Vibration Assisted Cutting of Gouda Cheese

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Abstract

Lebar A., Blatnik O., Junkar M., Orbanić H. (2012): **Vibration assisted cutting of Gouda cheese**. Czech J. Food Sci., **30**: 1–8.

The influence of vibrations on the process of cheese cutting applied in order to reduce friction and the cutting force was studied. The forces needed to cut through the cheese samples were measured against the variations of the temperature, cutting speed, and vibration frequency. The hypothesis which induced the research work was that assisting vibrations reduce the cutting forces and make the cutting easier for the user. In the experiments, Gouda cheese was used at 10°C and 22°C. The further, a conventional kitchen knife was used with four different cutting speeds from 12.5 mm/s to 75 mm/s and six vibration frequencies from 0 Hz to 150 Hz. The results confirmed the hypothesis presuming that up to 3.4 times lower forces are needed to cut through a cheese sample at 22°C, and 1.55 times lower when cutting cheese samples at 10°C. The results also confirmed the already known facts that the cutting forces increase with increasing cutting velocity, 2–4 times on average with cutting at 75 mm/s instead of 12.5 mm/s. Also, 2.5, times lower cutting forces were measured in cutting the cheese sample at 22°C instead at 10°C.

Keywords: cutting forces; friction forces; knife blade

Cutting the cheese with a steel blade knife is an arduous task. The main reason is the high friction in the interface between the cheese and steel. That is also why the cutting forces are higher than expected in spite of the cheese soft texture. With many cheese types also a lot of smearing occurs on the knife blade which additionally increases the friction force.

Recently, our research group joined the efforts with a major producer of small home appliances. Based on decades of industrial experiences in the research into and development of kitchen food slicers our industrial partners clarified to us that cheese is one of the most difficult food types to cut, as we learned in a conversation with Pogacar (B/S/H Company, Director of Development. Factory Nazarje, Consumer Products) in 2009. After a few, more or less unsuccessful cut-and-try experiments done by Kozlovič (2008), a thorough study of cheese viscoelastic properties was started by Blatnik (2009) in order to understand better the underlying cheese cutting mechanisms and to optimise the cheese slicing system.

In the mainframe of this study, the influence of electromechanically induced vibrations on the performance of cheese cutting was researched and is reported in this paper. Cheese is a member of a large group of materials with viscous and elastic properties exhibited at the same time, i.e. viscoelastic materials. As concerns the materials of viscoelastic type, it is known that if the material is stressed with a shear stress and then relaxed,

Partially supported by Slovenian Research Agency in the frame of the P2-0248 (C) project.

it never fully returns to its original shape and an observable permanent deformation remains as explained by Gunasekaran and Mehmet (2003). The extent and time dependence of the residual deformation are functions of many material and ambient parameters.

Regarding the overall characteristics, cheese is divided into four groups according to the texture: fresh, soft, semi-hard, and hard cheeses. Typical group representatives are Feta, Brie, Gouda, and Cheddar, respectively. Taking into account the complexity of the problem, we restricted our research to one type of cheese only, therefore the most frequently sold local cheese, Gouda, was selected.

The literature on cutting food and particularly cutting and friction forces is not abundant, probably due to the reason that the cutting performance has a direct impact on profitability. It was shown by Cavger *et al.* (2003) that by improving the performance of cutting broilers into parts, the profit of a poultry plant could be increased by up to 15.6%. On the other hand, McGorry *et al.* (2003) pointed out that the influence of parameters such as the knife sharpness and cutting force exposure on the performance and productivity has not yet been well documented. In order to prevent high cutting forces, vibration assisted cutting can be used as shown by King (1999). He also reported on the research into cutting frozen meat with blades vibrating at frequencies up to 1 kHz and found that a significant reduction of cutting forces occurred.

Regarding the cutting forces associated with cutting cheese, the results published are also scarce. Arnold *et al.* (2008) studied ultrasonic cutting of different types of cheese. They found out that the composition of the cheese affects the cutting forces and thus the labour needed to cut through the cheese. On the other hand, ultrasound cutting has a lot of disadvantages, namely expensive equipment, generation of loud noise and high heating of the blade, which is why it is mainly used in industrial cutting of frozen foods. The most informative data published on the cutting forces is due to Brown *et al.* (2005) who measured the cutting forces during cutting of cheese, beef, and bacon at different cutting speeds and different sample temperatures.

Based on the literature study and preliminary experiments, in the focus of our research were the cutting forces in the case that vibration assisted cutting of the cheese is performed.

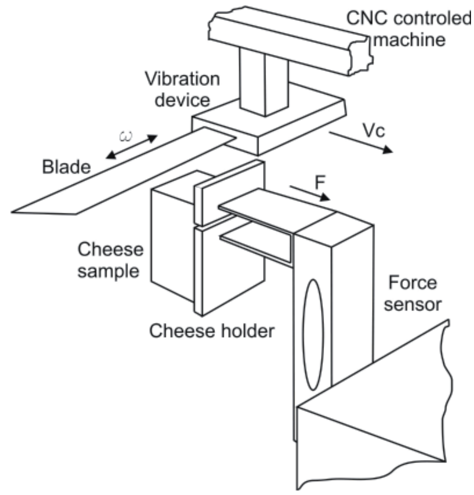

Figure 1. Measurement system – schematic image of knife blade, vibration frequency and direction ω, cutting speed direction υ_c, cheese holder, force sensor and cheese sample

MATERIAL AND METHODS

Sample preparation and fixing. Experiments on cheese cutting with and without knife blade vibrations were carried out using the system schematically shown in Figure 1. The cheese holder is made of acrylic glass plate with four metal prongs and a slit which enabled the blade to move through the sample completely and to slice cheese with thickness of 4 mm. The acrylic plate is connected with a metal holder to the force sensor and is firmly mounted on a massive base. Blade holder is mounted on to the vibration device and further onto the 2652A CNC machine produced by OMAX (Kent, USA), which travelled with traverse rate v_c in the direction towards the force sensor. In the case of vibrations assisted blade, it oscillated in the direction shown in Figure 1 and was labelled with frequency ω.

All of the experiments were conducted with Gouda type cheese originating from the same product batch with the commercial name Jošt and produced by the local manufacturer. This cheese has minimum 55% of residual dry matter, minimum 45% of fat in the residual dry matter, and typically 26.9% of milk fat. Jošt cheese is typically ripened for one month. Cheese samples of the size of 100 mm × 30 mm × 25 mm were cut out of blocks which were provided in hermetically sealed plastic packages. The packages were stored in a refrigerator at 10 ± 1°C for few days and unwrapped shortly before the experiments. The blocks were cut just before the experiment into smaller samples with the dimension 50 mm × 30 mm × 25 mm and put on prongs for the cutting force measurement. In order to maintain the temperature defined as precise as possible, the time of the measurement cycle was kept under two minutes. The samples for the experiments at ambient temperature (20°C) were temperature stabilised for at least three hours before the experiments. The temperature of the cheese samples was constantly monitored during the cutting with M-3890D USB digital thermometer (Metex Corp., Seoul, Korea), and the temperature rise of 1°C was observed during the cutting.

Equipment. The cutting tool used was a blade of a previously unused commercial kitchen knife (Domy basic 92656 by Silk d.o.o, Trzin, Slovenia) as shown in Figure 2 with the dimensions of 130 mm × 15 mm × 1 mm, which was placed on the device for vibrating the blade in the frequency range from 0 to 150 Hz and at amplitude of 1.3 mm. The vibrations were produced by the mechanism used in hydraulic swash plate pumps, where the electro motor rotations are transformed into lateral movements of the blade.

The knife blade was not sharpened during the experiments, but it was visually inspected at the end of each experiment and no noticeable bluntness of the cutting edge was observed. Additionally, no observable increase of the cutting force was observed at the end of the experiments with the same cutting parameters. Therefore it can

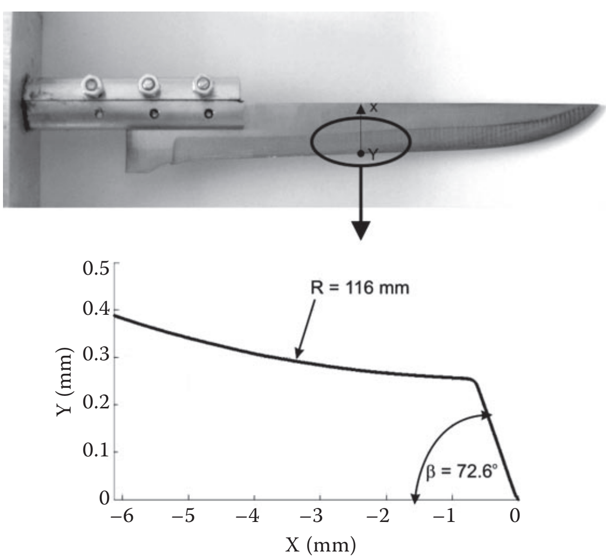

Figure 2. Knife blade (Domy basic 92656) used in experiments with the dimensions of 130 mm × 15 mm × 1 mm and knife profile as measured with contour system MarSurf XC 20

be concluded, that the knife sharpness remained unaltered during the experiments. The blade and the vibration device were placed on a CNC machine in order to achieve repeatable control cutting speeds and traverse movements of the blade in the traverse velocity range v_c from 12.5 mm/s up to 75 mm/second. The blade cut through the cheese sample and produced slices with the dimensions of 30 mm × 25 mm × 4 mm, which makes 750 mm^2 of the cutting surface. The resulting cutting force was measured with TH 1022 load cell made by the company Vishay Electronic GmbH (Selb, Germany). Electric signals were amplified with an amplifier HBM KWS 3S/5 (Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany), acquired with USB-6009 DAQ device at the sample rate of 300 Hz, and recorded by the program LabVIEW, both made by the company National Instruments (Woburn, USA).

Experimental conditions. In the cheese cutting experiments, four different cutting speeds were used. Based on the experience with commercial food slicers, low cutting speeds are appropriate for cheese slicing, therefore the cutting speeds v_c used were: 12.5 mm/s, 25.0 mm/s, 50.0 mm/s, and 75.0 mm/second. In the focus of the presented research was the cutting performance increase in the case of vibration assisted cutting. Six different vibration frequencies were used in the experiments to actuate the transversal blade movement ω: 0, 30, 60, 90, 120, and 150 Hz, the accuracy of vibration frequencies having been ± 3 Hz.

Two different cheese sample temperatures were used. One set of experiments was performed with the cheese samples at the room temperature of 22 ± 1°C, while the other set was cut at the cheese sample temperature of 10 ± 1°C thus representing the cutting of the cheese taken from the refrigerator.

For all parameter combination, i.e. four cutting speeds, six cutting frequencies, and two temperatures, four repetitions were made and the average values and standard deviations were calculated. In order to get an estimate of the friction force, after each set of experimental parameters one more pass was performed through the already cut sample. The procedure is compliant with procedure used by Brown *et al.* (2005) who tried to discriminate the forces attributable to cutting and friction between the side of the blade and cheese sample. Thus in our experimental work altogether 48 cuts in five cycles were performed which equals 240 measurements. During each experiment the signal from the force sensor was captured by DAQ card with the sampling rate of 300 Hz in the duration of 5 seconds. Additionaly, the maximal electrical power consumed by the vibration device was measured with an energy monitor Volcraft 3000 (Volcraft, Hirschau, Germany).

RESULTS AND DISCUSSION

Typical data acquired

The force signals acquired and shown in Figures 3 and 4 were obtained during 240 cutting experiments, but only four typical graphs of the cutting force vs. the knife blade position are shown in this figure. In these figures, the grey line represents the cutting force as detected by the force load sensor while the black line represents the low-pass (set at 7.5 Hz) filtered signal of the force signal acquired. The vertical line marks the beginning and end of the cheese samples cutting which was determined by a force larger than 0.1 N and this value has been set as the threshold for the cutting activity. The data points below the threshold were classified as non-cutting periods. The cutting time was determined by subtracting the time of the first point larger than 0.1 N from the last point where the force was greater than 0.1 N.

It can be noticed in Figure 4 that in both cases the cutting force ramps up due to the constant contribution of the cutting force and that of the steadily increasing viscosity friction force. The friction force increases with increasing cheese-blade interface surface and levels out during fully developed cutting. In the final stage of experiment, the cutting blade left the sample, therefore the cutting forces decreased to zero level. Regarding the comparison between cutting with (Figure 4b) and without vibrations (Figure 4a), a significant reduction of the cutting force can be observed.

Immediately after the cutting the knife blade made a second move through the already cut sample. In this instance, the measured force can be ascribed to pure friction force. The signals of the friction forces generally exhibited line charts very similar to those for the cutting forces but were lower in magnitude, from 60% to 75%. If Figures 3a and 3b are compared showing the cheese samples cutting at 10°C with and without vibrations, the decrease of the cutting force from 31.7 N to 22.0 N can be observed.

The reduction of the cutting force at a higher temperature (namely 22°C) is even greater than in the case of a lower temperature as can be observed in Figures 4a) and 4b). The forces are reduced from 11.4 N to 3.3 N which is 65% decrease. If Figure 3 is compared to Figure 4, much lower cutting forces are observed in cutting cheese at higher temperatures.

Mean maximum cutting forces, standard deviation, and friction forces

In Table 1 are presented the mean values of maximal force (max. F), standard deviation σ of maximal force, and friction force F_f from all 48 sets of cutting. As the cheese samples can have very

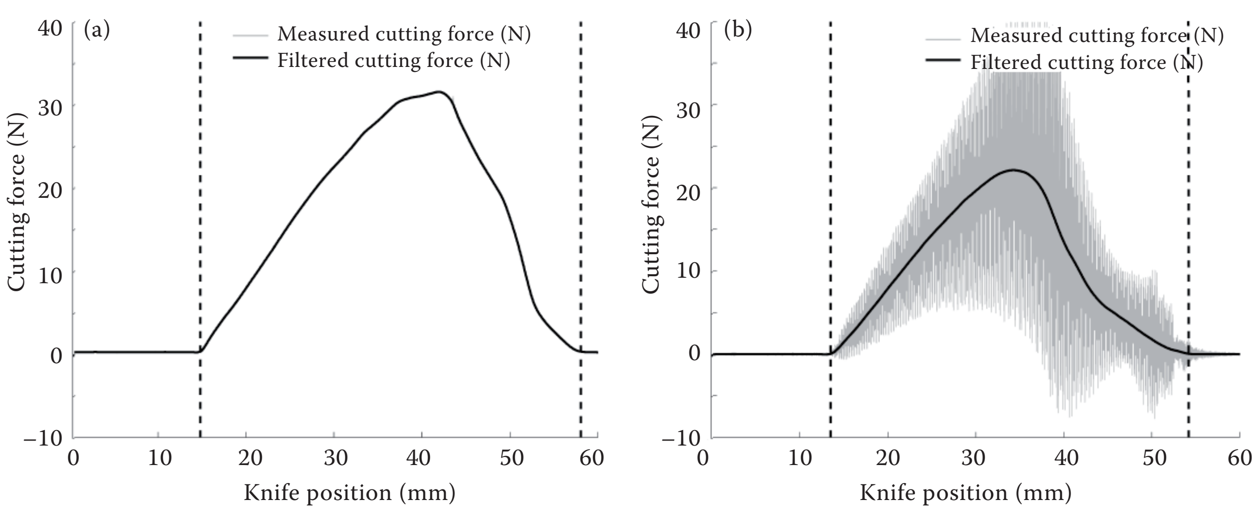

Figure 3. Cutting forces for cheese samples (30 mm × 25 mm) with cutting speed of 12.5 mm/s: (a) at 10°C without vibrations, (b) at 10°C with 120 Hz vibrations of the blade.

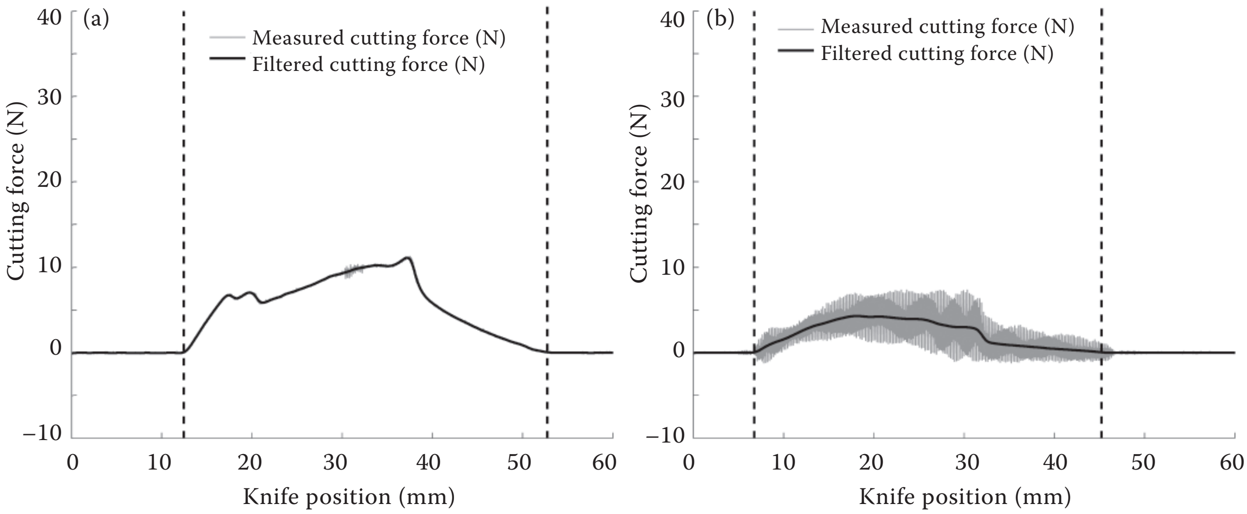

Figure 4. Cutting forces for cheese samples (30 mm × 25 mm) with cutting speed of 12.5 mm/s: (a) at 22°C without vibrations, (b) at 22°C with 120 Hz vibrations of the blade

inhomogeneous structure, e.g. cheese eyes, standard deviation σ varied from 2–10% in most cases. It can be also observed that higher temperature of the cheese samples or lower cutting speed result in lower cutting forces. Assisting vibrations of the blade resulted in the reduction of the cutting force at all cutting speeds, but optimal cutting force, i.e. the lowest one, was found at vibrations with frequency of 120 Hz.

Statistical analysis was applied to complete the collection of the measurement results. The results were collected and sorted in groups with respect to the temperature (10°C and 22°C), knife vibration frequency (0, 30, 90, 120, and 150 Hz), and knife velocity (12.5, 25, 50, and 75 mm/s). First, the overall differences inside the measurement groups, i.e. with only one parameter varied, were tested. By using Kruskall-Wallis test in Matlab, it was shown with P-value 0.05 that the data in the groups did not come from the same population, however, with one exception; at the vibration frequency of 90 Hz maximal forces could not be reliably distinguished when cutting velocities changed from 12.5 mm/s to 75 mm/s.

Afterwards, more detailed analysis was performed by using Kruskal-Wallis one way analysis of variance on ranks in software package Sigmaplot (Systat Software, Inc., San Jose, USA). More exactly, the results of pairwise multiple comparison – Tukey test, are presented in Table 1 as subscripts and superscripts in the column with standard deviations. The results of analysis for the data groups

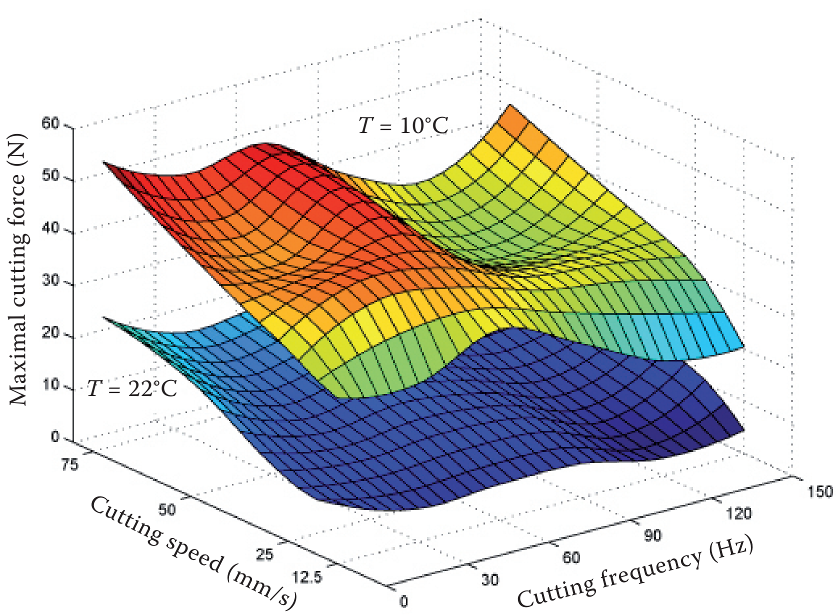

Figure 5. 3D surface of bicubic interpolation of mean cutting forces in respect to cutting frequencies and cutting speeds from 192 cutting experiments

Table 1. Mean maximal forces, standard deviation σ with number of significant differences (at constant frequency η; at constant cutting speed v_c) and estimated friction forces F_f for all 48 cutting sets

ν (Hz)	v_c (mm/s)	T = 22 ± 1°C			T = 10 ± 1°C		
		mean max. F (N)	σ (N)	F_f (N)	mean max. F (N)	σ (N)	F_f (N)
0	12.5	11.4	0.5 η: 2; v_c: 5	2.9	31.6	1.1 η: 2; v_c: 2	10.6
	25	12.0	0.4 η: 2; v_c: 1	4.2	36.8	3.2 η: 2; v_c: 3	10.4
	50	22.1	0.2 η: 3; v_c: 1	9.1	46.2	1.8 η: 3; v_c: 1	14.7
	75	26.8	0.8 η: 3; v_c: 5	10.1	57.5	2.0 η: 3; v_c: 3	20.5
30 ± 3	12.5	6.3	0.4 η: 3; v_c: 1	2.0	30.2	3.1 η: 1; v_c: 3	11.7
	25	9.8	0.7 η: 3; v_c: 0	4.1	37.7	1.5 η: 0; v_c: 4	13.3
	50	14.5	0.3 η: 3; v_c: 0	5.7	41.4	2.6 η: 0; v_c: 1	16.6
	75	20.0	0.2 η: 3; v_c: 1	7.0	51.1	0.1 η: 1; v_c: 2	17.5
60 ± 3	12.5	6.8	0.4 η: 1; v_c: 2	2.7	36.4	2.4 η: 3; v_c: 4	6.6
	25	10.8	0.7 η: 0; v_c: 0	4.2	42.3	2.2 η: 3; v_c: 4	13.8
	50	16.7	0.4 η: 0; v_c: 0	4.8	49.4	0.5 η: 2; v_c: 3	20.2
	75	20.6	0.5 η: 1; v_c: 2	6.1	51.4	0.3 η: 2; v_c: 3	27.2
90 ± 3	12.5	6.5	1.7 η: 1; v_c: 2	2.5	29.5	1.5 η: 1; v_c: 3	4.4
	25	9.8	0.6 η: 0; v_c: 0	3.1	31.4	0.8 η: 0; v_c: 3	9.9
	50	13.2	1.3 η: 0; v_c: 0	5.1	34.4	5.0 η: 1; v_c: 0	12.5
	75	17.4	1.9 η: 1; v_c: 1	5.9	42.4	4.9 η: 0; v_c: 4	10.8
120 ± 3	12.5	3.3	2.0 η: 2; v_c: 3	1.6	22.0	0.7 η: 1; v_c: 4	4.1
	25	4.8	2.1 η: 1; v_c: 1	2.6	29.7	1.3 η: 0; v_c: 2	7.6
	50	9.6	0.4 η: 1; v_c: 1	2.6	31.0	2.4 η: 1; v_c: 2	9.6
	75	15.2	3.4 η: 2; v_c: 2	6.0	37.0	3.2 η: 0; v_c: 4	8.9
150 ± 3	12,5	4.5	0.1 η: 1; v_c: 1	1.7	20.4	1.3 η: 3; v_c: 4	2.4
	25	11.7	4.1 η: 0; v_c: 0	2.3	26.9	0.3 η: 3; v_c: 4	4.1
	50	14.4	0.1 η: 0; v_c: 0	2.8	39.2	1.7 η: 3; v_c: 1	9.5
	75	19.2	1.7 η: 1; v_c: 1	5.7	47.0	0.8 η: 3; v_c: 4	10.6

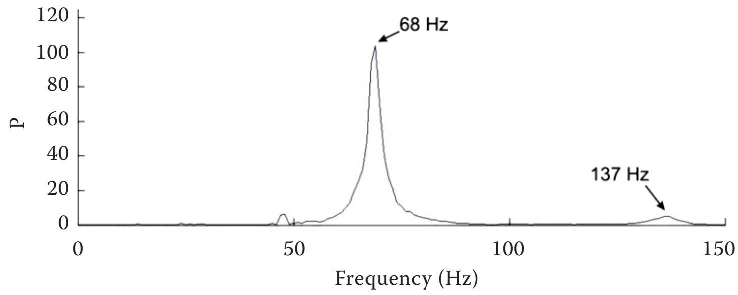

Figure 6. The spectral analysis of the impulse test of the blade

with constant frequency are labelled with η and the results for the groups with constant cutting speed are labelled with ν_c. Maximal number of significant differences between maximal forces in the case of constant frequency groups equals three [max(ν) = 3]and in the case of constant velocity groups equals five [max(ν_c) = 5].

In the groups where a small number of significant differences occurs, the dependence between the quantities is very weak and is blurred by the dispersion of the measurement noise. It can be observed that in some groups the number of significant differences is higher at 10°C then at 22°C (150 Hz) (Table 1).

DISCUSSION

In our work, the initial hypothesis that in vibration assisted cutting of cheese a lesser cutting force is needed has been validated as shown in Table 1. It can be observed that up to three times smaller cutting force was needed to cut the sample using vibrations than without them.

In Figure 5, smoothed data of the measured maximal cutting force as a function of the cutting blade vibration frequency and cutting speed is shown. The experimental data was smoothed by means of bicubic filter. Three major characteristics of the cutting force with respect to the cutting speed and assisted vibrations were found.

In the first place, it can be noticed that maximum cutting forces increase with the cutting speed, regardless of the vibration frequency or sample temperature. The first reason for this effect can be found in the increase of the estimated friction force due to the viscous friction which appears at the cheese-blade contact. The estimated viscous friction F_f is speed dependant (Eq. 1) and thus the force produced by the viscous friction is higher at higher speeds. The second reason is that cheese can be considered a bio-polymer, which exhibits viscoelastic properties as stated by Gunasekaran and Mehmet (2003). One of the viscoelastic material properties is that all polymers are rate dependant as explained by Kamyab *et al.* (1998) and Fang *et al.* (2009), thus the cutting forces are rate dependant and increase with increasing cutting speed.

In the second place, the expected characteristic dependence of the cutting forces on the cheese sample temperature can be confirmed. At any cutting speed or assisting vibration frequency, the cutting forces are larger at lower cheese sample temperatures. Such behaviour can be explained by the temperature dependence of the cheese viscosity coefficient η(*T*) (Eq. 1), which decreases with increasing sample temperature and, therefore, also the friction force decreases. At the same time, another effect contributes to the cutting forces reduction with increasing temperature. This is due to the fact that Young's modulus *E* decreases with the increase in temperature *T*. This effect is known as material softening.

As we are interested in the influence of vibrations on the cutting force, the third and the most interesting characteristic is the influence of the assisting frequency on the cutting force. In general, significantly lower friction forces and cutting forces are needed if higher frequencies of the blade assisting vibrations are used, thus confirming our hypothesis. This observation can be explained by heating of the cut material due to the material deformation, frictional heating, and dissipation of the mechanical energy from the vibrations of the blade (Schneider *et al.* 2009). As we did not measure lateral forces, we acquired maximum power consumed by the motor and found out that the motor needs from 8–12% higher maximum power for low frequency vibrations and from 15–20% more for the vibration of the blade at 120 Hz and 150 Hz than in the case of vibrating the blade without cutting. Our assumption is that this power is needed to overcome the shear stress *τ* that occurs due to the viscous friction as seen in Eq. 1, As stated by Gunasekaran and Mehmet (2003), these stresses can lead to the creation of mode III cracks and thus the lowering of the cutting force.

$$\tau = \frac{F_f}{A} = \eta(T) \times \frac{v}{h} \qquad (1)$$

where:

τ – shear stress

η – viscous friction coefficient (in our case for fat)

v – speed of vibration

h – thickness of the fat film between the blade and cheese

The trends explained in the previous paragraphs are generally in good correspondence with the experimental results as can be observed in Figure 5, with two major exceptions at 60 Hz and 150 Hz. At these frequencies, the cutting force rises significantly and disturbs the behaviour of the cutting system. It was found in additional tests that these peaks can be attributed to the resonant frequencies of the knife blade. The frequency power spectrum was measured with the impulse test and the resulting spectrum is given in Figure 6 where peaks at 68 Hz and 137 Hz can be observed. Lateral vibrations of the blade cause additional friction due to the increased forces normal to the cutting plane. The effect is not worrying, since the resonant frequencies can be shifted towards higher frequencies by a proper design of the knife blade.

CONCLUSIONS

The cutting experiments confirmed the expected trends, such as the increase of the cutting force at higher cutting speeds or at a decreased sample temperature, as reported by many other researchers.

Regarding the reduction of the cutting force in cutting with assisting vibrations of the blade perpendicular to the cutting speed, two explanations were given in this paper, based on the literature and experiments. The friction force is reduced due to the heating of the cheese in steel-blade contact because of the vibrations; on the other hand, the cutting forces are reduced due to the mode III cracks which are caused by the shear forces that are induced by the vibrations of the blade.

This leads to the conclusion that the vibration assisted cutting could be a very promising technique both in the industrial practice where optimisation is required in view of productivity and in the branch of small kitchen appliances where the comfort for the user is searched for.

Acknowledgments. The authors would like to thank the company B/S/H d.o.o. (Nazarje, Slovenia) for supporting the research into the vibration assisted cutting of cheese.

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Received for publication August 13, 2009
Accepted after corrections April 27, 2011

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