Article citation info:
KOWALIK K, SYKUT B, MARCZAK H, OPIELAK M. A method of evaluating energy consumption of the cutting process based on the example of hard cheese. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2013; 15 (3): 241–244.

Konrad KOWALIK
Barbara SYKUT
Halina MARCZAK
Marek OPIELAK

A METHOD OF EVALUATING ENERGY CONSUMPTION OF THE CUTTING PROCESS BASED ON THE EXAMPLE OF HARD CHEESE

METODA BADANIA ENERGOCHŁONNOŚCI PROCESU CIĘCIA NA PRZYKŁADZIE SERA ŻÓŁTEGO*

The article demonstrates a method of measuring energy requirements of a cutting process as researched at the Department of Process Engineering, Safety and Ecotechnology. The specially constructed workstation and examples of results obtained are presented. The cutting process has been conducted using stainless steel and low-friction coated blades with each blade's entry conditions variables, such as speed and the angle of entry, determined. In order to compare cutting resistance caused by friction between the blades' surface and the cut substance, wire cutting has also been performed.

***Keywords**: cutting, slicing, energy consumption, blade angle, speed, coating.*

W artykule przedstawiono metodę badania energochłonności procesu cięcia opracowaną w Zakładzie Inżynierii Procesowej, Bezpieczeństwa i Ekologii. Zaprezentowano skonstruowane stanowisko badawcze oraz przykładowe wyniki badań wykonane z wykorzystaniem tego stanowiska. Proces cięcia prowadzono nożami ze stali narzędziowej oraz pokrytymi powłokami charakteryzującymi się małym współczynnikiem tarcia, przyjmując w planie badań dla każdego noża zmienne wejściowe: kąt ostrza oraz prędkość cięcia. Aby porównać opory cięcia wynikające z tarcia materiału o powierzchnię noża przeprowadzono także cięcie materiału drutem.

***Słowa kluczowe**: cięcie, energochłonność, kąt ostrza, prędkość, powłoka.*

1. Introduction

One of many types of processes of industrial technology are comminution processes. They are associated with high energy consumption. One of the most frequently employed is cutting to specific size and shape. Desired shapes are dictated by available technoy, usability, and, for produce, organoleptic effect.

The main factor that affects the cutting process and its energy consumption is the firmness of the material which is related to its composition, internal structure, and, in agriculture or food processing, particular produce type, variety, sample origins, place or conditions of production [6, 7, 8, 9]. In case of raw materials for food production, conditions and type of thermal processing (boiling, blanching, drying, microwaving) [13, 14] are also of significant importance.

There are also other factors influencing efficiency and energy consumption of the cutting process; they are related to the construction and use of a particular device, including the shape and kinematic-dynamic parameters of the cutting element. Until the present time, many researchers working on the cutting process have focused on improving the design of the cutting device, analysis of the blade parameters and their role in the process [2, 3, 5, 12].

Energy consumption of the cutting process is higly correlated with friction between the cutting tool and the cut substance. In slicing or cutting to size, friction depends on the physical properties and the type of material used to manufacture the blade and specific characteristics of the surface coming into contact with the substance being worked upon [1].

Some food items (e.g. hard cheese) are characterised by a high friction factor. Lowering of this undesirable friction during cutting can be achieved by, e.g., raising the blades temperature or reducing the surface of the cutting blade coming into contact with the produce being cut (e.g. wire cutting) [4, 10, 11].

A review of literature related to energy consumption of the cutting process showed that most studies have been done with the use of high durability machinery and speed maintenance in quasi-static conditions. Measuring systems at testing stations described in scientific literature, usually enable measuring of applied force in only one direction, parallel to the direction of the main motion, which, in some conditions, does not allow for a full analysis of the full range of forces that are significant for the whole process [3, 4, 5, 10, 11, 13, 14].

The above limitations prompted us to create our own method and a workstation for reaserching energy consumption of the cutting process.

2. The Goal

The purpose of our research was to use the new method in evaluation of the effect that particular tools have on energy consumption in the cutting process.

3. Reaserch Methodology

3.1. The Workstation

"Cutting Resistance Reaserch Workstation" has been designed and constructed in the Department of Process Engineering, Safety and Ecology at the Mechanical Engineering Faculty of the Lublin Univer-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** sity of Technology. A patent application has been filed and the design is protected under applicable intellectual property and industrial design laws of the Republic of Poland.

One of the distinguishing qualities of this design is the capacity to register, at the same time, forces acting in two perpendicular directions: parallel and perpendicular to the direction of the main force. A schematic of the workstation's layout is presented in Fig. 1.

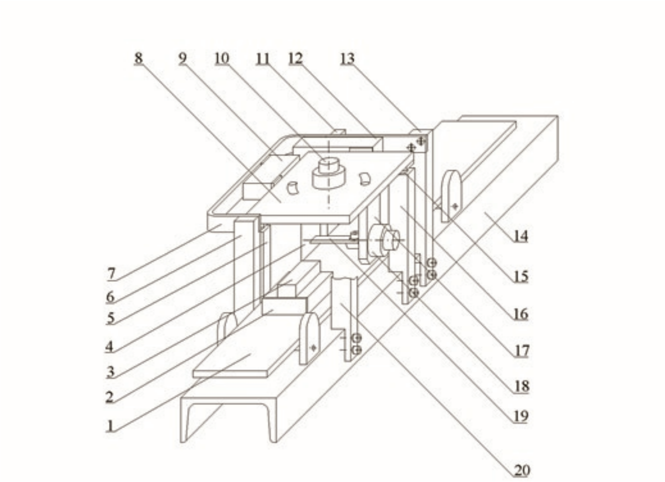

Fig. 1. Layout schematic: 1 – steel beam, 2 – grip, 3 – cut sample, 4, 5, 6 – posts, 7 – outside band, 8 – measuring plate, 9 – induction sensor, 10 – knife position control dial, 11 – post, 12 – induction sensor, 13 – post, 14 – base, 15 – ball bearings, 16 – post, 17 – mount, 18 – knife position control dial, 19 – knife, 20 – post

Workstation's layout presented in drawing 1 shows the horizontal base (14), on which steel beam 1 moves lengthwise. Grip 2 for the cut sample is positioned on the beam. The beam is powered by hydrolic pressure. Mount 17 is attached below the rectangular measuring plate (8) and it holds the knife (19) with the knife position control dial (18). Plate 8 with the knife position control dial 10 moves on ball bearings (15), which are on top end of vertical posts 4, 5, 16, and 20. Induction sensors 9 and 10 that measure forces acting in two mutually perpendicular directions, are fastened to the outside band (7), which is mounted on posts 6, 11 and 13. Information from the sensors, via electronic measuring devices and the data card is passed on to a computer with a 'Testing' application installed. This application has been created to kontrol the input from the installed data card and enables reception of signals, their processing, visualisation and storage.

The workstation makes it possible to change the cutting knife which enables evaluation of any influence of blade geometry (blade angle, thickness, etc.). It is also possible to adjust the position of the knife, i.e. entry angle and the angle of the cutting edge. Sample grip 2 is replacable and can be chosen according to any requirements related to the properties od the sample to be cut (shape, size or method of cutting).

Another important feature of the workstation is the possibility of performing the process at higher speeds than the quasi-static that can be achieved while employing a high durability machine, Intron, most commonly used by reaserchers in this field). At the present time the range is 50–450 mm·s^{-1}. The workstation is equipped with a photo-optical system that allows for controlling of the actual speed whille cutting the sample.

On the basis of data collected from the measuring system, and specifically the registered tracking of the cutting force, the value for slicing work may be arrived at from the following equation:

$$L = \int_S F \cdot ds = \sum_i F_i \cdot \Delta s \text{ , (J)} \tag{1}$$

where:

$\sum_i F_i$ – the sum of forces registered while cutting the sample (N),

Δs – distance that the sample travels betweet subsequent registered values of of the force in time (m).

Unitary energy consumption of the cutting process defined as work needed in order to slice through a unit of surface area of the sample is calculated from the following:

$$e_j = \frac{L}{A} \text{ , } \left(J \cdot m^{-2}\right) \tag{2}$$

where:

L – slicing work (J),

A – surface area of the sample that has been cut (m^2).

3.2. Tools and Materials

During the energy consumption research, as the material subjected to the cutting process we have used hard cheese 'Podlaski' from OSM Wloszczowa (the producer). This produce is characterised by uniform structure and fat content of 45% in dry matter. Slices of 10 mm were cut off the top surface of cuboid samples of the cheese (Fig. 2).

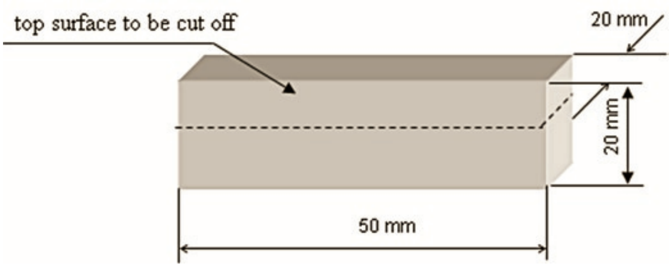

Fig. 2. Cheese samples' dimensions

Flat knives, 1.5 mm thick, 27 mm in length and 70 mm wide have been used. In order to obtain a plane graph based on 'Statistica' package we had to use a set of knifes with blade angles varying from 5° to 45°. The cut was a regular slice. The angle between the cutting edge and the direction of the cut 90°. The clearance angle was 0°.

In order to lower friction and, as a result, the energy consumption, the cutting proces was performed employing knives coated with TiN (Titanium-Nitrogen) and AS48 (trade name of fluoropolymer coating produced by 'PFP Polska'). Basic testing was done with steel knives intended for cold cutting (NC6). The knives used are shown in Fig. 3.

Additionally, we have performed test cutting with chrome-molybdenum steel wire with 0.3 mm diameter. This choice has been made based on initial research and literature.

All the cutting has been done in the same reaserch plane with entry values (independent variables): β – knife blade angle, V – cutting speed, and exit values (dependent variables): directly determined: F – cutting force, indirectly determined: e_j – unitary energy consumption of the cutting process. The value of energy consumption of the cutting, constituting a variable dependent on the model of research, has been

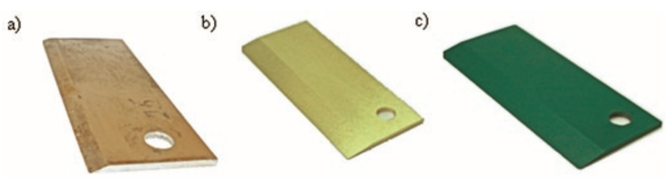

Fig. 3. Test knives: a) steel NC6, b) TiN coated, c) AS48 coated

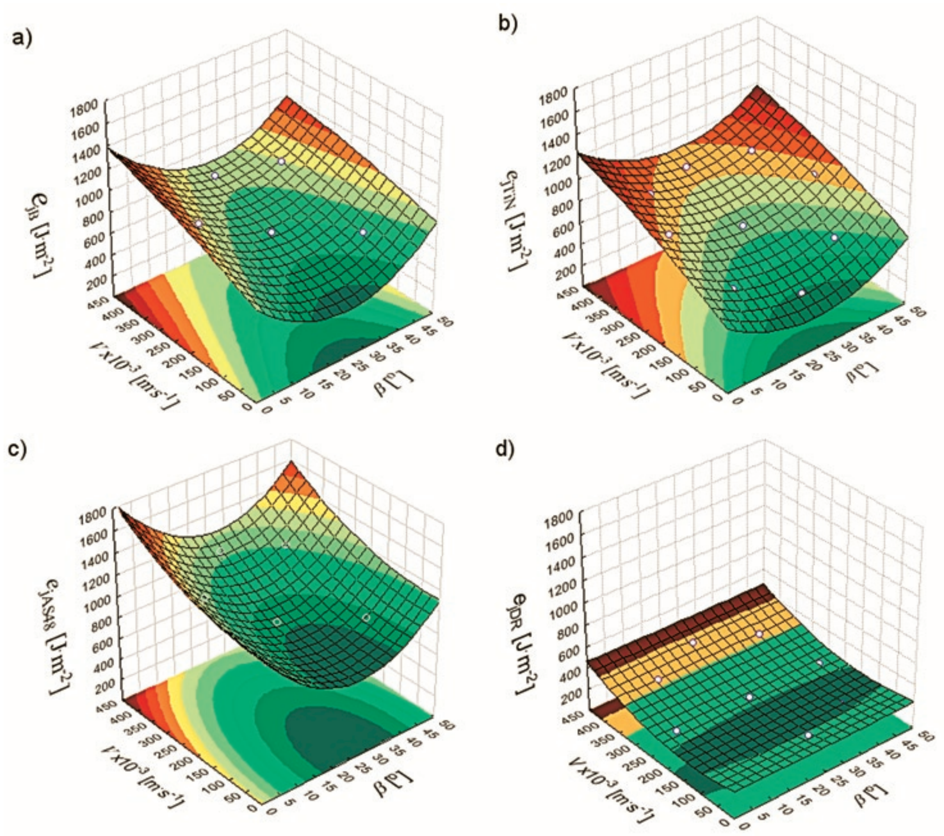

Fig. 4. Graphs presenting result planes for all cutting tools: a) steel NC6 knife, b) TiN coated knife, c) AS48 coated knife, d) wire

related to the unit of surface area of the cut substance. Thus, we have arrived at the unitary energy consumption of the cutting process.

A computerised image analysis workstation was employed in order to measure the surface area of the cut samples. Values of differences of energy efficiency of the cutting process while using steel NC6 as compered to energy efficiency of the cutting process while using other cutting tools has been calculated as follows:

$$R_{(X)} = \frac{\left(e_{jB} - e_{j(X)}\right)}{e_{jB}} \cdot 100, \quad (\%) \tag{3}$$

where:

e_{jB} – unitary energy consumption of the cutting process with a steel NC6 knife (J·m^{-2}),

$e_{j(X)}$ – unitary energy consumption of the cutting process with other cutting tools (J·m^{-2}).

Relevance of the calculated differences was tested with the Student t-test for independent testing.

Table 1. General format of the eperimental matrix

No.	Entry values X_i			
	Coded matrix		Physical form	
	X_1	X_2	β [°]	V x10^{-3} [m·s^{-1}]
1.	– α	0	5.0	225.0
2.	1	1	39.1	348.7
3.	+ α	0	45.0	225.0
4.	–1	1	10.9	348.7
5.	0	0	25.0	225.0
6.	–1	–1	10.9	101.3
7.	0	+ α	25.0	400.0
8.	0	0	25.0	225.0
9.	1	–1	39.1	101.3
10.	0	– α	25.0	50.0

4. Test results and analysis

For plane graphs of the experimental research we used the module *Planowanie Doświadczeń* of *Statistica 9.0 PL* software package. Central-compositional plane for a standard rotary-uniform plane with two independent variables was accepted. The general format of the eperimental matrix adopted for the research plane in a normalised (coded) and physical form is shown in table 1.

The presented values of cutting speed V also constituted the independent variable for the single-factor regression analysis while cutting with wire.

The mathematical model of the cutting process has a basic formula shown in the following equation (4):

$$Y = b_0+b_1x_1+b_2x_2+b_{12}x_1x_2+b_{11}x_1^2+b_{22}x_2^2 \tag{4}$$

Values of unitary energy consumption of the cutting process and differences resulting from cutting with various cutting tools are shown in table 2. Cases for which the calculated differences are statistically relevant, assuming the relevance of α=0.05, are highlighted in gray.

Best results understood as lowered energy consumption are highest for the wire cutting technique. Differences in energy consumption vary from 54.1% to 80.3%. Best results were achieved while cutting with the speed of 0.225 m·s^{-1}, and worst for 0.050 m·s^{-1}.

Slicing cheese with a TiN coated knife lowered the unitary energy consumption in all points of the test up to the value of 21.1%. Differ-

Table 2. Values of unitary energy consumption of the cutting process and differences resulting from cutting with various cutting tools

β [°]	V x10^{-3} [m·s^{-1}]	e_{jB} [J·m^{-2}]	e_{jTiN} [J·m^{-2}]	R_{TiN} [%]	e_{jAS48} [J·m^{-2}]	R_{AS48} [%]	e_{jDR} [J·m^{-2}]	R_{DR} [%]
10.9	101.3	664.4	543.3	18.2	923.2	-38.9	183.5	72.4
25.0	50.0	485.3	390.5	19.5	684.5	-41.0	222.6	54.1
25.0	400.0	868.6	848.6	2.3	1164.1	-34.0	355.1	59.1
10.9	348.7	911.5	897.6	1.5	1156.6	-26.9	331.4	63.6
5.0	225.0	1064.1	878.2	17.5	1341.0	-26.0	209.3	80.3
39.1	348.7	904.9	894.8	1.1	1125.7	-24.4	331.4	63.4
45.0	225.0	867.4	838.4	3.3	987.5	-13.8	209.3	75.9
25.0	225.0	688.4	660.9	3.9	833.5	-21.1	209.3	69.6
39.1	101.3	724.6	571.8	21.1	908.0	-25.3	183.5	74.7
25.0	225.0	688.4	660.9	3.9	833.5	-21.1	209.3	69.6

ences approaching this value were reached in four points accross the plane of the research. The biggest difference values appeared for the lowest values of cutting speeds.

Cutting with the knife coated with AS48, caused an increase in unitary energy consumption in comparison to the steel NC6 knife. The lowest variation of unitary energy consumption of the cutting process was observed at the speed of 0.225 m·s^{-1}. Result planes for all cutting tools are shown in Fig. 4.

All result planes, except the wire cutting (d) conducted for just one variable V, share many similarities. Regression equation describing the wire cutting of cheese shows a polynomial of the second degree (8). For the tested values of the independent variable V, the lowest value of the energy consumption process appeared at the cutting speed of 0.1013 m·s^{-1}.

Established regression equations describing relationships among the variables are:

• for the process performed with steel NC6 knives:

$$e_{jB} = 846.35769 - 33.26005 \cdot \beta + 0.66846 \cdot \beta^2 + 1.53258 \cdot V - 0.000699 \cdot V^2 - 0.00955 \cdot \beta V; \quad R^2 = 0.93485 \quad (5)$$

• for the process performed with TiN coated knives :

$$e_{jTiN} = 583.33605 - 23.87759 \cdot \beta + 0.49226 \cdot \beta^2 + 1918.20684 \cdot V - 1039.86427 \cdot V^2 - 4.46894 \cdot \beta V; \quad R^2=0.99632 \quad (6)$$

• for the process performed with AS48 coated knives:

$$e_{jAS48} = 1326.18205 - 44.67264 \cdot \beta + 0.80701 \cdot \beta^2 - 20.323399 \cdot V + 2705.00281 \cdot V^2 - 2.24283 \cdot \beta V; \quad R^2=0.9073 \quad (7)$$

• for the process performed with wire:

$$e_{jDR} = 237.2352 - 715.031 \cdot V + 2673.851 \cdot V^2; \quad R^2 = 0.9594 \quad (8)$$

5. Conclusions

An analysis of the results allowed us to arrive at the following conclusions:

1. Experimental research confirmed suitability of the proposed research method for analyses addressing energy consumption of the cutting process.
2. Experimental research confirmed the existence of statistically significant differences in energy consumption of the cutting process while using a steel NC6 knife and knives coated with TiN or AS48. In the assumed research plane, in case of cutting with TiN, the differences in energy consumption approached statistically relevant values reaching 21.1%. These were points corresponding to the lowest cutting speeds of the assumed plane of research. Energy consumption differences observed while cutting with AS48 coated knife appear to be statistically relevant in all points of the researched plane. However, this is the result of the increased energy consumption of the process.
3. Experimental research indicated that the wire cutting unitary energy consumption of the process significantly differs from the unitary energy consumption of the steel NC6 cutting process , with the results ranging from 54.1% to 80.3%.
4. With the exception of the wire, the characteristics of changes in the unitary energy consumption were similar. It increased with the speed applied. It was minimal for blade angle of 25°.
5. Mathematical models of relationships between the energy consumption and entry values for the presented cutting techniques could provide a tool for technicians and designers in efforts of controlling and directing the cutting process with the highest energy efficiency.

References

1. Dowgiałło A. Doświadczalna weryfikacji teorii mikroostrzy. Postępy Techniki Przetwórstwa Spożywczego 2002; 2: 15–17.
2. Flizikowski J, Bieliński K, Bieliński M. Podwyższanie energetycznej efektywności wielotarczowego rozdrabniania nasion zbóż na paszę. Wyd. ATR – OPO, Bydgoszcz 1994.
3. Goh SM, Charalambides MN, Williams JG. On the mechanics of wire cutting of cheese. Engineering Fracture Mechanics 2005; 72: 931–946.
4. Kamyab I, Chakrabarti S, Williams JG. Cutting cheese with wire. Journal of Materials Science 1998; 33: 2763–2770.
5. Nadulski R, Wawryniuk P. Wpływ wybranych parametrów konstrukcyjnych zespołu tnącego na proces cięcia warzyw. Inżynieria Rolnicza 2003; 8: 297–305.
6. Opielak M. Rozdrabnianie materiałów w przemyśle rolno-spożywczym. Badanie wpływu konstrukcji rozdrabniacza i cech materiału rozdrabnianego na jakość i energochłonność procesu. Wyd. Politechniki Lubelskiej, Lublin 1996.
7. Opielak M. Analiza teorii procesu rozdrabniania materiałów w przemyśle rolno-spożywczym. Folia Societatis Scientiarum Lublinensis. Technika 1999; 8: 95–106.

8. Opielak M, Komsta H. Kierunki doskonalenia konstrukcji urządzeń rozdrabniających w przemyśle spożywczym. Zeszyty Naukowe Politechniki Opolskiej 2000; 61: 167–173.
9. Popko H, Miszczuk M. Badania oporów krajania niektórych produktów spożywczych. Zeszyty Problemowe Postępów Nauk Rolniczych 1989; z. 354: 147–151.
10. Schneider Y, Zahn S, Rohm H. Power requirements of the high-frequency generator in ultrasonic cutting of foods. Journal of Food Engineering 2008; 86: 61–67.
11. Schneider Y, Zahn S, Schindler C, Rohm H. Ultrasonic excitation affect friction interactions between food materials and cutting tools. Ultrasonic 2009; 49: 588–593.
12. Sykut B, Kowalik K, Opielak M. Badanie wpływu kątów ostrza i przystawienia na opory krojenia produktów spożywczych. Inżynieria Rolnicza 2005; 9: 339–344.
13. Szarycz M, Fidos M, Jałoszyński K. Wpływ zakresu ciśnień podczas suszenia mikrofalowego pod obniżonym ciśnieniem selera korzeniowego na kinetykę procesu i pracę cięcia rehydrowanego materiału. Inżynieria Rolnicza 2006; 4: 239–246.
14. Ślaska-Grzywna B. Wpływ parametrów obróbki cieplnej selera na siłę cięcia. Inżynieria Rolnicza 2008; 6: 175–180.

Konrad KOWALIK, Ph.D. (Eng.)
Barbara SYKUT, Ph.D. (Eng.)
Halina MARCZAK, Ph.D. (Eng.)
Prof. Marek OPIELAK, Ph.D., D.Sc. (Eng.)

Department of Process Engineering, Safety and Ecology
Institute of Transport, Combustion Engines and Ecology
Mechanical Engineering Faculty
Lublin University of Technology
ul. Nadbystrzycka 36, 20-618 Lublin, Poland
e-mails: k.kowalik@pollub.pl; b.sykut@pollub.pl; h.marczak@pollub.pl, m.opielak@pollub.pl