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Unitary energy in the black radish cutting process

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Summary. The article presents the methodology and results of measurement of the unitary energy in cutting black radish. The values of the unitary energy of cutting the root parenchyma of black radish sampled in several areas were analysed. To compare the values of the unitary cutting energy related to the differences in the structure of the black radish root, the samples were cut at the longitudinal and transverse orientation of the fibres relative to the movement of the working tool. The cutting process was carried out using knives with a sharpening angle of 5°, 10°, and 15° and cutting velocity values of 100 mm·s^{-1}, 200 mm·s^{-1}, 300 mm·s^{-1}, and 400 mm·s^{-1}. The results obtained were subjected to mathematical analysis in Statistica 8.0 software. The statistical analysis showed a significant correlation between the value of the unitary energy and sampling site, the knife sharpening angle and the velocity of knife movement. The highest value of the unitary cutting energy was obtained at a sharpening angle of β=15° and the lowest value was observed when the knife with the β=5° sharpening angle was used. The unitary cutting energy decreased with the increase in the knife movement velocity.

Key words: unitary cutting energy, knife sharpening angle, cutting velocity.

INTRODUCTION

The cutting process is one of the basic methods for fragmentation of materials in the food industry. Cutting vegetables is often a precise operation, in particular when cubes, strips, or slices of the products must be obtained. Achievement of the required shapes is only possible with the use of non-worn devices and appropriately selected cutting parameters [12, 16, 17].

The cutting process is determined by many factors, including the structure of the material and the structure of the cutting tool [1, 6, 7, 13, 18, 27]. A knife is an element operating directly on the plant, and its parameters determine the energy required for cutting the plant material and the magnitude of the working resistance of the machine. Cutting knives act like sharp wedges pushing into the structure of the cut material. Differently-shaped knives are used for cutting vegetables. The most frequently used knives include flat knives with a comb-shaped blade, knives with a spade-shaped blade and flat knives with a straight continuous blade [11, 12, 20, 28].

Based on the results of investigations on cutting carrots, celery, potatoes, etc. conducted so far, it can be assumed that the knife cutting angle has the greatest impact on the process of cutting. Additionally, the knife movement velocity has a significant effect on the cutting resistance. Cutting energy values are also influenced by biological factors, storage conditions and the internal structure of the material [2, 3, 8, 22, 23, 25, 30].

It should be noted, however, that high cutting efficiency cannot be achieved when the cutting parameters are inappropriately selected and the working elements are excessively worn. Too low cutting velocity may lead to rapid wear of the knives, whereas excessive cutting velocity leads to the formation of a large cutting bevel or even incomplete cutting of the material. Minimisation of the knife sharpening angle reduces energy loss. Optimisation of the cutting process can improve the quality of the raw material and reduce the consumption of required energy [4, 10, 24, 29, 31].

Recently, the consumption of black radish in Poland has increased due to its taste and nutritional values. The vegetable contains a variety of vitamins, proteins, sugars, and minerals. Its root has a complex structure, which may cause difficulties in the cutting process. Therefore, it is essential to select the appropriate structure and working parameters of the cutting device in order to improve cutting performance [5, 9, 14, 15, 19, 26]. Despite the increased interest in black radish, there are no research results in Polish and international literature concerning cutting this vegetable. Hence, the black radish was chosen as the model raw material in these investigations.

The aim of the study was to evaluate the impact of the technical parameters of the cutting process, i.e. the cutting angle and knife velocity per unitary energy for samples collected from various fragments of the black radish differing in the structure and cut at the longitudinal and transverse orientation of the fibres relative to the movement of the working tool.

MATERIALS AND METHODS

The raw material used for the investigations was the Murzynka variety of black radish. The research material was collected between postharvest day 2 and 7. The vegetables were stored in a ventilated room at the temperature of 4°C and 95% relative air humidity. The shape of the black radish roots was nearly round. Their diameter was 8±0,5 cm. Roots of this size were selected by a roller sorter.

Parenchyma tissues were excised along axis *y* from the upper (wg), middle (ws), and lower (wd) layers, since sampling the core required the highest unitary energy. This had been indicated by earlier laboratory analyses.

The structure of the black radish is heterogeneous. The highest and lowest density of fibres is noted in the upper and middle layers, respectively.

The site of excision of the root material samples is shown schematically in Fig. 1.

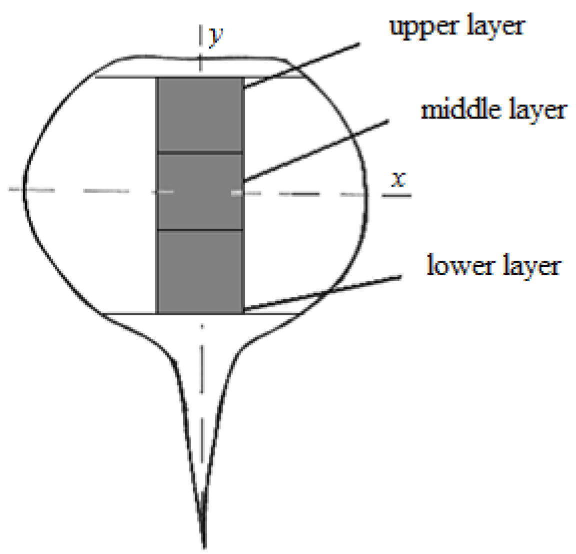

Fig. 1. Site of material sampling

A cuboid with the height of 45 mm and 15 mm side of the base was excised along axis *y* (core) from the root and divided into three cubes with 15 mm side. The apical part and the rootlet were discarded. The material prepared in this way was cut longitudinally and transversely to the parenchyma fibres relative to the cutting plane.

In the investigations, we used straight NC6 steel knives (1,5 mm thick, 27 mm long, and 70 mm wide) with the sharpening angle of 5°, 10°, and 15°. The knife cutting velocity was 100, 200, 300, and 400 mm·s^{-1}. The angle between the cutting edge and the cutting direction was 90°. The value of the relief angle was 0°.

The investigations were performed in ten replicates (for the longitudinal and transverse arrangement of the fibres, each knife sharpening angle, and each velocity value).

The measurements were carried out on the workbench for analyses of cutting resistance developed at the Faculty of Mechanical Engineering, Institute of Transport, Internal Combustion Engines and Ecology, Lublin University of Technology [21]. One of the most important distinguishing features was the possibility of recording the forces operating simultaneously in two perpendicular directions: parallel and perpendicular to the direction of the main movement. The scheme of the workbench is presented in Fig. 2.

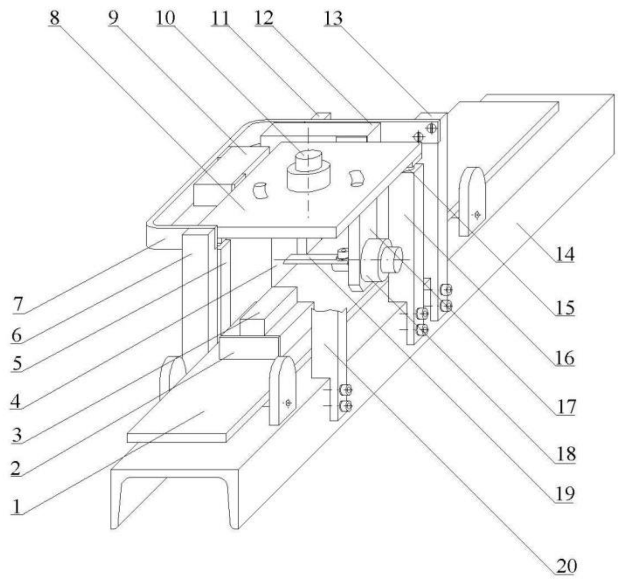

Fig. 2. Workbench scheme: 1 - steel beam, 2 - holder, 3 - cut sample, 4, 5, 6 - columns, 7 - band, 8 - measurement plate, 9 - inductive sensor, 10 - knife control plate, 11 - column, 12 - inductive sensor, 13 - column, 14 - bed, 15 - ball, 16 - column, 17 - hanger, 18 - knife control plate, 19 - knife, 20 - column

The working system of the workbench consisted of a horizontal bed (14) with a steel beam (1), which moved longitudinally and was driven by a hydraulic cylinder with a sample holder (2). A knife (19) with a rotational control plate (18) was mounted with a hanger (17) on a rectangular plate (8). The plate (8) with a rotational control (10) moved on balls (15) located on the upper ends of the vertical columns (4, 5, 16, and 20). A band (7) with inductive sensors (9, 12) measuring forces in two mutually perpendicular directions was fastened to columns 6, 11, and 13. The information from the sensors was transferred by electronic meters and the measurement card to the computer equipped with the program "Pomiar" [Measurement]. The program was devised to support the measurement card and it facilitated the reception and processing of signals as well as data visualisation and archiving.

The workbench facilitated the changing of the cutting tool; hence, it was possible to assess the impact of the tool geometry, e.g. the knife sharpening angle.

Another important trait of the workbench was the possibility of applying velocities (from 50 to 450 mm·s^{-1}) higher than those obtained by the Intron strength device, which is used most frequently by researchers in this discipline.

Based on the data provided by the measurement system (recorded cutting force), it was possible to determine the cutting work value and calculate the unitary energy of cutting from equation 1, which is defined as work required for cutting a unit area of the material:

$$Ej = \frac{L}{A} \quad (1)$$

where:
Ej – unitary energy of cutting [J·m^{-2}],L – cutting work [J],A – sample surface area [m^{2}].

The results obtained were analysed statistically with the package Statistica 8.0. Multivariate analysis of variance ANOVA was performed to determine the significance of the differences between the sampling site and cutting velocity and the unitary energy of cutting. Inference was made at the significance level of 0,05. Detailed analyses of the mean confidence intervals were carried out with Tukey's test. Regression analysis was employed to derive equations for the unitary energy of cutting relative to the knife sharpening angle and cutting velocity.

RESULTS AND DISCUSSION

Figures 3-5 show graphs of the mean values of the unitary energy of cutting for black radish samples collected from the specified layers and cut longitudinally and transversely relative to the fibres with knives characterised by sharpening angles from 5° to 15°. The different letters at the mean values in the graphs indicate significant differences between them.

The value of the unitary energy of cutting at the knife sharpening angle of β=5° (at cutting velocity of 100 mm·s^{-1}) was 292,855 J·m^{-2} for the upper layer sample, 271,813 J·m^{-2} for the middle layer sample, and 285,388 J·m^{-2} for the sample collected from the lower layer. In comparison with the results obtained at the longitudinal orientation of fibres, the transversely cut samples were characterised by higher values, i.e. 299,613 J·m^{-2}, 284,482 J·m^{-2}, and 296,222 J·m^{-2}, respectively. The results also indicated that the increase in the cutting velocity was accompanied by lower values of the unitary energy of cutting for each of the sampling sites and orientation. The lowest cutting energy value at the velocity of 400 mm·s^{-1} was used to cut the parenchyma from the lower layer at the longitudinal orientation of the fibres (123,273 J·m^{-2}). As shown by Tukey's test of differences significance, there were statistically significant differences between the unitary energy of cutting for the black radish samples at the longitudinal and transverse orientation of fibres.

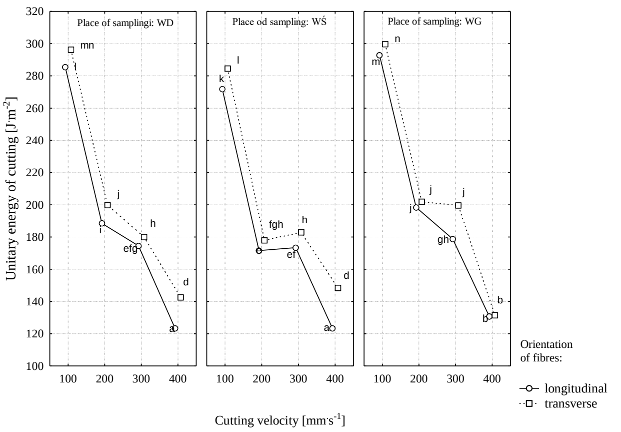

Fig. 3. The relationship between the unitary energy of cutting with the knife at the sharpening angle of β=5^{o} and the cutting velocity and sampling site at the longitudinal and transverse orientation of fibres

Figure 4 presents the mean values of the unitary energy of cutting obtained at the sharpening angle of β=10^{o} and the velocity from 100 to 400 mm·s^{-1}. The highest value (252,896 J·m^{-2}) of the unitary energy of cutting in this case was noted for the sample collected from the middle part of black radish parenchyma oriented transversely to the fibres and cut at the velocity of 100 mm·s^{-1}. The lowest cutting energy at the velocity of 400 mm·s^{-1} was required in the longitudinal sample collected from the lower part of the analysed root; its value was 119,898 J·m^{-2}. The mean values of the unitary energy of cutting relative to the longitudinal and transverse orientation of the samples in homogeneous groups ($p \leq 0,05$) indicate that (in the majority of cases) the values of the parameter differ significantly. This is associated with the varied structure of the raw material. In the longitudinal section of the black radish, the highest density of fibres was noted in the upper layer, whereas the middle layer exhibited the lowest density.

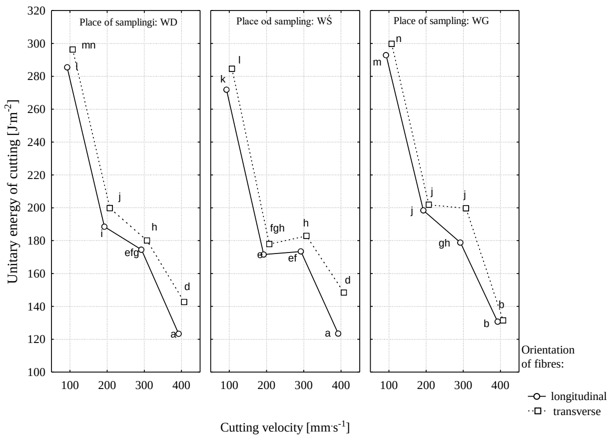

Fig. 4. The relationship between the unitary energy of cutting with the knife at the sharpening angle of β=10^{o} and the cutting velocity and sampling site at the longitudinal and transverse orientation of fibres

The experimental results of cutting the black radish root parenchyma with the knife with the sharpening angle of β=15° (in the range of the velocities applied) indicate that the mean values of the unitary energy of cutting were in the range from 144,257 to 426,352 J·m^{-2} for samples with the longitudinal orientation of fibres and from 149,125 to 442,146 J·m^{-2} for samples with the transverse orientation of fibres (Fig. 5). The highest value of the unitary energy of cutting at the velocity of 100, 200, and 300 mm·s^{-1} in the black radish samples with longitudinally and transversely arranged fibres was noted for the upper layer samples. An exception was the process of sample cutting at the velocity of 400 mm·s^{-1}, where the highest values of unitary energy were obtained for the lower layer. The results of calculations demonstrate that the values of the parameters differed significantly in most cases.

The analysis of the results presented in Figures 6 and 7 revealed that, regardless of the orientation of the black radish fibres (longitudinal or transverse), the lowest values of unitary energy of cutting were obtained in the case of the knife with the sharpening angle of 5^{o}, while the highest value was found for the sharpening angle of 15^{o}. An increase in the cutting velocity caused a decrease in the unitary energy of the process.

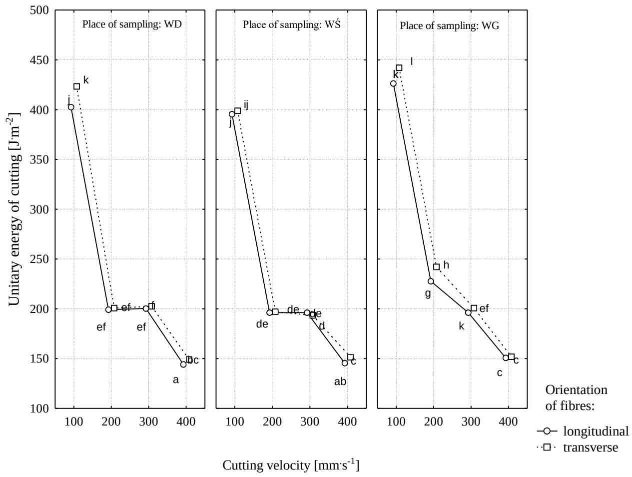

Fig. 5. The relationship between the unitary energy of cutting with the knife at the sharpening angle of β=15o and the cutting velocity and sampling site at the longitudinal and transverse orientation of fibres

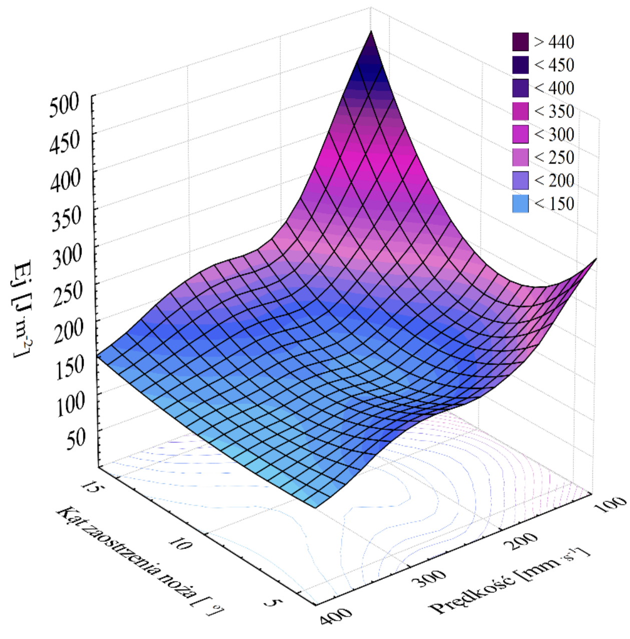

Fig. 6. The impact of the cutting velocity and knife sharpening angle on the unitary energy of cutting black radish parenchyma at the longitudinal orientation of fibres

The impacts of the knife sharpening angle β, distance from axis y and the cutting velocity v on the value of the unitary energy of cutting Ej for the black radish samples were described with multiple regression equations.

The relationship for the black radish samples arranged longitudinally can be described with the equation:

$$Ej = 0{,}047y^2 + 0{,}002v^2 + 1{,}99\beta^2 - 1{,}574v - 35{,}18\beta + 548{,}253 \quad (1)$$

$R^2 = 0{,}816$; $\alpha \leq 0{,}05$

The changes in the unitary energy of cutting black radish samples with transverse arrangement of fibres can be defined as:

$$Ej = 0{,}05y^2 + 0{,}002v^2 + 1{,}964\beta^2 - 1{,}63v - 35{,}033\beta + 568{,}283 \quad (2)$$

$R^2 = 0{,}831$; $\alpha \leq 0{,}05$

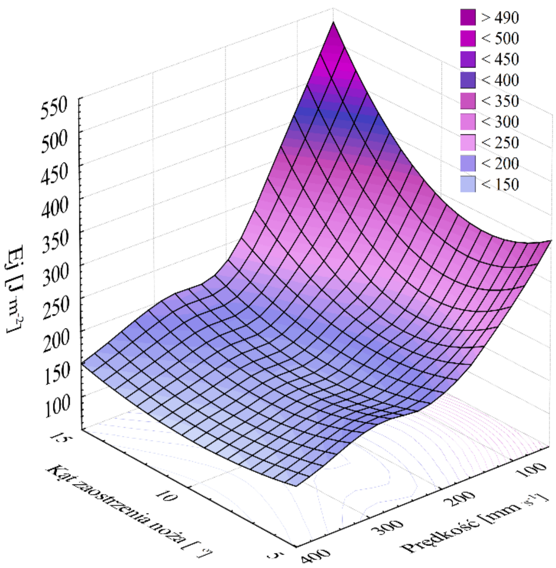

Fig. 7. The impact of the cutting velocity and knife sharpening angle on the unitary energy of cutting black radish parenchyma at the transverse orientation of fibres

The results indicated a significant effect of the knife sharpening angle and cutting velocity on the unitary energy of cutting. The high determination coefficients indicated a good fit of the equations with the results obtained.

CONCLUSIONS

1. The experimental analyses of the working characteristics of the unitary energy of cutting have validated the usefulness of the proposed research method for investigation of problems related to cutting materials with a varied internal structure.
2. In the experimental conditions, an effect of the anisotropy of the material and fibre orientation on the values of the unitary energy of cutting was observed. The unitary energy of cutting was lower at the transverse orientation of the fibres.
3. The cutting velocity in the range from 100 $mm \cdot s^{-1}$ to 400 $mm \cdot s^{-1}$ had a significant impact on the unitary energy of cutting of the black radish samples. An increase in the knife cutting velocity was accompanied by a decrease in the unitary energy of cutting.
4. The appropriate selection of the geometry of the cutting tool contributed to the reduction of the cutting energy. The highest value of the unitary energy of cutting was obtained at the knife sharpening angle of β=15° and the lowest value was observed at the sharpening angle of β=5°.
5. Further investigations of cutting plant materials with various cutting tools and at their different parameters are advisable.

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