Rheological and strength properties of dynamic loading during cutting of finished flour products

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Abstract. This article presents the findings of scientific research on the rheological and strength properties under dynamic loading conditions when cutting finished flour products. The study explores the main rheological characteristics and technological coefficients of rye bread cutting equipment, along with the results of cutting technology for various product types under dynamic bread loading. It is observed that as the speed of blade-material interaction increases, the viscous properties of the deformable body decrease due to the inertia of the viscous components. Structural elements undergo spontaneous reorganization at varying frequencies in response to heat, highlighting a range of frequencies that dictate the ability to reconstruct all structural elements. The utilization of thin plate-like knives in multi-knife cutting machines is discussed for their high efficiency in cutting bread and bread products, minimal contact surface area, low tooling material consumption, and promising applications.

1 Introduction

Important research is being carried out in the world to increase the variety of flour products and their production, to improve the quality of bread products, and to improve existing production techniques and technologies with modern equipment. In this regard, it is important to improve the technological processes of processing and cutting finished flour products, to develop optimal technological conditions and parameters for improving the quality of flour products, and to put new technologies into practice. Bread cutting is a kind of cutting of materials in general, and it is distinguished by the specific features of the technological process, which consists of dividing the product with a cutting tool into parts with predetermined dimensions and quality of the surface.

The main condition for the sliding cutting process is the relative movement of the cutting tool and the product. The cutting process can occur in the relative displacement of the cutting tool and the product. Depending on the direction of this movement, cutting is usually divided into cutting and sliding cutting. During cutting, the cutting tool moves perpendicular to the blade in relation to the product, and in sliding cutting at an acute angle to the blade.

Cutting is one of the main technological processes in the food industry. The cutting process is widely used in the fish and meat, gastronomic, and confectionery industries in the formation of desserts, and the production of halwa briquettes, pasta, bread, and bun products.

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The cutting process can be accelerated by the correct selection of the cutting tool, the movement of the material to be cut, and the cutting body. These products have different physical and mechanical properties, which are determined by different cutting methods, cutting speeds, and cutting tools. The bakery obtained as a result of cutting must meet certain requirements regarding the accuracy of the shape of the product, its dimensions, and the smoothness of the cut surface.

2 Materials and methods

Scientific research aimed at speeding up the processing of ready-made food products, researching the technological processes of cutting flour products and improving devices, and increasing the technological reliability of thin plate knives for sliding cutting is important. In food processing, when the tool blade of the knives affects the half-space of homogeneous deformable bodies, the stress increases in the joints and the sticking part of the body in the joint zone changes to a plastic state. The further increase of external stress does not contribute to the growth of stress in this zone but causes an increase in the rate of plastic deformation. Decay in the joint zone is carried out due to plastic compression of the material under the influence of external forces. There are two different processes going on in the uploaded material at the same time. Deformation is a change in the arrangement of molecules between chains, which is prevented by molecular and intermolecular bonds [1].

The effect of micro teeth on the material during the test movement of the needle is characterized by a very rapid application of the load, in which high elastic deformation does not occur due to viscous resistance to the flow, and an initial small cut appears in the product. Table 1 presents the main rheological properties of bread as a food product during dynamic loading [2].

In the conducted experiments, the value of relative deformation was 0.17 the value of compression was 16.3-31.2 MPa, and the frequency varied between 3-30 Gs.

Table 1. Rheological classification of rye bread.

№	ω, Gs	3	5	8	20	30
1	E_{din}, kPa	97.6	113.1	128.0	156.0	183.4
2	G_1, kPa	77.6	86.4	95.0	111.6	128.8
3	G_2, kPa	20.0	26.7	33.0	44.4	54.6
4	$tg\delta_1$	0.26	0.31	0.34	0.40	0.42
5	η*, kPa*s	4.00	3.34	1.65	1.48	1.37
6	T_P, c	1.55	0.81	0.29	0.17	0.12

The data in Table 1 show that the dependence of $tg\delta_1$ on the E_{din} value has an increasing character. The values of the dynamic modulus of elasticity obtained at much higher rates of deformation *(ω=20-30 Gs)* are 1.5-2 times greater than the values under static conditions. Therefore, the use of static modulus values in calculations can lead to a significant error. At the same time, at the minimum values of ω, it was possible to compare E_{din} with research data on uniaxial compression of rye bread, biscuit ready-made flour products, and other raw layered products under quasi-static conditions. This testifies to the methodological validity of using the elastic-viscous body model in the indicated range of values of deformations and frequency changes.

Increasing the rate of impact on the structure of the studied object, characterized by the parameter ω, leads to a significant dissipation of energy compared to the amount of energy stored in the sample as a result of deformation. This can be seen from the fact that the value of modulus G_2 increases by 2.70 times, while the value of G_1 increases only by 1.66 times (Table 1). The frequency dependence of the relaxation duration T_r is especially evident, and ω decreases from 1.55 to 0.12 s, i.e. 12.9 times, when it increases from 3 to 30 Gs. This aspect shows an increase in the plastic properties of the structure.

It is known that by giving crosslinks visco-elastic properties to food polymers, they significantly stop the restructuring of macromolecules. The higher the speed of interaction of the blade with the material, the lower its viscous properties are manifested due to the inertia of the viscous components of the deformable body. For this reason, viscoelastic materials are themselves in dynamic modes of loading [3].

The results of the experimental data were processed in EHM ES 1022. The adequacy of various approximating models was checked according to Fisher's criterion: linear, quadratic, exponential, and level. For all studied rheological properties, the most accurate model of regression equation $y=A_0x^{v}{}_0$ was obtained.

The values of empirical coefficients A_0 and v_0 for rye bread are presented in Table 2.

The conducted studies allow us to show the frequency dependence of the dynamic modulus of elasticity and the phase angle in the form of the following equations:

$$E_{din} = \omega^a \cdot e^b, \tag{1}$$

$$tg\delta_1 = \omega^c \cdot e^d, \tag{2}$$

Here: y is the base of natural logarithms.

Table 2. Technological coefficients of rye bread cutting equipment.

Coefficient	Description					
	E_{din}	G_1	G_2	$tg\delta_1$	η^*	T_P
A_0	73.6	61.4	13.3	0.22	6.26	4.32
v_0	0.26	0.21	0.42	0.20	-0.48	-1.09

After the transformations, the empirical equation relating the complex modulus of elasticity and the phase angle can be obtained:

$$E_{din} = (tg\delta_1)^{a/c} \cdot e^{d-d^{a/c}}$$

$$or$$

$$E_{din} = (tg\delta_1)^n \cdot e^k \tag{3}$$

Table 3 shows the values of the level indicators of equations (1), (2), and (3) for wheat bread with different shelf life.

Equation (3) allows us to describe the E_{din} value of the complex modulus of elasticity in terms of a certain phase angle δ_1, which does not depend on the vibration frequency of the sample. Similar results were obtained for other types of ready-made flour products.

Table 3. The values of wheat bread cutting process indicators.

T	Coefficient values					
	a	v	c	d	n	k
1	0.27	4.66	0.16	-1.35	1.69	6.95
4	0.27	5.11	0.18	-1.55	1.52	7.47
24	0.27	5.62	0.19	-1.67	1.38	7.92

It is possible to use the value of the comparative work of shear a_r one of the characteristics of the strength properties of the studied structures. In the first series of experiments, it was found that a_r values are characterized by a large spread of experimental data. This is explained, on the one hand, by certain changes in the properties of the studied ready-made flour products, and on the other hand, by the fact that the transmission and redistribution of stresses in the sample mass is inadequate and has a static nature, based on the characteristics of the breakdown process. Therefore, experiments in this section were carried out with a large number of parallel measurements (n = 10) [4].

Observation of the removable surface of the samples showed that two rough and smooth zones are clearly expressed in the direction of the blade movement. In our opinion, the appearance of a clearly expressed bumpy zone is connected with the presence of significant frictional forces on the blade faces and sides of the finished flour product. Frictional forces move the adhering layers of the product together with the blade and tear them apart. This assumption is confirmed by experiments on the lubrication of knives with vegetable oil, in which no surface damage is observed due to a decrease in frictional forces. So, for example, for a biscuit ready-made flour product, with an increase in T, the bulging zone decreases from 34.1% of the total shear area at T=0 to 7.2% at T=6 hours and is maintained at T=8 hours completely disappears for the samples [5].

The presence of undulations in the smooth zone can be associated with two stages of failure - slow and fast stages - by analogy with the failure of highly elastic polymer materials. The slow stage describes the recompression of the material and the accumulation of energy due to high elastic deformation. The rapid stage is associated with the progressive crack failure of the material. The slow stage gives a rough surface of the cut, and the fast stage gives a smooth zone [6].

This is because the mechanism of slow breaking of elastomers generally consists of elementary actions, which include both the elimination of intermolecular interactions during the formation of conglomerates of protein molecular bonds and the chemical bond breaking of bonds. includes further disconnection. As the fault zone deepens, bonds are formed and begin to break one after another. Disruption of individual conglomerates occurs in random places, so after the formation of a new surface and shortening of the ends of protein macromolecules, ridges, and depressions appear on the surface, which together form a rough surface. As the loading rate increases, the highly elastic rough zone does not develop, while the smooth zone occupies almost the entire surface.

3 Results and discussion

Experiments have shown that the smallest comparative work of cutting corresponds to knives with a sharpening angle α=15-200. Cutting with knives with α=15-200 is characterized by large values of ar. This phenomenon has also been noted by other researchers when cutting some types of food raw materials and is explained by the fact that the cutting blade can "gap" or break off under abrasive pressure at low α.

The increase in a_r at α > 20^0 is associated with additional energy consumption for increased deformation of ready-made flour products in the cutting direction. In this case, the material is first pressed with a knife blade and then cut. As α increases, the cut quality deteriorates. Sometimes a part of the material is cut off from the sample.

Experiments have shown that the value decreases when the angle of installation of the blade is changed from β 0^0 to 30^0, and when β is increased from 30^0 to 60^0, the relative work of cutting increases. A decrease in a_r in the range of $0 \leq \beta \leq 30^0$ is associated with the appearance of sliding cutting elements, and an increase in β to the value of 60^0 leads to an increase in the friction of the chamfers and blade side surfaces on the material being cut [7].

Based on the obtained results, an experimental study of the process of cutting bread products was carried out, and their results were covered in the published work.

In this case, the friction force increases faster than the shear stress decreases. It should be noted that even at an angle of β=15^0 there is an effect of improving the quality of the cut surface.

The dependence of the value of a_r on T, δ, α, β is described by a third-degree polynomial:

$$y = в_0 + в_1 x + в_2 x^2 + в_3 x^3 \quad (4)$$

The values of the constant coefficients of this equation for the case of cutting rye bread are presented in Table 4.

Table 4. Coefficients of the technological process of cutting rye bread.

Parameters	**Coefficients**			
	v_0	v_1	v_2	v_3
T	2.78	$1.2 \cdot 10^{-1}$	$-1.4 \cdot 10^{-2}$	$4 \cdot 10^{-4}$
δ	0.93	2.1	$2 \cdot 10^{-1}$	-0.43
α	2.45	$-3.2 \cdot 10^{-2}$	$2 \cdot 10^{-4}$	$6 \cdot 10^{-6}$
β	2.72	$-2.0 \cdot 10^{-2}$	$1.3 \cdot 10^{-3}$	$-1.3 \cdot 10^{-5}$

Table 5. Cutting of various types of products and indicators of its process.

Flour products	**Special cutting works $a_r \cdot 10^{-3}$ [Dj/m^2]**						
	1	**4**	**8**	**12**	**16**	**20**	**24**
Rye bread	2.77	3.12	3.11	-	3.29	-	3.47
Wheat bread	2.34	2.89	3.16	3.20	3.24	3.52	3.52
Bread boards	1.85	2.03	2.20	2.32	2.54	2.71	2.73
Biscuit	0.91 W=32 % t=3 c	0.95 W=30 % t=10 c	0.78 W=28 % t=3 c	0.80 - -	0.82 W=28 % t=10 c	0.85 - -	0.88 W=28 % t=20 c
Wet pasta tubes	0.32	0.35	0.41	-	0.60	-	0.61

Table 5 presents the experimental results of measuring the comparative work of cutting all types of ready-made flour products under different durations of storage.

Calculating the value of the ultimate breaking stress according to the known stresses, the cutting work a_r, the geometric characteristics of the blade, and the cutting object:

$$\sigma_s = \frac{K \cdot cos\frac{\alpha}{2}\left[A_p - d \cdot l\left(2\tau B + \frac{E\delta}{sin\,\alpha/2}\right)\right]}{d\delta\left(\frac{\pi-\alpha}{2}\right)}; \quad (5)$$

Here *d, l* are the diameter and height of the sample, respectively; *K* is the coefficient describing the ratio of the cross-sectional area to the normal and high roughness zones; $K=l_n/l$; l_n is the length of the smooth zone; τ - friction stress.

Table 6. Results of cutting technology of different types of products.

Semi-finished	**Special cutting works $a_r \cdot 10^{-3}$ [Dj/m^2]**						
	1	**4**	**8**	**12**	**16**	**20**	**24**
Rye bread	11.2	29.9	38.5	52.5	80.0	112.7	143.4
Wheat bread	12.4	25.3	40.0	56.3	70.6	67.8	118.5
Bread	1.52	3.26	4.87	5.64	7.62	9.01	10.08
Biscuit	0.41 W=32 % t=3 c	0.92 W=30 % t=10 c	1.42 W=28 % t=3 c	1.70 - -	1.98 W=28 % t=10 c	2.15 - -	2.30 W=28 % T=20 c
Raw pasta tubes	0.43	0.46	0.49	-	0.54	-	0.62

The results of calculating the value of δ_s according to the data of Table 5 are presented in Table 6. In this case, the value of V was equal to 12 mm, and the thickness was equal to δ=0,5 mm. The results of measurements in quasi-static modes of data loading show that these values are close enough (the relative difference is around 15-30%).

4 Conclusion

The smallness of the contact surface, the low consumption of tooling materials, and the ease of use indicate their promise in the use of thin plate-like knives in multi-knife cutting machines with high efficiency in cutting bread and bread products. The technological reliability of knives is related to their complex characteristics, such as cutting ability, and stability. The first two characteristics depend on the micro geometry of the blade, and the next one is determined by the geometry and tension of the plate-like blade. The combination of laboratory research and production tests made it possible to determine the durability of thin-plate knives with different methods of blade formation, as well as to find the maximum allowable value of relative cutting ability in terms of cutting quality.

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