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ASSESSMENT OF VARIABILITY OF THE MAXIMUM CUTTING FORCE IN RELATION TO THE BEETROOT PULP STRUCTURE

Elżbieta Kusińska*, Agnieszka Starek

Department of Food Engineering and Machines, University of Life Sciences in Lublin

*Contact details: ul. Doświadczalna 44, 20-280 Lublin, e-mail: elzbieta.kusinska@up.lublin.pl

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ABSTRACT

The paper presents methodology and results of measurement of the research on the process of cutting Beta vulgaris L beetroot in laboratory conditions, where values of the maximum cutting force of beetroot tissues collected from specific layers (upper layer, central layer, lower layer) were analysed. Variable parameters in the experiment were: knife sharpening angle (2.5º; 7.5º; 12.5º and 17.5º) and velocity of its movement (0.83 mm·s^{-1}, 1.66 mm·s^{-1}, 2.49 mm·s^{-1}, 4.15 and 10 mm·s^{-1}). The obtained data were subjected to mathematical analysis with the use of Excel and Statistica 6.0 software. Statistical analysis of results proved significant dependence of the maximum cutting force value on changes of mechanical properties of tissues in relation to the place of collecting samples, the knife sharpening angle and its movement. The highest value of force was obtained during cutting with a knife of the sharpening angle of ϕ=17.5º and the lowest during the use of a knife with ϕ=2.5º. Along with the increase of the knife movement velocity, the cutting force decreased. The best quality of samples was obtained with the use of the velocity which was 2.49 mm·s^{-1} and 4.15 mm·s^{-1} with knives with the cutting angle of 2.5º and 7.5º.

Introduction

Cutting applied in the fruit and vegetable industry is most frequently used at the processing of vegetables and fruit. It is used for generation of such stress conditions in the required place, that tissues are seperated into layers, which leads to the breach of the processed plant structure (Nadulski et al., 2013).

The cutting process is one of fragmentation methods, which aims at obtaining a product of a particular dimension and shape. It follows from organoleptic, technological and utility reasons. Vegetables for salads or juices require a higher degree of fragmentation while those designed for thermal processing require lower one (Sykut et al., 2005).

Factors, which have a considerable impact on the course of the material cutting process are mainly its strength properties which are strictly related to its structure, a plant habit and individual varietal properties, the place of collecting pulp and crop conditions (Bohdziewicz and Czachor, 2010; Ślaska-Grzywna, 2008).

Kinematic and dynamic parameters are the second group of factors. Tests on the cutting process are carried out in particular on account of improving the structure of cutting units, analysis of the blade parameters and their function in the cutting process. The cutting device structure must be adjusted to the characteristic properties and the raw material dimensions (Kowalik et al., 2013).

A beetroot (*Beta vulgaris L.*) is among vegetables, which are often consumed in Poland. It is characterized with a high content of vitamins, mineral salts (Ca, P, Mg, Fe), protein, sugars and biologically active compounds, which have a considerable significance in the human nutrition. Annual consumption of this vegetable is within 12 to 14 kg per one citizen (Kazimierczak et al., 2011; Rekowska and Jurga-Szlempo, 2011).

Popularity of this raw material is determined by simple cultivation, which does not require high expenditures, low climatic and soil requirements and a possibility of long storing, which allows consumption of a fresh raw material almost through an entire year. Popularity of this crop results also from a possibility of its storing. Roots of beetroot are used in the industry for production of juices, frozen vegetables, beetroot salad or natural food colour (Czapski et al., 2011).

During various technological processes (during collection of crops, storage and processing) changes which cause decrease of the value and quality of a vegetable may take place in the product (Kidoń and Czapki, 2007). Thus, so much attention is paid to the investigation of the structure of a beetroot root. Additionally, suitably selected cutting method may ensure high quality of the final product (Kusińska and Starek, 2012).

The objective and the scope of research

The objective of the paper was to examine the impact of the place from which a sample is collected of the root pulp on the cutting force of a beetroot. Variable parameters in research were: the knife sharpening angle and its movement velocity.

The scope of the paper included initial preparation of raw material, cutting out tissues from beetroot bulbs from three places, carrying out the test of cutting the material and its statistical description.

Research methodology

Average density for the investigated raw material was 1,061 $kg \cdot m^{-3}$, and moisture 86.1%. New Napoleon variety beetroots constituted the research material. It is an early variety. It has a rounded root with a smooth polished skin. The inside of the root is dark red and rings are visible in the cross section of a root.

Vegetables were from private field crops of Lubelskie Voivodeship. Beetroots were cultivated on the second class soil. Fertilization and conditioning as well as protective treatments were carried out with the use of mechanical equipment. Manual collection in the technological maturity stage was carried out. The harvested vegetables were selected on account of the shape and size, specimens with visible damage or with disease symptoms were rejected. Mature bulbs were selected. The beetroot shape was similar to the round one with an average dimension of 8±0.5 cm.

Material for research was collected after the second day from the harvest date to the seventh day. Vegetables were stored in a ventilated room in the temperature which was 4ºC and the relative moisture of air of 95%.

Pulp tissues were cut along the axis *y* from the layer: upper (wg), central (ws) and lower (wd). The place of cutting the material was presented in figure 1.

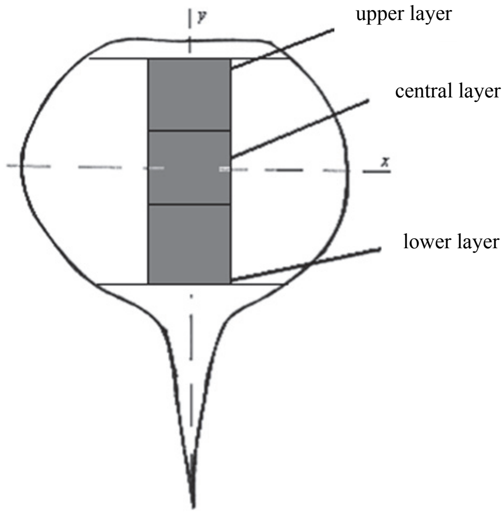

Figure 1. Place from which materialwss cut out

From the root along axis *y* a cuboid 60 mm high and with the side of the base of 20 mm was cut out and then divided into three cubes with 20 mm side. The top part and a rootlet was rejected. The material prepared this way was subjected to cutting with the use of TA.XT plus texturemeter maintaining a fixed orientation of a blade towards tissue, which was cut in half. The knife setting angle towards the axis of the collected material was 0º. Simple knives with the following sharpening angle were used: 2.5º; 7.5º; 12.5º; 17.5º. Knives were of the following dimensions: length 900 mm, width 70 mm, thickness 3 mm. Pulp tissues of a beetroot were placed on the base of the device along the axis *y*, and then where loaded with a cutting element with speeds which were: 0.83 $mm{\cdot}s^{-1}$, 1.66 $mm{\cdot}s^{-1}$, 2.49 $mm{\cdot}s^{-1}$, 4.15 $mm{\cdot}s^{-1}$ and 10 $mm{\cdot}s^{-1}$. These speeds were selected due to the possibility of observation of the material deformation course, breaching its structure during cutting and outflow of juice from the beetroot.

As a result of the measurement, plots which presented relation of the cutting force and the knife movement, were obtained. From them the maximum value of the cutting force was determined (fig. 2). In the A-B area, the force increases from zero to the value, which causes squeezing of the material by a knife. In this area material is thickened. It is a threshold value of the cutting process. In the C point, there is a maximum cutting force, which decreases gradually to) (point D), in which the process ends.

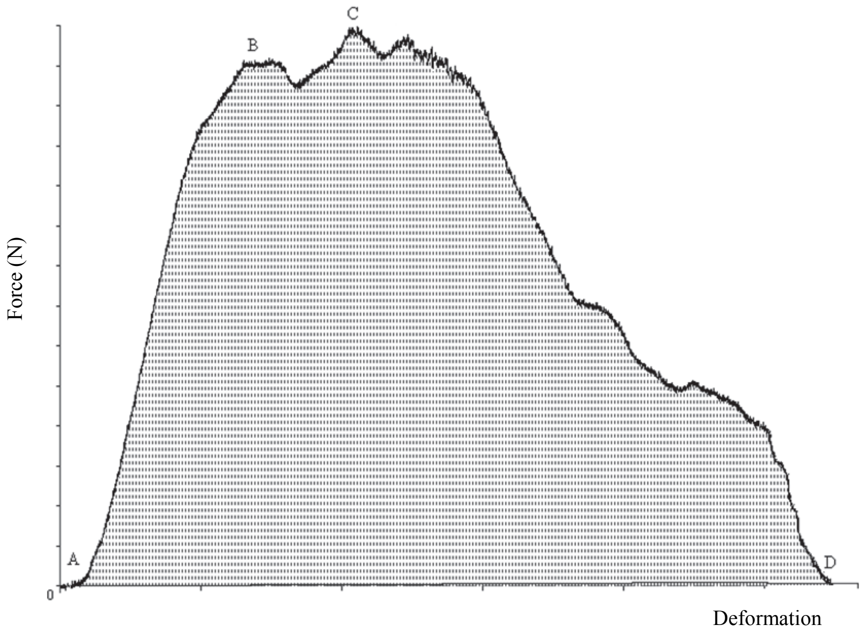

Figure 2. Exemplary relation force-deformation obtained during cutting

Tests were carried out in 10 repeats (for each knife, each speed and the place of collecting the material). The tests results were subjected to the regression analysis and the analysis of variance at the level of significance $\alpha = 0.05$.

Research results and their analysis

Results of measurements of the maximum cutting force of a beetroot F_{max} were presented in figure 3-7. Various letters provided at the average values prove the significant differences.

Based on the results obtained in the experiment of cutting the root tissues of a beetroot with the knife movement velocity of 0.83 $mm \cdot s^{-1}$ it was reported that the average values of the maximum cutting force are within 12.4 to 35.3 N. The highest average value of the cutting force was obtained at the knife sharpening angle of ϕ=17.5º (for the upper layer of a beetroot), whereas the lowest average value of the cutting force is assigned to the angle of ϕ =2.5º (for a lower layer of the investiagted material). A considerable increase of force at the change of the knife sharpening angle from ϕ=7.5-12.5º takes place. For example for the material from the upper layer, value of the maximum cutting force increased from 16.5 N to 29.3 N.

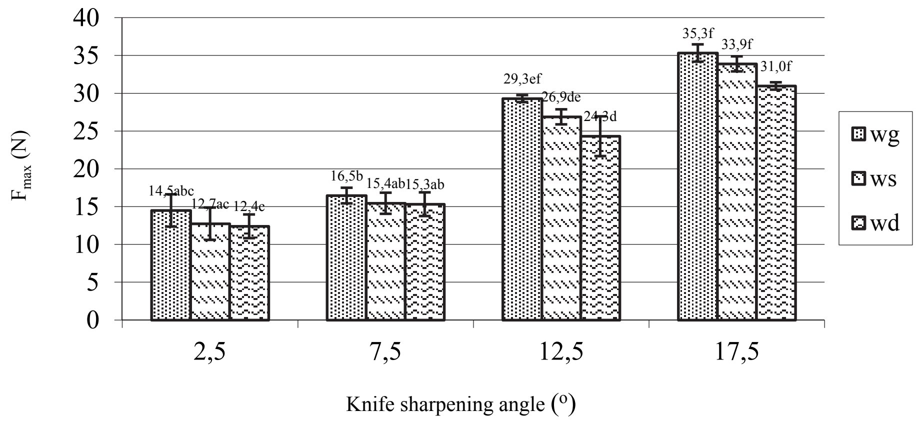

Figure 3. Maximum cutting force of beetroot in relation to the place from which samples were collected and knife sharpening angle at the velocity of knife movement of 0.83 mm·s^{-1}

Figure 4 presents the set of average maximum values of cutting forces obtained at the knife speed of 1.66 mm·s^{-1}. Nature of changes is the same as in figure 3. In this case also along with the increase of the knife sharpening angle, the maximum cutting force increases. The highest cutting force occurs for the knife with the sharpening angle of ϕ=17.5º for tissues which come from the upper layer of a beetroot and is 33.9 N, whereas the lowest for ϕ=2.5º for the bottom layer of the investigated root – 9.9 N. Along with the increase of the knife movement velocity the maximum cutting force decreases. The biggest difference in forces values during the speed changes was reported for a knife with the sharpening angle of ϕ=7.5º for the lower layer. At the knife speed of 0.83 mm·s^{-1} the cutting force value was at the level of 15.3 N, and after the increase of the speed, the value decreased to 11.5 N.

Further increase of the knife movement velocity resulted in the decrease of the maximum cutting force. Average values of the cutting force of the investigated biological material are within 9.8 N to 32.7 N. After cutting the material, the highest force is required for tissues from the upper layer of raw material and the lowest for the lower layer. For the raw material cut with the knife with the sharpening angle of ϕ=7.5º the cutting force of material from the upper layer is 14.5 N, from the central layer 11.5 N and from the lower layer 10.9 N.

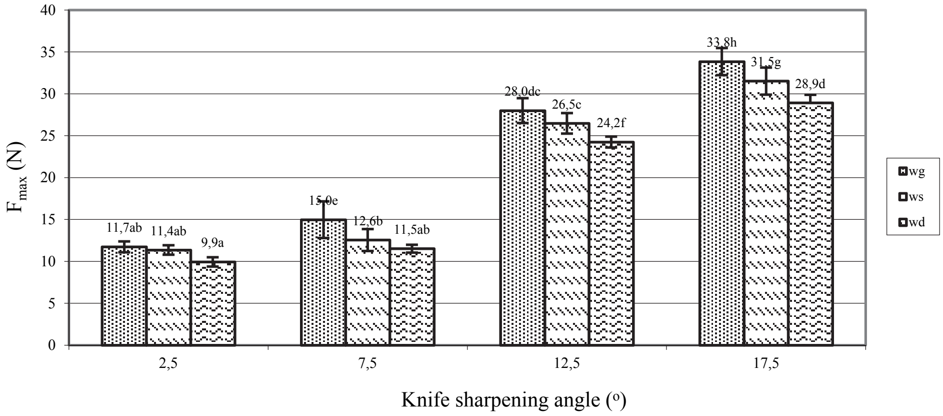

Figure 4. Maximum cutting force of beetroot in relation to the place samples from which samples were collected and the knife sharpening angle at the knife movement velocity of 1.66 mm·s⁻¹

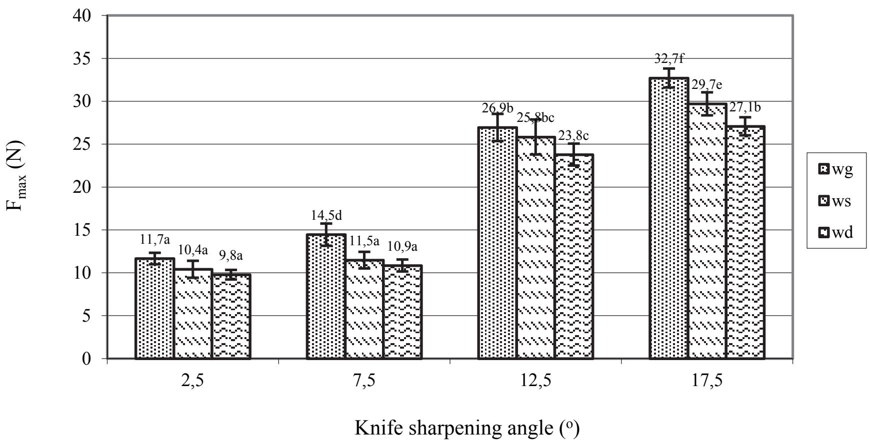

Figure 5. Maximum cutting force of beetroot in relation to the place from which samples were collected and the knife sharpening angle at the knife movement velocity of 2.49 mm·s⁻¹

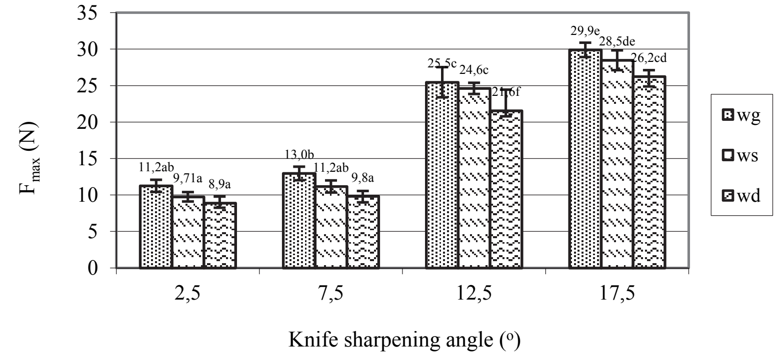

Figure 6. Maximum cutting force of beetroot in relation to the place from which samples were collected and the knife sharpening angle at the knife movement velocity of 4.15 mm·s^{-1}

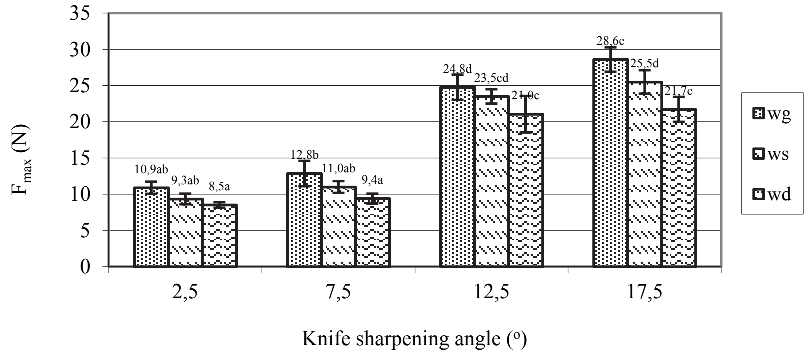

Figure 7. Maximum cutting force of beetroot in relation to the place from which samples were collected and the knife sharpening angle at the knife movement velocity of 10 mm·s^{-1}

It was found out that the lowest values of the cutting force occurred when the set knife movement velocity was 10 mm·s^{-1}. For the knife sharpening angle of ϕ=2.5º the value of the cutting force from the upper layer was 10.9 N, from the central layer 9.3 and from the lower layer 8.6 N in comparison to the results at the speed of 0.83 mm·s^{-1} it is respectively lower by 3.6 N, 3.4 N and 3.9 N. Figure 7 shows that the highest value of force was used for cutting tissues from the upper layer of the root with a knife of the sharpening angle of ϕ=17.5º (28.6 N).

During the research, the attention was paid to deterioration of the quality of the cut material along with the increase of the knife sharpening angle and the decrease of the knife movement velocity.

The researched relations were described with the following regression equations:

$$F_{wg} = 22{,}794 + 12{,}767\phi - 1{,}91\ln v - 0{,}296\phi^2 - 42{,}527\ln\phi \quad (1)$$

$$R^2 = 0.991,\ \alpha \leq 0.05$$

$$F_{wś} = 23{,}397 + 14{,}59\phi - 1{,}969\ln v - 0{,}347\phi^2 - 49{,}143\ln\phi \quad (2)$$

$$R^2 = 0.988,\ \alpha \leq 0.05$$

$$F_{wd} = 21{,}464 + 12{,}74\phi - 2{,}222\ln v - 0{,}302\phi^2 - 42{,}91\ln\phi \quad (3)$$

$$R^2 = 0.978,\ \alpha \leq 0.05$$

where:

F_{wg}, F_{ws}, F_{wd} – the maximum cutting force respectively for the upper, central and lower layer, (N)

ϕ – knife sharpening angle, (°)

v – knife movement speed, (mm·s^{-1})

R^2 – coefficient of determination,

α – level of significance of differences.

Analysis of variance showed that the place of sample collection, the knife sharpening angle and its movement velocity has a significant impact on the value of the maximum cutting force of a beetroot.

Observations made during cutting the raw material may be presented as follows: for the speeds of the cutting test which were 0.83 mm·s^{-1} and 1.66 mm·s^{-1} of the maximum cutting force are the highest. After cutting samples have a smooth surface, however, low speeds cause considerable stresses on the surface of the material when the knife gets deeper in the material, which causes great deformations of raw material and the outflow of juice.

For the speed which was 10 mm·s^{-1} values of the cutting force are the lowest. However, it has no advantageous reference to the quality of the final raw material. During the test, a sample breaks down instead of being cut. Pieces of a beetroot have a discontinuous structure and uneven thickness of the cut off part, which causes losses in the material and decreases the quality.

When planning laboratory research of another raw materials, one should focus on setting speeds which are 2.49 mm·s^{-1} and 4.15 mm·s^{-1}. At both set speeds, samples are cut one time and the cutting surface is quite uniform. In such cases the cut off fragments of a beetroot have a strictly defined structure, a regular shape and a desired form without damages.

The obtained standard deviations from the values of average cutting forces prove a considerable heterogeneous nature of the investigated raw material. Probably they result from a heterogeneous internal structure of a beetroot.

Conclusions

1. The place of tissue collection has a significant impact on the value of the maximum cutting force of a beetroot. The highest cutting force was obtained for tissues from the upper layer and the lowest for the material collected from the lower layer. It is related to the non-uniform structure of beetroot pulp and various mechanical features.
2. The relation of the maximum cutting force of the knife sharpening angle proved that the biggest angle of knife sharpening the highest cutting force of pulp. The highest force was obtained during cutting with a knife of the sharpening angle $\phi=17.5^{o}$ and the lowest during the use of a knife with $\phi=2.5^{o}$.
3. The cutting speed in the tested scope from 0.83 $mm \cdot s^{-1}$ to 10 $mm \cdot s^{-1}$ significantly influences the cutting force of a beetroot. Along with the increase of the knife movement speed, the maximum cutting force decreases.
4. The best quality of samples was obtained with the use of the speed which was 2.49 $mm \cdot s^{-1}$ and 4.15 $mm \cdot s^{-1}$ with knives with a cutting angle 2.5º and 7.5º.

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Elżbieta Kusińska, Agnieszka Starek

OCENA ZMIENNOŚCI MAKSYMALNEJ SIŁY TNĄCEJ W ZALEŻNOŚCI OD BUDOWY MIĄŻSZU KORZENIA BURAKA ĆWIKŁOWEGO

Streszczenie. W artykule przedstawiono metodykę oraz wyniki pomiaru badań procesu cięcia buraka ćwikłowego *Beta vulgaris* L. w warunkach laboratoryjnych, gdzie analizowano wartości maksymalnej siły cięcia tkanek korzenia buraka ćwikłowego pobranych z określonych warstw (warstwa górna, warstwa środkowa, dolna). Parametrami zmiennymi w doświadczeniu były: kąt zaostrzenia noża (2,5º; 7,5º; 12,5º i 17,5º) oraz prędkość jego przemieszczania (0,83 mm·s^{-1}, 1,66 mm·s^{-1}, 2,49 mm·s^{-1}, 4,15 mm·s^{-1} i 10 mm·s^{-1}). Uzyskane dane poddano analizie matematycznej korzystając z programu Excel i Statistica 6.0. Analiza statystyczna wyników wykazała istotną zależność wartości maksymalnej siły cięcia od zmian cech mechanicznych tkanek zależnie od miejsca pobrania próbek, kąta zaostrzenia noża i jego przemieszczenia. Największą wartość siły uzyskano podczas cięcia nożem o kącie zaostrzenia ϕ=17,5º, a najmniejszą podczas użycia noża o ϕ=2,5º. Wraz ze wzrostem prędkości przemieszczenia noża siła cięcia malała. Najlepszą jakość przeciętych próbek otrzymano przy zastosowaniu prędkości wynoszących 2,49 mm·s^{-1} i 4,15 mm·s^{-1} nożami o kącie zaostrzenia 2,5º i 7,5º.

Słowa kluczowe: burak ćwikłowy, siła cięcia, kąt zaostrzenia noża, przemieszczenie