) showed that the forecast energy requirement for grinding match the experimental data presented in Fig. 2 well.

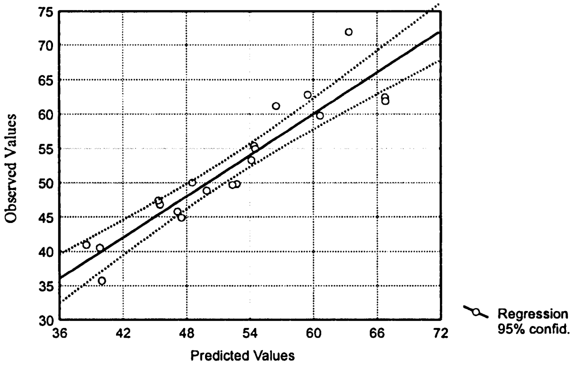

Fig. 2. Degree of compatibility the results calculated from the Eq. (2) and experimental values of grinding energy consumption for the studied barley varieties (points lie on line in the case when the compatibility has the correlation coefficient r=1.0).

As has been stated earlier, the parameters assumed for the previous calculations take into account phenomena accompanying crushing or flaking of kernels. From the cognitive point of view, resistance features that were next analysed are connected with kernel behaviour during loading up to the threshold of immediate resistance (reflecting kernel damage) according to the Eq. (3):

$$E = f(c, b, h, \Delta h_1, \Delta h_2, \Delta h_3, \Delta h_4, \Delta h_p, F_1, F_2, F_3, F_4, \alpha, L_1, L_4, L_p, L_{j1}, L_{j4}, L_{jp}). \quad (3)$$

Equation (4) resulted from the statistic analyses of the chosen barley varieties with the application of multiple regression:

$$E = -286.98\Delta h_2 + 58.169\Delta h_4 + 0.925F_3 + 37.893 \quad (4)$$

with the correlation coefficient r = 0.9308 and significance level $p<0.00000$.

Similarly as in the Eq. (2), energy consumption during grinding is related to the deformation value up to the threshold of plasticity and immediate resistance, and to the value of the force up to the threshold of biological resistance.

It can be gathered from the Eqs (2) and (4) that the force value up to the threshold of biological resistance influences energy consumption during grinding. As can be seen in Fig. 1, the value of this force is almost identical and well correlated to the value of the force up to the plasticity threshold (F_2=0.968F_3+0.05 at r = 0.996). Neglecting the value of the force up to the threshold of biological resistance in the analyses leads to its substitution by the force up to the plasticity threshold in the Eq. (4). The proposed change shows that the features that influence the grinding process in a significant way are connected with the two thresholds, i.e., the threshold of plasticity and the threshold of immediate resistance. The relation presented in the proposed form describe energy consumption during grinding accurately as well (r = 0.925). These two thresholds are already well recognised and described in the materials resistance research.

What follows, for the correct description of energy consumption it is necessary to determine the values of deformation and the force up to the plasticity threshold, as well as deformation up to the threshold of immediate resistance. The value of the force up to the threshold of immediate resistance did not show any significant influence on the energy consumption during grinding according to the above analyses.

Non-linear relations

At the further stage of analyses, it was assumed that among the resistance characteristics considered there are some that do not show any linear influence on the energy consumption during grinding. Their contribution to the course of this process could then be neglected. In order to obtain a more accurate description, analyses were also carried out for the regression function of the second degree and some chosen interaction. Among the possible interactions the ones used for analyses were relations between kernel thickness on one hand, and the loading force and deformation on the other. The analyses were carried out for the dimensional and resistance features (up to the collapse threshold inclusive) and the following equation was obtained:

$$E = -279.5\Delta h_2 + 86.052\Delta h_3 - 0.652F_5 - 86.29\Delta h_5^2 - 0.043F_1^2 + 0.052F_3^2 + 0.0003F_5^2 + 0.007L_4^2 - 0.00036L_5^2 + 0.173hF_4 + 132.71\,. \quad (5)$$

For the features up to the threshold of immediate resistance the following equation was worked out:

$$E = 0.010hF_4 + 24.44\Delta h_4^2 - 142.87h\Delta h_2 + 0.788F_1 + 78.322h\Delta h_1 + 46.179\,. \quad (6)$$

The correlation coefficient for the Eq. (5) obtained was r = 0.9810, which allows to state that energy consumption during grinding can be accurately described using the characteristics gained in the single-particle compression process.

In the Eq. (5) there appear features that are connected with all the characteristic thresholds of the collapse curve, which is confirmed by their significance for the detailed descriptions of the grinding process; however, an interpretation of this equation is not easy and requires further studies and analyses. In the case of Eq. (6) (r = 0.9618) the values of forces and deformations up to the threshold of biological resistance were not significant. In the Eqs (5) and (6) there are also interactions, which draws attention to the necessity of taking into account the features connected with barley kernels dimensions for the purpose of studies and analyses.

It has be found out that kernel resistance alone as determined by the values of the forces up to the threshold of immediate resistance does not exert any significant influence on the course of the grinding process in the assumed research conditions. The above can be explained by the fact that in the case of hammer mills the immediate values of forces are considerably higher than the forces up to the threshold of immediate resistance due to the hammer's impact on kernels.

Attention should be drawn to the fact that a large part of measuring machines used for resistance testing allows only for the determination of the force value and deformation up to the threshold of immediate resistance. Basing only on these two parameters (used in the statistical analysis) it is possible to determine grinding energy consumption for the studied barley varieties according to the Eq. (7):

$$E = \mathrm{a}\Delta h_4 + \mathrm{b}F_4^2 \quad (7)$$

where a, b - constants.

The degree of compatibility between the results on energy consumption calculated from the Eq. (7) and the experimental studies is lower than in the previous equations, and for that reason it is advisable to carry out a more accurate analysis of resistance characteristics with the view of the grinding process. The above relation is only significant when the materials with similar size and shape are compared (as these latter parameters influence the values of forces and deformations in the compression process considerably). It doesn't take into consideration the size and shape of a particle. For the studied barley varieties the above relation can be presented in the form of a graph (Fig. 3).

$E = 54.97\Delta h_4 + 0.00055F_4^2$

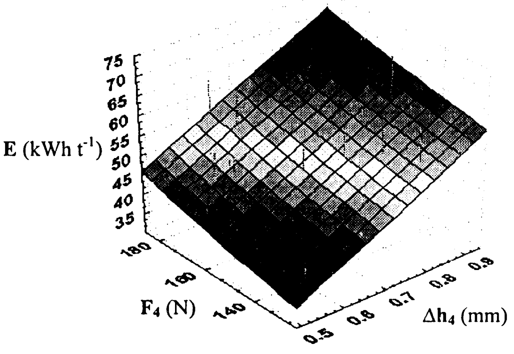

Fig. 3. Relation between grinding energy consumption and the force and deformation at the immediate resistance threshold for the studied varieties of barley.

Particle size

The mean particle size of the ground material was another feature analysed while looking for the influence of the resistance features of barley kernels on the course of the grinding process. Similarly as in the case of energy consumption, the analyses were carried out for the linear and non-linear regression functions for all the resistance features and for the features up to the threshold of immediate resistance.

The forms of equations obtained by means of multiple regression with the choice of the best variable set, have been presented in Table 1.

The equations presented in Table 1 confirm the existence of relation between the quality of the obtained products and kernel's resistance characteristics. Among the decisive factors there are deformations up to the proportionality threshold and the threshold of immediate resistance, as well as the values of forces up to the plasticity threshold. An increase of deformation up to the threshold of resistance and an increase in the force value up to the plasticity threshold results, as in the case of relations on energy consumption, an increase in the mean particle size. Deformation up to the proportionality threshold in inversely proportional for the quality of the ground material.

A more accurate description requires taking into consideration forces and deformations (considered in the equations) that are related with other threshold as well, and considering mutual relations between kernel size and the features determined in the uniaxial compression test.

No significant influence of the forces up to the threshold of immediate resistance on the quality of the ground material was found for the studied barley varieties.

CONCLUSIONS

The studies carried out allow to determine that grinding energy consumption and the mean diameter of refined particles depend significantly on the kernel resistance features as obtained from the uniaxial compression test.

In the case of the studied barley varieties, energy consumption during grinding is best described by the deformations up to the threshold of immediate resistance, the force and deformation up to the plasticity threshold, and the force required for reaching the threshold of collapse. Within the study range assumed no influence of the value of the force required to reach the threshold of immediate resistance on the grinding energy consumption.

The analysis carried out for the chosen barley varieties is a part of studies carried out for other raw materials with differentiated sizes,

T a b l e 1. Regression equation for the relation between the average particle size and the dimensional and resistance properties of the studied barley varieties

Equation form	Correlation coefficient	Level of significance
Linear functional relation		
$d\acute{s}=-0.337\Delta h_3 + 0.0519\Delta h_4 + 0.520\Delta h_p + 0.002F_2 + 0.0002F_5 - 0.00037L_5 + 0.439^{1)}$	0.918	0.0001
$d\acute{s} = 0.0628\Delta h_4 - 0.395\Delta h_1 + 0.0015F_2 + 0.437^{2)}$	0.831	0.0000
Non-linear functional relation (degree 2)		
$d\acute{s} = 0.070\Delta h_4 - 0.012b^2 - 0.000001F_5^2 + 0.000007L_5^2 + 0.000009L_u^2 - 0.0236L_{j5}^2 + 0.283L_{ju}^2 + 0.594^{1)}$	0.971	0.0000
$d\acute{s} = -0.07b + 0.019h\Delta h_4 - 0.033h\Delta h_2 + 0.035^{2)}$	0.922	0.0000

1) equation for all the dimensional and resistance characteristics, 2) equation for the dimensional and resistance characteristics up to the threshold of immediate resistance.

dimensions, and resistance characteristics. Description of all the relations by means of a general equation for the results obtained will allow for the verification and choice of the features that characterise grinding process in the most significant way.

LIST OF SYMBOLS

Δh_1 - deformation up to kernel proportionality threshold

Δh_2 - deformation up to kernel plasticity threshold

Δh_3 - deformation up to kernel biological resistance threshold

Δh_4 - deformation up to kernel immediate resistance threshold

Δh_5 - deformation up to kernel collapse

Δh_p - deformation up to the phase of kernel plastic flow

Δh_u - deformation from the kernel immediate resistance threshold up to collapse threshold

α - proportionality coefficient (ration between force value and deformation established for proportionality threshold)

F_1 - loading force for the kernel proportionality threshold

F_2 - loading force for the kernel plasticity threshold

F_3 - loading force for the kernel biological resistance threshold

F_4 - loading force for the kernel immediate reistance threshold

F_5 - loading force for the kernel collapse threshold

L_1 - work for the kernel deformation up to the proportionality threshold

L_4 - work for the kernel deformation up to the immediate resistance threshold

L_5 - work for the kernel deformation up to the collapse threshold

L_p - work for the kernel deformation up to the state of plastic flow

L_u - work for the kernel deformation from to the immediate resistance threshold up to the collapse threshold

L_{j1} - energy for kernel deformation up to the proportionality threshold

L_{j4} - energy for kernel deformation up to the immediate resistance threshold

L_{j5} - energy for kernel deformation up to the collapse threshold

L_{jp} - energy for kernel deformation up to the phase of plastic flow

L_{ju} - energy for kernel deformation from the immediate resistance threshold up to collapse threshold.

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