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To cite this article: N Barakaev *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **848** 012007

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Research of strength properties of half-finished products

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Abstract. The article covers experimental study of knives with different sharpening angles to determine the strength properties of molded half-finished product and associated energy consumption for cutting. Determination of the values of the limiting shear stress of products depending on moisture content of the dough and the radius of rounding of the knife.

1. Introduction

The main problems of the food industry are the intensification and optimization of technological processes, the introduction of new progressive types of equipment [1] for rational processing modes that ensure increased production efficiency, reduced energy costs and raw material losses, and improved product quality.

Cutting is a technological method of machining various materials. Due to the difference in the physical and mechanical properties of this or that material, which affects the cutting process, various requirements are imposed on the modes and methods of cutting, as well as on cutting tools.

For products and half-finished products of the food industry, mainly blade cutting and its variation, called sliding cutting, are used. This type of cutting is also widely used in various sectors of the national economy like agricultural production, light industry, etc.

The interaction of knives with macaroni tubes is associated with specific geometric characteristics of the cutting tool, i.e. radius of curvature of the blade, sharpening angle, parameters of the longitudinal microrelief, etc.

The interaction itself has a shock (impulse) character. Hence, it is obvious that it is necessary to study the strength characteristics of the cutting object in combination with the above parameters.

2. Methods

In our case, by analogy with dynamic testing of metals and plastics, impact strength is taken as the main criterion characterizing the strength properties of the object under study. Taking into account the specifics of the section, a plate knife was used as a working medium, and the parameter obtained experimentally, as shown in the works of A.A. Surashov [2] and N.N. Solovyov [3], can be called the specific work of cutting A_0 , J/m²

Installation for the study of the strength properties of macaroni tubes is developed on the basis of a pendulum plant and consists of a frame, a pendulum, a knife holder, a plate knife, a device for holding a sample, a scale and an arrow.

The work of the installation is as follows. The pendulum with a knife is fixed with a trigger in the raised position; the tube bundle is installed in the holder. After that, lifting the trigger, release the



pendulum. The kinetic energy is spent on cutting the beam, and the rest makes the pendulum rise in the opposite direction by a certain angle.

The cutting work is determined by the formula:

$$A = Gl(\cos \varphi - \cos \varphi_0) \quad (J) \quad (1)$$

where: G is the gravity of the pendulum, N; l is the length of the pendulum (the distance from its axis to the center of gravity), m; φ and φ_0 are the lifting angles of the pendulum, respectively, before and after the destruction of the sample, degree.

Specific cutting work was determined by the formula:

$$A_0 = \frac{A}{F}, \quad \left[\frac{J}{m^2} \right] \quad (2)$$

where: A is total work of cutting, J; F is the area of the cut section of the cassette, m^2 .

In the experiments, we used lamellar knives with a straight cutting edge made of 9KS steel with a hardness of HRC = 58 units. The taper angle of the cutting edge ranged from 0.2 to 1.0 mm. The knives were set at different angles to the longitudinal axis of the pendulum: the angle was changed from 0° to 60° . The cut quality was assessed by the K_I index, which characterizes the degree of preservation of the cross-section of the macaroni tubes when cutting the circular shape. Macaroni tubes 40 mm long and 5 mm outer diameter were tightly packed into a cylindrical cassette $\varnothing 30$ mm with a slot in the central part for the passage of a plate knife fixed to a pendulum. The cassette is installed on the head frame so that its longitudinal axis is perpendicular to the cutting plane.

The parameters of the microgeometry of the cutting edge are the most important characteristics that determine the cutting ability of knives, the level of energy consumption and the quality of the formed surface. The edge-rounding radius is one of the main parameters of microgeometry. On the other hand, the dominant factor in the formation of the structural and mechanical properties of a half-finished product is its moisture content. Therefore, it seems appropriate in the initial series of the experiment to find out the degree of mutual influence of these factors on the value of the specific work of cutting [4].

In accordance with the methodology for carrying out a multifactorial experiment [5], a planning matrix has been developed (table 1). To exclude the influence of the sequence of the experiments on the results of the experiment, the sequence of each experiment was randomized.

The results of the experiments were expressed by the value of the specific work A_0 J/ m^2 . This series of experiments was carried out with a plate knife thickness $\delta = 0.2$ mm; angle of installation equal to 0° ; sharpening angle equal to 15° . Strong baking flour was used for kneading.

Each factor, according to the experiment design matrix, was varied at five levels. Symbols of factors and parameter values at each level are given below (table 2).

The first factor (x_1) is the moisture content of the dough varied from 28% to 32%. The second factor (x_2) is the radius of the blade rounding, and is from 3.5×10^{-3} mm to 20.5×10^{-3} mm.

The use of the central compositional company of the second-order time planning allows obtaining a curvilinear dependence of the output parameter (in our case, the specific cutting work) on variable factors: dough moisture and rounding radius, as well as to evaluate the effects of the interaction of factors.

After processing the experimental data, we obtain the following regression equations:

$$y = 0.292 - 0.055x_1 + 0.0455x_2 + 0.0165x_1^2 + 0.011x_2^2 - 0.015x_1 \cdot x_2. \quad (3)$$

The value of the Fisher criterion, calculated on a computer, is $F_p = 4.17$.

To check the adequacy of the obtained regression equation, the calculated value of the Fisher test was compared with its tabular values [5].

Fisher table value was determined for a significance level of 0.05 according to the number of degrees of freedom when determining the variance of adequacy

$$f_1 = (n - n_0) - n^1 \quad (4)$$

and repeatability dispersion:

$$f_2 = n_0 - 1 \quad (5)$$

where: n is the number of experiments; n^1 is the number of significant coefficients of the regression equation; n_0 is the number of experiments at the central point; K is the number of factors.

The tabular value of the Fisher criterion at $f_1=3$ and $f_2=4$ for a 5% significance level is $F_{0.05} = 6.5914$. Thus, the calculated F_p value is less than the tabular value, i.e. at the accepted level of significance (0.05), then the resulting equation adequately describes the process under study.

To use the obtained equation when finding the values of the varied factors, we will decode the variables included in the equation. Then the equation takes the form:

$$Y=3.5510-0.1551W-0.0332\rho_1+0.0018W^2+0.0003\rho_1^2-0.0008W\rho_1, \quad (6)$$

where: W is the moisture content of the dough, %.

The obtained equation is valid only for the experimentally investigated values of moisture content and the radius of rounding of the blade and can be used to determine a rational combination of the recipe for kneading macaroni dough and the parameters of sharpening the blade.

The graphic interpretation of the regression equation is shown in figure 1, where the dough moisture values are plotted on the x_1 -axis, the blade-rounding radius is on the x_2 -axis, and the specific cutting work values are on the y-axis. The appearance of the response surface allows us to conclude that an increase in the moisture content of the dough and a decrease in the radius [2] lead to a decrease in the specific work value.

As can be seen from figure 1, the effect of the radius of the blade rounding is most pronounced at the minimum values of humidity. An increase in the moisture content of a half-finished product reduces its strength properties, characterized by the value of the specific work.

The reason for this is that an increase in humidity leads to an increase in the plasticity of the half-finished product. This, in turn, causes the localization of the breaking stresses $\sigma_{\max}$ directly under the blade and a decrease in the part of the cutting work spent on deformation of the bundle of macaroni tubes.

3. Results

The strength characteristics, as known, are not a constant of the material, but depend on the loading conditions of the object under study [6]. Therefore, in relation to the tasks set, in the future, the influence of the geometric characteristics of the cutting tool (knife thickness, sharpening angle, angle of installation) on the main indicator, the specific work of cutting, was studied.

The experimental dependences of the specific work of cutting on the thickness of the knife are shown in figure 2a.

The analysis of the curves shows that with an increase in the thickness of the knife, the specific work of cutting increases linearly, and with thicknesses of more than 0.8×10^{-3} mm, the linear dependence $A_0=f$ (8) is violated. This can be explained by the large deformation of raw products under the action of compressive stresses, leading to rupture of the layer of green products at the very top of the knife wedge and, consequently, to a decrease in A_0 . With increasing knife thickness, the cut quality deteriorates ($K_i = 0.80 \div 0.82$).

The results of an experimental study of knives with different sharpening angles are shown in figure 2-b. It can be seen from the figure that the smallest specific cutting work corresponds to knives with a taper angle $\alpha=15-20^\circ$.

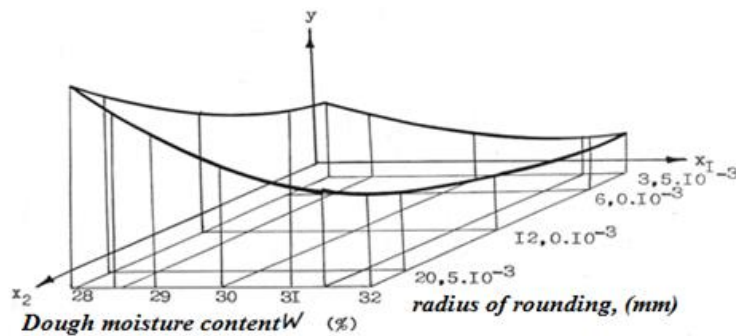


Figure 1. Response surface, reflecting the values of the ultimate shear stress of products depending on the moisture content of the dough and the radius of rounding of the knife.

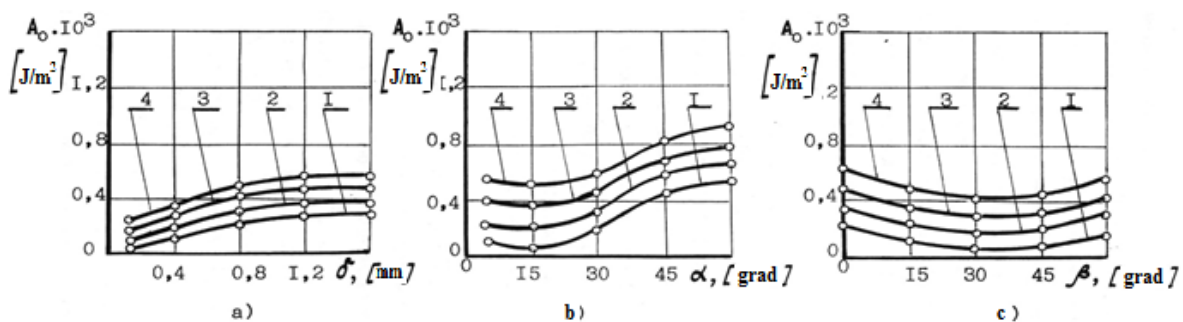


Figure 2. Dependences of the specific work of cutting. A) on the thickness of the knife, b) on the angle of sharpening, c) on the angle of installation of the knife 1- $W=28\%$; 2- $W=29\%$; 3- $W=30\%$; 4- $W=31\%$.

The process of cutting with knives with a sharpness angle of 5-150 is characterized by large values of specific work. Other researchers when cutting certain types of food raw materials [7] also noted this phenomenon. The reason here lies in the fact that obtaining a thin-blade cutting tool with a small sharpening angle (about 50) is a difficult technological problem due to the low strength of the cutting edge. In most cases, when sharpening, the cutting edge wraps or breaks off under the pressure of the abrasive. This causes an increase in the width of the cutting edge and a decrease in the cutting ability of the knife.

The increase in the specific work of cutting at angles of more than 20° is associated with additional energy consumption for the increased deformation of the raw macaroni bundle, pressed with a knife wedge, and then cut. With an increase in the taper angle, the cut quality deteriorates ($K_1 = 0.79$). From the above, it follows that in terms of energy, the angle of sharpening of the knife in the range of 15° - 20° is optimal.

The influence of the angle of inclination of the blade on the specific work of cutting is shown in figure 2-c. The knife blades were set perpendicular to the direction of movement of the pendulum at an angle of 0° (normal cutting), 15° , 30° , 45° , 60°

As can be seen from figure 2-c, A_0 decreases with a change in the knife installation angle β from 0° to 30° , and with a further increase from 30° to 60° , the specific cutting work A_0 at knife installation angles $\beta = 0^\circ$ - 30° is associated with the appearance of sliding cutting elements, and a further increase in the angle of installation of the knife 30° - 60° causes an increase in the friction of the chamfers and the side surface of the knife against the material being cut. In this case, the friction force grows faster than the cutting force R decreases.

In the case of cutting with a knife with a blade angle of 30° , the quality of the cut surface is significantly improved. This is due to an increase in the cutting ability of the knife due to the work of the micro-teeth of the longitudinal relief of the blade and a decrease in the actual contact area of the material with the cutting edge.

It should be noted that even at an angle of inclination $\beta = 15^\circ$, the effect of improving the quality of the cut surface takes place.

The dependences of A_0 from δ , α and β obtained in the one-factor experiment mode are described by a polynomial of the third degree:

$$Y = b_0 + b_1x + b_2x^2 + b_3x^3 \quad (7)$$

The values of the constant coefficients B_0 , B_1 , B_2 , B_3 , obtained by processing the experimental data using the least squares method for each series of experiments, are shown in table 3.

4. Discussion

The obtained experimental data in accordance with the results of the preliminary calculation of the cutting forces allows concluding that with a high moisture content of the half-finished product, a significant part of the energy during chopping cutting is spent on deformation of the tube layer, and an increase in the knife installation angle (or slip coefficient) increases friction costs. With a decrease in the moisture content W of the dough and an increase in the thickness δ of the knife, the specific cutting work increases.

The optimal angle of sharpening of the cutting edge of the knife α from the point of view of the minimum energy consumption for cutting raw pasta lies in the range $\alpha = 15^\circ \div 20^\circ$.

A qualitative assessment of the cut shows that, according to the parameter A_0 , the chopping cutting is significantly inferior to the sliding one. When the knife is installed to the cutting direction within the range of $\beta = 25^\circ - 30^\circ$, the cut quality is improved.

Table 1. Planning matrix.

X_1	X_2	X_1^2	X_2^2	$X_1 \cdot X_2$	Experiment No.	Y
-1	-1	+1	+1	+1	3	0.31
+1	-1	+1	+1	-1	6	0.24
-1	+1	+1	+1	-1	8	0.43
+1	+1	+1	+1	+1	9	0.30
-1.414	0	+2	0	0	1	0.41
+1.414	0	+2	0	0	7	0.24
0	-1.414	0	+2	0	5	0.25
0	+1.414	0	+2	0	4	0.38
0	0	0	0	0	2	0.29
0	0	0	0	0	12	0.29
0	0	0	0	0	13	0.30
0	0	0	0	0	10	0.29
0	0	0	0	0	11	0.29

Table 2. The value of parameters on each step.

Level designations	-1.414	-1	0	+1	+1.414
Moisture values, W , %	28	29	30	31	32
Rounding radii values, ρ , mm	$3.5 \cdot 10^{-3}$	$6.0 \cdot 10^{-3}$	$12.0 \cdot 10^{-3}$	$18.0 \cdot 10^{-3}$	$20.5 \cdot 10^{-3}$

Table 3. The value of constant coefficients.

Parameters	Coefficients			
	B ₀	B ₁	B ₂	B ₃
B	0.93	2.09	0.20	-0,43
α	2.45	-0.032	$0.2 \cdot 10^3$	$0.6 \cdot 10^5$
β	2.72	-0.02	$0.13 \cdot 10^2$	$0.13 \cdot 10^4$

There is a certain consistency between the values of A_0 [J/m²] and K_1 , when the minimum value of A_0 corresponds to large values of K_1 with varying geometric parameters of the cutting tool. However, this correspondence remains only in the zone of small values of the slip coefficient (or the angle of installation of the knife is 0°-30°). With a further increase in slip due to an increase in the angle of installation and a corresponding improvement in the cut quality (according to the parameter K_1), the value of A_0 , having passed its minimum value ($A_0=0.12-0.22$ J/m²), begins to increase significantly, which causes an increase in costs work on friction of the tool against the cut material.

Hence, it can be seen that the parameter A_0 characterizes well the strength characteristics of the molded half-finished product and the associated energy consumption for cutting, however, in comparison with the value of cutting forces, it cannot serve as a criterion when choosing the geometry of the tool and cutting modes in terms of the quality indicators of the cutting equipment.

5. Conclusions

Structural-mechanical and strength properties of a layer of raw macaroni tubes depend on the complex of technological rheological properties of macaroni dough, molding conditions, features of the geometric shape of the half-finished product and the density of their packing in the layer.

The study of the strength properties of the layer of raw macaroni carried out under conditions of specific loading characteristic of their cutting, allows limiting the set of variable geometric factors (knife sharpening angle, blade width, etc.). In this case, it is necessary to focus on those values of the factors that correspond to the minimum value of the specific work of cutting A_0 [J/m²].

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