Int. Agrophysics, 2008, 22, 89-97

INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Turgor and temperature effect on fracture properties of potato tuber (*Solanum tuberosum* cv. Irga)**

A. Zdunek[1]*, *M. Gancarz*[1], *J. Cybulska*[1], *Z. Ranachowski*[2], *and K. Zgórska*[3]

[1]Institute of Agrophysics, Polish Academy of Sciences, Doświadczalna 4, 20-290 Lublin, Poland
[2]Institute of Fundamental Technological Research, Polish Academy of Sciences, Świętokrzyska 21, Warsaw, Poland
[3]Plant Breeding and Acclimatization Institute, 05-140 Serock, Poland

Received September 13, 2007; accepted January 23, 2008

A b s t r a c t. Fracture properties of plant tissue are important for consumers and industry. The mechanical properties of tissue depend on turgor and temperature. These two parameters can change significantly fracture properties by influencing on failure mode of a tissue. Tissue cracking during mechanical test can be analysed using contact acoustic emission (AE). The goal of the research is analysis of changes in fracture properties of potato tuber tissue in a function of turgor and temperature. In this research, a system for measuring acoustic signals within the audible frequency range is used. The AE is applied in two mechanical tests: texture profile analysis (TPA) and single edge notched bending (SENB). Samples of potato tuber tissue were treated in different concentration of mannitol for turgor control. For temperature control two methods were used in different temperature ranges; cooling for one day at temperatures 2-20°C and immersion in water for 10 min at temperatures 40-70°C.

The experiment shows that fracture properties significantly change with turgor. Use of the acoustic emission shows that the cell wall rupturing is a dominant failure mode when cell-cell adhesion is relatively strong, for example for highly turgid samples in temperatures up to room temperature. The cell-cell debonding is dominant mode when adhesion decreases as a result of maceration or when low intracellular pressure decreases force between cells. In a future acoustic emission would be used for evaluation of texture attributes of plant tissue related to fracture properties, like crispness, crunchiness, juiciness and mealiness.

K e y w o r d s: acoustic emission, potato, texture, fracture, TPA, SENB, turgor, temperature

*Corresponding author's e-mail: azdunek@demeter.ipan.lublin.pl
**This scientific work was financed from Polish national budget for science in years 2005-2008 as the research project No. 2 P06T 089 28.

INTRODUCTION

Fracturing is one of the main processes influencing food texture. For wet food products like fruits and vegetables, fracture properties play important role for quality assessment by consumers and industry. Many texture attributes of plant tissues are connected with fracture properties. Crispness and crunchiness, most investigated in literature properties, are strictly related to sound generated during eating (Christensen and Vickers, 1981; Dacremont, 1995; Drake, 1963; Fillion and Kilcast, 2000, 2001; Harker *et al.*, 1997). Juiciness and mealiness, two opposite properties, are governed by a way of cracking process too (Gross *et al*., 2002). First of them depends on a number of fractured cell walls. The second one is dependent on fracturing between cells when no juice is released from the cells. The way of crack propagation (failure mode) during mastication or during mechanical deformation depends on relative strength of cell walls and middle lamellas (Niklas, 1982). Furthermore, the strength of the middle lamella changes during ripening, thus the failure mode changes during storage. Apart of natural changes, other factors like turgor or temperature would change failure properties too.

Turgor is a tension of cell walls caused by intracellular pressure. It decreases during storage. Turgor can change as a result of osmotic process as well (Lin and Pitt, 1986). When a concentration of an external solution is lower than within cells, tissue soaks external water up and turgor increases. When the concentration of the external solution is

higher than within cells water is released from the cells and the turgor decreases. High turgor *ie* high cell wall tension, changes preliminary condition of deformation process. An additional energy necessary to break the cell wall will be smaller. Therefore, a failure strain usually has lover values when tissue is more turgid (Pitt and Chen, 1983; Zdunek and Konstankiewicz, 2004). When tissue has very low turgor, for example when plasmolysis has occurred, cells respond very poorly to deformation and on a stress-strain curve a toe-in is observed. High turgor changes the strength of cell-cell adhesion, because intracellular pressures of neighbouring cells act in opposite directions. It decreases the failure susceptibility in the middle lamellas (Niklas, 1982).

Temperature catalyzes enzymatic degradation of pectin during storage. This is especially strong in apples, where storage causes significant degradation of pectin in middle lamellas and triggers mealiness properties (Ilker and Szczesniak, 1990; Lapsley *et al.*, 1992; Van Buren, 1979). Cooking causes tissue maceration (Bateman, 1968; Ng and Waldron, 1997; Waldron *et al*., 1997, 2003). From the mechanical point of view, maceration reduces strength between cells. In summary, temperature can cause changes in failure mode of a cellular mechanical skeleton in a plant tissue. Decreasing the strength of the middle lamella causes failure between cells.

Fracture properties of plant tissues are usually investigated using destructive mechanical tests: compression, tension, bending *etc*. Texture profile analysis (TPA) is used for simulation of eating process. The test is performed in two cycles to the same deformation level of a sample. The deformation level should be as high as possible as to damage the sample, but it should not crush the sample completely in the first cycle (Alvarez *et al*., 2002). Therefore, TPA seems to be useful test for obtaining fracture properties of a material tested. Recently, a new mechanical tests called single edge notched bending (SENB) has been introduced for analysing the fracture properties of plant tissue (Alvarez *et al*., 2000). In the test rectangular sample with a notch is bended to breaking up. From sample geometry and from failure force obtained from force-bending curve, a critical stress intensity factor can be calculated. This material parameter is tried to correlate with textural properties of a tissue, like crispness or crunchiness (Harker *et al*., 2006; Vincent, 2004; Vincent *et al*., 2002). However, from the mechanical point of view, the critical stress intensity factor is a force criterion for starting cracking propagation up within material.

Zdunek and Konstankiewicz (2004) proposed using acoustic emission method (AE) together with mechanical test for direct monitoring of cracking processes in deformed plant tissue. An acoustic emission sensor being with a contact with sample through solid body can detect elastic waves generated during sudden cracking process inside the sample. It was proved that a source of the acoustic emission in cellular plant tissue like potato tuber tissue or apple tissue is breaking cell walls. Also cell-cell debonding was not excluded as a potential source. The acoustic emission starts during deformation at different strain and stress depending on turgor and strain rate. This is due to changes in the preliminary stress level in the wall and to limited permeability of cell walls, respectively. The acoustic emission was also applied in texture profile analysis of potato and apple (Zdunek and Bednarczyk, 2006). It was shown that a number of acoustic emission counts during the test increases if the tissue is more turgid. A system used in above research measured acoustic signal in ultrasound frequencies, not useful for human senses.

Zdunek and Ranachowski (2006) developed a new system for acoustic emission measurements during puncture test. However, the system can be used for other tests as well if a proper probe would be used. The AE system works in both ultra and audible frequency ranges depending on number and types of sensors used. Zdunek and Ranachowski (2006) obtained strong acoustic signal during puncturing of apples in the range 1-75 kHz. However, potential application of the system for instrumental evaluation of such audible attributes like crispness or crunchiness requires special focusing on using sensors for this range of frequencies where human senses are sensitive, so up to 20 kHz.

In this paper a new system for acoustic emission with a sensor with range 1-16 kHz will be used. The goal of the research is analysis of fracture properties of potato tuber tissue by this system in TPA and SENB tests. The fracture properties will be changed by osmotic treatment and temperature treatment of potato samples.

MATERIAL AND METHODS

Two types of mechanical tests were performed: texture profile analysis (TPA) and single edge notched bending (SENB). During mechanical deformation the acoustic signal was recorded. The mechanical tests were performed using a universal testing machine Lloyd LRX with 500N load cell and the program Nexygen (Lloyd Instruments Ltd, Hampshire, UK) provided with the apparatus. A crosshead speed of 20 mm min^{-1} was used in both mechanical tests.

The acoustic emission during the mechanical tests was recorded using a head with an acoustic emission sensor. The scheme of the head is shown in Fig. 1. The head consists of two parts. Top part is made of ertacetal and the bottom part is made of duraluminium. They are screwed to each other. To the top surface of the duraluminium part acoustic emission sensor is glued. A 4381V (Bruel&Kjear, Narum, Denmark) sensor was used working in audible range 1-16 kHz. The sensor was connected by a 2 m long cable to AE Signal Amplifier (EA System S.C., Warsaw, Poland) with adjustable amplifying. The amplifier had a high-pass filter at 1 kHz and low-pass filter at 20 kHz. Next, the analogue signal was converted into digital one by A/D board Adlink PCI 9112 (Adlink Technology Inc., Taipei, Taiwan). The sampling rate of each channel was 44 000 samples per second at a resolution

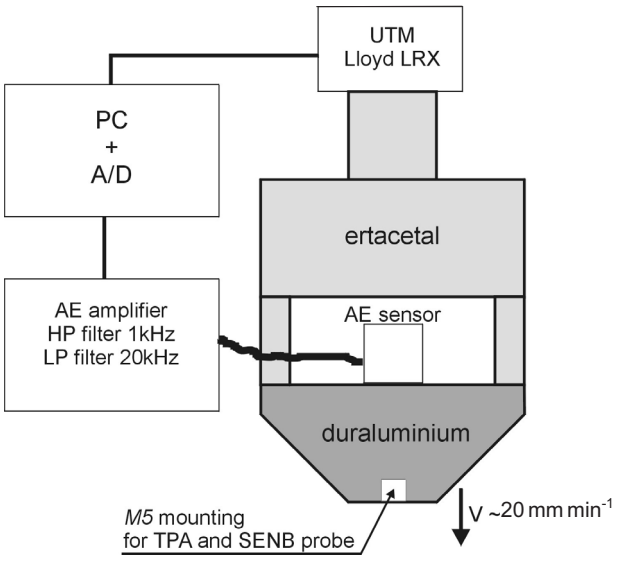

Fig. 1. System for acoustic emission measurements in the range 1-16 kHz during mechanical tests of plant tissue. AE sensor-4381V, A/D - Adlink PCI 9112, UTM –universal testing machine.

of 16 bit per ±1.25 V. The second channel of the A/D board was used for recording an analogue signal of force delivered from Lloyd LRX machine.

A typical record of a time dependence of acoustic emission signal is presented in Fig. 2. A section of the signal where measurable oscillations are detected is called AE event (Ranachowski, 1997). Within a time period of an event the consecutive AE signal amplitudes exceed the preset threshold called the AE discrimination level. A basic assumption taken after practi- cal observations is approximation of the registered AE signal produced by the impulse AE source to a shape of damped sinusoid. It is possible to preset a certain signal threshold and register (count, in other words) every moment when current

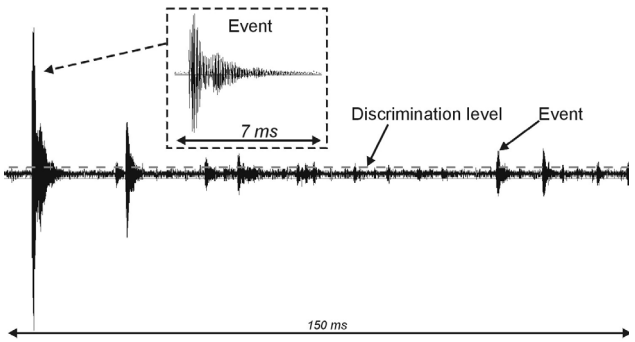

Fig. 2. Acoustic emission signal. AE event is a part of the signal where measurable oscillations over discrimination level are detected.

amplitude of AE signal would cross that threshold. That strategy of tracing the activity of AE source is called AE count processing. Usually, number of AE events is recorded in a time intervals, called AE events rate. In this experiment the time interval of 100 ms was chosen. The number of AE events recorded in the whole TPA test is noted as N_{TPA} and in the SENB test as N_{SENB}. In the each time intervals, if any AE events is detected, its maximum amplitude A_t is recorded. The mean A_t in the whole test is noted as A_{TPA} or A_{SENB}, respectively.

Texture profile analysis was performed on cylindrical samples in two cycles. Maximum degree of deformation applied was 40% of initial sample height for both cycles. Maximum deformation levels were chosen close to failure points of this material as it is suggested by Alvarez *et al.* (2002). Based on a literature review, TPA requires cracking of the test material to simulate the destructive process during eating. On the other hand, deformation should not be too far to prevent the compression of the small pieces of the initial sample in the second cycle which causes springiness and cohesiveness to become physically meaningless. The probe always returned to the trigger point after the first cycle. No rest period was programmed between the TPA compression cycles. After the second cycle, the probe returned to the starting point.

Cylinders for TPA with a diameter of 11 mm were cut using a core borer from the core of the tuber in a direction perpendicular to the stem-distal axis. Next, the samples were trimmed to a length of 13 mm using two vertically guided and parallel razor blades in such way to avoid skin, cortex and vascular bundles in the sample.

The textural parameters were calculated by the 'Nexygen' software from the TPA curves. Hardness 1 is the force peak of the first cycle. Hardness 2 is the force peak of the second cycle. Cohesiveness is calculated as the ratio of the area under the curve of the second cycle to the area under the curve of the first cycle. Springiness is the ratio L2/L1, where L2 is the time or distance from the beginning of the second cycle to hardness 2 point and L1 is the time or distance from the beginning of the test to the hardness 1 point. The other texture parameters that the software can calculate are not considered here.

Single edge notched bending was performed on rectangular beams according to modified ASTM Specification E-399 standard. In the experiment, samples of different dimensions, than it is suggested in the standard were used. The main criterion of choosing of sample dimensions was having strong acoustic signal during bending. Thus, it was necessary to double the sample dimensions comparing to that used by Alvarez *et al.* (2000). It was found that sample of potato tissue of height W=16 mm and width B=8 mm emits strong enough signal in the system used. According to the standard, S/W=4 (span/height) is suggested (Williams and Cawood, 1990). To keep the ratio, the span should be 64 mm.

It was not possible to cut samples longer than L=40 mm from the tubers used in this experiment. Therefore, it was decided to set the span S=32 mm and use S/W=2 ratio. Samples were cut from a potato tuber using two blades guillotines. In the middle of the sample a notch with depth of a=8 mm was cut by a sharp knife.

SENB allows determination of a critical stress intensity factor K_c. The K_c can be obtained using formula:

$$K_c = \frac{P_c S}{BW^{\frac{3}{2}}} f\left(\frac{a}{W}\right), \quad (1)$$

where: S is the span, P_c is a failure force.
Function $f(a/W)$ is given as:

$$f\left(\frac{a}{W}\right) = \frac{3A(a/W)^{\frac{1}{2}}}{2(1+2a/W)(1-a/W)^{\frac{3}{2}}}, \quad (2)$$

where:

$$A = 1.99 - a/W(1-a/W)(2.15 - 3.93a/W + 2.7a^2/W^2) \quad (3)$$

K_c has a physical meaning if following formula is true:

$$Bc \geq 2.5\left(\frac{K_c}{\sigma_y}\right)^2, \quad (4)$$

where: B_c is minimal width of a sample used, σ_y is a failure stress in uniaxial compression of the same material. It was checked after the experiment that the formula (4) is true for all results obtained.

The potato variety (*Solanum tuberosum* cv. Irga) was used in the experiment. The material was cultivated and delivered by Department of Storage and Processing of the Institute of Plant Breeding and Acclimatization in Jadwisin, Poland. The potato tubers were stored from harvesting until the date of the experiment (March 2006) at 3-6°C and relative humidity higher than 94%. In the laboratory, the material was stored at 4-6°C for one week prior to testing. Before the experiment, whole potato tubers were conditioned at room temperature for 24 h and samples were cut for both tests just before testing.

For turgor manipulation 84 tubers were chosen, divided into two groups and from each tuber two cylindrical samples (totally 84 samples) or two bar samples (totally 84 samples) were taken. Next, samples were divided into 7 batches and 6 of them were osmotically manipulated. One batch was control series. The samples turgor was changed by soaking in different mannitol solutions for 24 h according to procedures reported by Pitt and Chen (1983). The following mannitol solutions with phosphate buffer (0.02 M K_2HPO_4 and 0.02 M KH_2PO_4) were used: 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 M. Two litres of each solution were prepared where 24 samples (12 cylindrical and 12 rectangular) where placed. The volume of the bathing was about 23 times larger than the volume of the manipulated samples. From each bath after 24h of treatment and from control series, five samples were picked up for measuring resulting osmolality. Those samples were crushed and sedimented, next the osmolality of juice was measured using cryoscopy Osmomat 030-D (Gonotec, Germany).

For temperature manipulation 72 tubers were chosen. Firstly, tubers where moved from storage conditions to room temperature for 24 h. Tubers were divided into two groups and from each of them two cylindrical samples (totally 72 samples) or two rectangular samples (totally 72 samples) were taken. Next, the samples were divided into 6 batches. Each series was used for different temperature manipulation. Temperature manipulation was performed in different ways in two ranges. For cooling the whole tubers were placed in the refrigerator at 2, 10, and 20°C for 24 h. Next, samples were taken from the tubers and tested immediately at room temperature. Samples at 40, 60, and 70°C were obtained by immersion in the water solution: 1.2 mM $CaCl_2$, 2 m M $MgCl_2$, 0.5 g l^{-1} KCl, 60 mg l^{-1} ascorbic acid, 4 g l^{-1} malic acid, 1 g l^{-1} sodium disulphite, 5 M NaOH to pH 3.5. The samples were placed in the solution for 10 min and tested immediately after that.

Results were statistically analysed using Statistica software. In each experimental series, 12 samples were used. The mean values were calculated with confidence intervals at α=0.05.

RESULTS AND DISCUSSION

Turgor effect

Soaking of potato samples in mannitol solution causes changes in tissue osmolality (Table 1). The osmolality reached in the samples after 24 h treatment increases when higher mannitol concentrations are used for treatment. The turgor is impossible to measure directly, however it can be stated that high osmolality of tissue corresponds with low turgor in the tissue. The turgor changes are noticeable as changes in samples firmness. Samples treated in low mannitol concentration show low osmolality and are more firm

Table 1. Mean value of osmolality of potato samples after 24 h soaking in different mannitol solutions. Standard deviations are presented in the brackets

Mannitol solution (M)	Osmolality (Osmol kg^{-1})
0.1	0.279 (0.002)
0.2	0.324 (0.001)
0.3	0.386 (0.002)
0.4	0.450 (0.004)
0.5	0.501 (0.005)
0.6	0.607 (0.005)
Control	0.330 (0.003)

and on contrary, samples treated in high miannitol concentration show high osmolality and are significantly softer.

The experiment shows that the mechanical and fracture properties of potato tissue are affected by turgor. Figure 3 shows TPA and SENB mechanical parameters in a function of tissue osmolality. The hardness 1 increases with osmolality up to 0.4 Osmol kg^{-1}, next decreasing of this parameter is observed (Fig. 3a). In result, no correlation is observed (R^2=0) for changes of hardness 1 in the function of osmolality. Hardness 2 increases almost in the whole osmolality range (R^2=0.68), however a tendency to decreasing is noticed above 0.5 Osmol kg^{-1}, similarly to hardness 1 (Fig. 3a). Cohesiveness constantly increases with osmolality (R^2=0.80) and, as it was for hardness 1 and 2 at the highest osmolality, the value decreases slightly (Fig. 3b). Springiness (Fig. 3c) and critical stress intensity factor (Fig. 3d) of potato tuber tissue seem to decrease linearly in the whole range of osmolality (R^2=0.64 and R^2=0.80, respectively).

The changes in TPA parameters with osmolality can be interpreted by changes in tissue fracture properties. This phenomenon was described by Zdunek and Bednarczyk (2006) for potato and apple tissue. The results obtained in this experiment confirm these results. Turgid samples *ie* with low osmolality, can reach the failure point before the deformation level 40% applied. Since, macro-cracking causes force drops down the failure force usually is the same as the hardness 1. At it was observed in many experiments, the failure force and failure strain increases if sample loses turgor (Pitt and Chen, 1983, Zdunek and Konstankiewicz, 2004). According to this, the hardness 1 also increases with decreasing sample turgor up to the turgor value when the failure strain meets the deformation level 40%. Macro-cracking propagates in the sample within period from the moment at the failure strain to the moment when the deformation level is reached. If the turgor decreases, the macro-cracking process becomes shorter. After the turgor level, when failure strain meets the deformation level 40%, hardness 1 starts to decreases with osmolality due to lower sample stiffness. In this stage no macro-cracking occurs, thus no significant stress energy is released during compression. Following this, hardness 2 also depends on macro-cracking scale in the first cycle. Samples highly damaged in the first cycle usually show lower hardness 2 due to a low stress relaxation. Some part of elastic energy during sample compression is released in the form of cracking. It causes that area under the force-time curve depends on an amount of the energy released. Less energy released in the first cycle in the cracking process causes increase elastic energy in the second cycle. This leads to increase cohesiveness with decreasing turgor. Samples become less springy when they

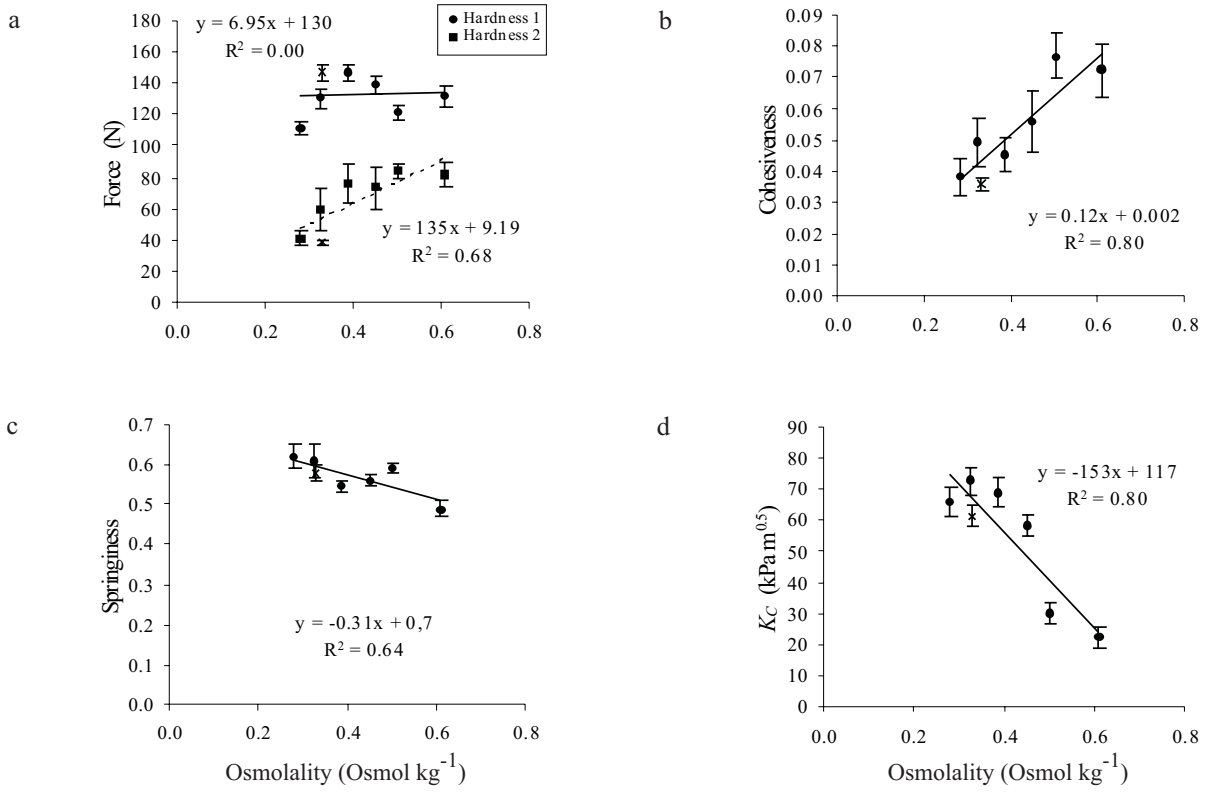

Fig. 3. TPA and SENB mechanical parameters in a function of tissue osmolality after 24h treatment in mannitol solutions. Crosses represent control samples.

lose water (Fig. 3d). According to the definition, springiness is the ratio L2/L1 where L1 is the deformation at hardness 1 and L2 is the deformation at hardness 2. For turgid samples the L1 is actually the failure strain which increases with decreasing turgor. For soft tissue when no cracking occurs the L1 is related to modulus of elasticity which decreases with turgor decrease. L2 depends on sample relaxation after the first cycle. If sample cracked in the first cycle (highly turgid samples) and the relaxation is low, then TPA probe touches the sample later in the second cycle and deformation to hardness 2 is shorter. If the sample did not crack in the first cycle (less turgid samples), the relaxation is high and L2 is much longer on TPA curve. Since both L1 and L2 increase with turgor decrease the results in Fig. 3c show that springiness is affected more by L1, thus development of cracking processes in the first cycle, than L2.

The critical stress intensity factor is a force criterion of the beginning of cracking. However, at a certain sample geometry and the notch depth, the K_C depends linearly on failure force only (Eq. 1). In the experiment, the failure force, and thus K_C decreases with turgor decrease (Fig. 3d). In the SENB, tissue cracking starts from the notch tip and it propagates to the top surface of the sample. Lower failure force of tissue means that the strength of the cell wall or/and intracellular pectin has decreased when turgor decreased. Probably the second reason is responsible for it due to decrease intracellular pressure acting in opposite directions in neighbouring cells. It causes decrease of the cell-cell adhesion what is the reason of easier cracking propagation between cells and in result decreasing of the failure force in the SENB.

The acoustic emission allows direct monitoring of cracking occurring during the test (Zdunek and Bednarczyk, 2006; Zdunek and Konstankiewicz, 2004; Zdunek and Ranachowski, 2006). In Fig. 4, the number of AE events and the mean AE amplitude in a function of osmolality obtained in TPA and SENB is presented. Both AE descriptors decrease exponentially with increasing osmolality of the potato samples. Both determination coefficients R^2 are higher than in the case of mechanical parameters for TPA and are at similar level in the SENB. It was shown in previous paper that in potato tuber both fracturing the cell walls and cell-cell debonding would be the source of acoustic emission (Zdunek and Konstankiewicz, 2004). Taking into account that cell walls are considered as elastic material when it breaks, the elastic energy can be suddenly released and it can propagate in the material to the sensor. Middle lamellas made of pectin are plastic. Therefore, loosing connection between the cells rather does not generate elastic waves.

High turgor causes a smaller additional energy required for cell wall breaking due to some initial cell wall tension. Therefore, more cell walls would be ruptured per deformation

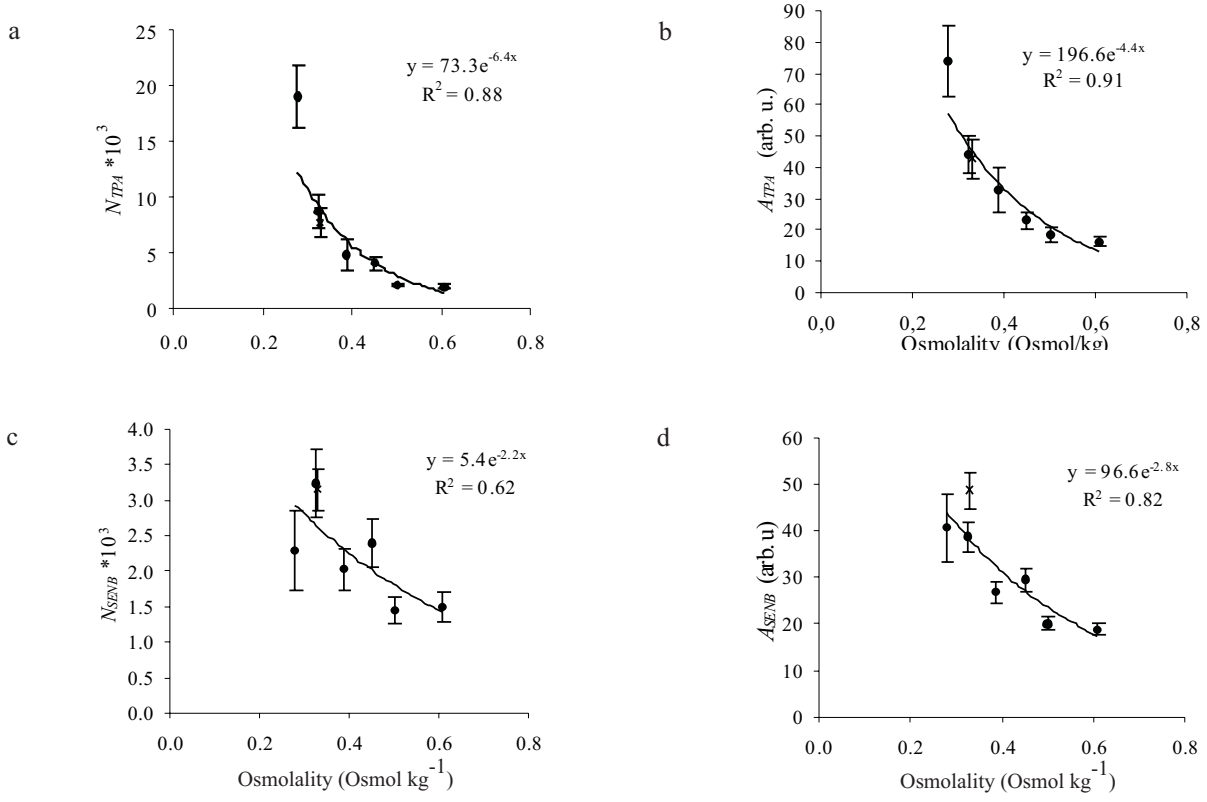

Fig. 4. AE events N_{TPA}, N_{SENB} and AE mean amplitude A_{TPA}, A_{SENB} obtained in TPA and SENB in a function of tissue osmolality after 24 h treatment in mannitol solutions. Crosses represent control samples.

unit. Turgor can also control a failure mode. Higher turgor increases cell-cell adhesion which causes that tissue tends to fail trough cell wall rupturing. On the contrary, low turgor decreases cell-cell adhesion and tissue tends to fail between cells without walls rupturing. It suggests that turgor changes a number of acoustic emission sources per deforma- tion unit. Figure 4a and c show that number of AE events decreases exponentially with osmolality. Concluding, the decreasing number of AE events with decreasing turgor (increasing osmolality) is result of a smaller number of ruptured cell walls during the test. Similar results to curves presented in Fig. 4a and c were obtained in previous experiment for other potato variety and using other AE descriptor *ie* AE counts, in the TPA (Zdunek and Bednarczyk, 2006).

The coustic emission amplitude depends on the stress level in the AE source, the elasticity of the material and the distance from the AE source to the sensor. If the stress level in the AE source is high, the elastic energy released because of cracking would be higher; the amplitude of the AE signal will be higher too. The stress level in the cell wall at its rupturing is independent on turgor because the turgor does not change strength of the wall material. Thus, the decrease of AE mean amplitude with decreasing turgor decrease cannot be explained by changes in the stress level in a moment of rupturing. The elasticity of the material governs propagation of the elastic waves in the material. Damping of the elastic waves is smaller in a firm material than in a soft material. Plant tissue with low turgor is soft. It means that elasticity of the material is relatively low. It causes damping of the elastic waves and decreasing signal amplitude recorded by the sensor when turgor decreases (Fig. 4b and d).

Temperature effect

Figure 5 shows changes of TPA and SENB mechanical parameters in a function of sample temperature. Changes of TPA and SENB mechanical parameters with temperature can be analysed in two ranges for potato samples. In the range 2-20°C actually no significant changes are observed with temperature. Placing samples in a water solution and increasing the temperature from 40 to 70°C causes significant decrease in the parameters analysed. The changes seem to be different for different parameters. Hardness 1 (Fig. 5a) and springiness (Fig. 5c) at 40°C has the same value as for 20°C and next the parameters decrease significantly with increasing temperature, while hardness 2 (Fig. 5a), cohesiveness (Fig. 5b) and K_C (Fig. 5d) at 40°C have significantly higher values than for 20°C and only after that they decrease constantly. This momentary increase of the three parameters at 40°C would be caused by placing samples in the water solution. The samples increase their turgor by osmosis what causes similar effects to that described earlier.

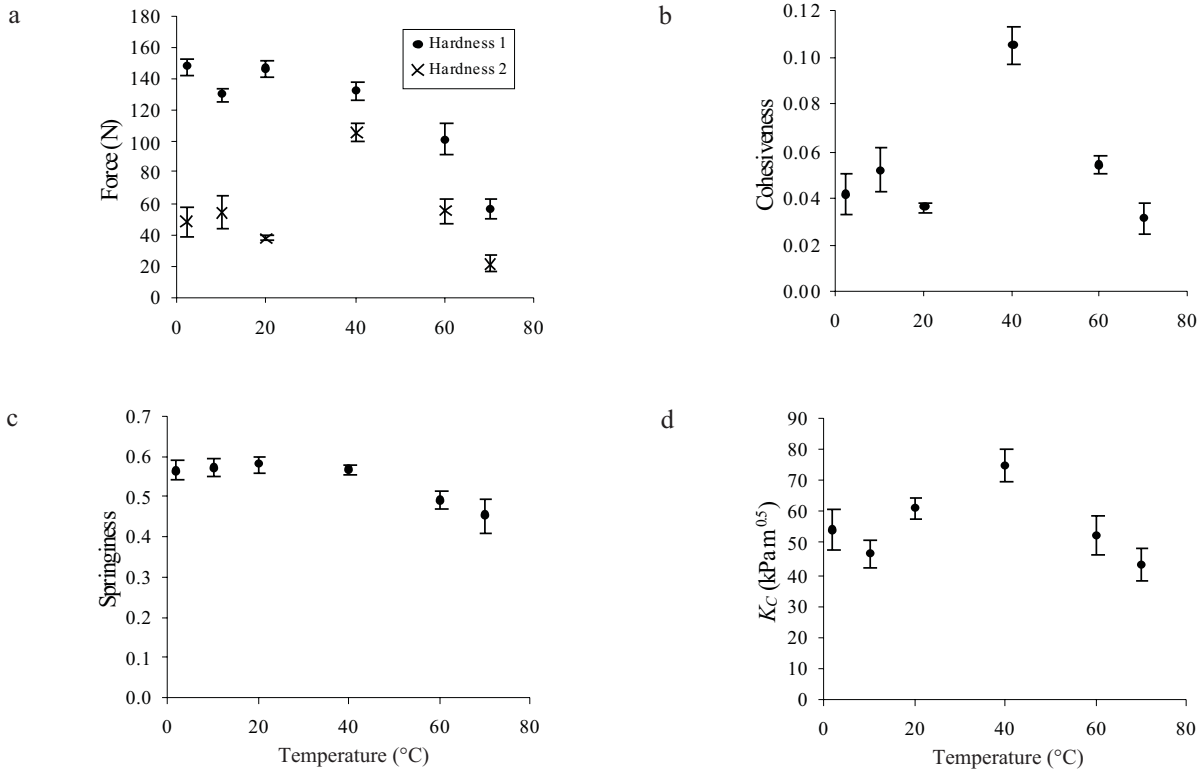

Fig. 5. TPA and SENB mechanical parameters in a function of tissue temperature.

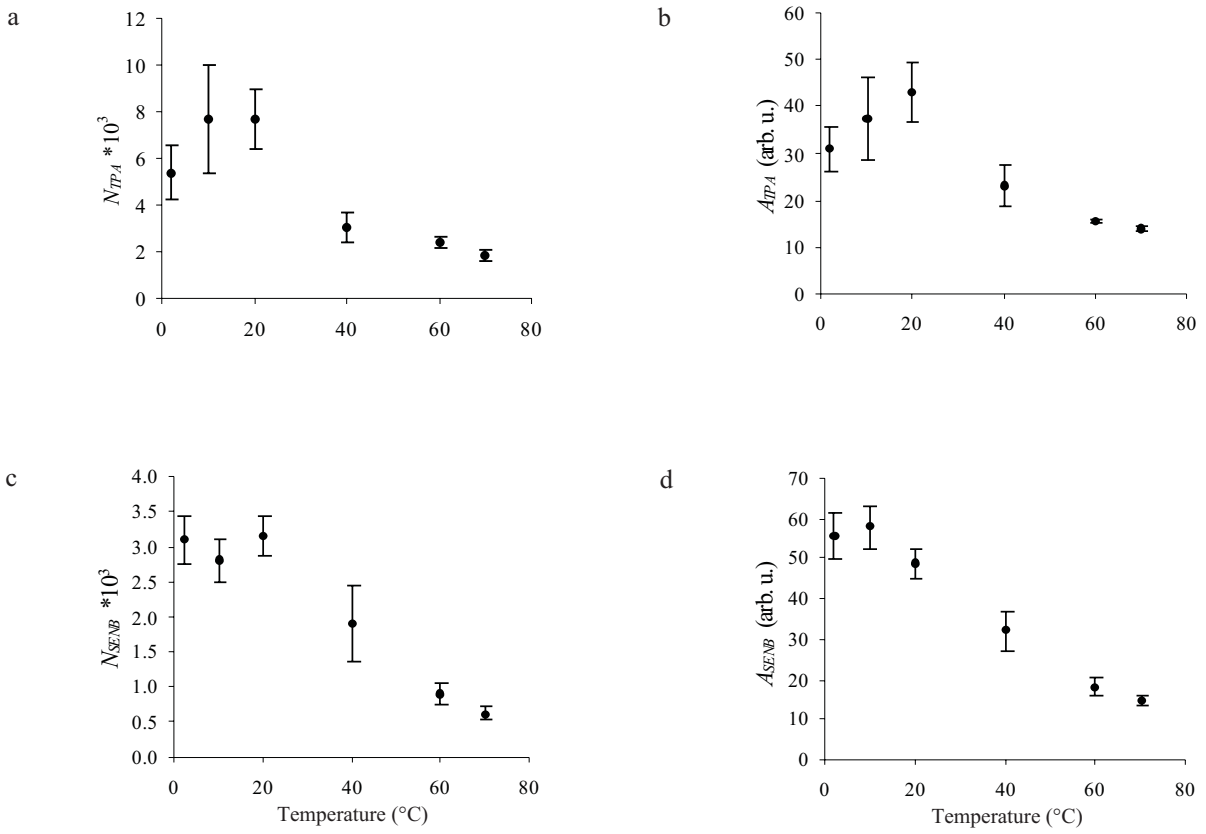

Fig. 6. AE events N_{TPA}, N_{SENB} and AE mean amplitude A_{TPA}, A_{SENB} obtained in TPA and SENB in a function of tissue temperature.

Temperature is a catalyst of enzymatic pectin degradation. The results show that placing samples for 1 day in the temperature 2-20°C does not accelerate the pectin degradation and the potato tissue does not change its mechanical properties. Immersion in higher temperatures (30-60°C) starts process similar to cooking in a form of maceration. The maceration decreases the cell-cell adhesion and the potato tissue become softer. It causes decrease of fracture mechanical parameters due to decrease of the strength of one of the elements of the tissue mechanical skeleton (Fig. 5). The pectin degradation changes the way of cracking propagation of potato tissue too. Potato tuber tissue is considered as a compact structure with no intercellular spaces (about 1% only) which has tendency to crack through cell walls rupturing. The maceration changes this to fracturing between cells. In result, maceration decreases the number of ruptured cell walls and thereby the number of AE events in the mechanical test (Fig. 6a and c). Softening of the material increases damping of acoustic signal on the way to the sample surface and decreases its amplitude (Fig. 6 b and d).

CONCLUSIONS

1. Turgor and temperature have a significant effect on the fracture properties of potato tuber tissue. These two parameters can change the failure mode of the tissue between cell wall rupturing and cell-cell debonding.

2. The cell wall rupturing is the source of acoustic emission. Therefore, the use of acoustic emission allows to obtain information about the failure mode in a plant tissue sample.

3. Decreasing number of acoustic emission events means a smaller number of ruptured walls that can inform also about tendency of the material to failure between cells. This would be useful in practice for evaluation of some texture attributes of plant tissue related to the type of cracking processes, like crispness, crunchiness, juiciness and mealiness.

4. The experiments show that cell wall rupturing is a dominant failure mode when cell-cell adhesion is relatively strong, for example for highly turgid samples in temperatures up to room temperature.

5. The cell-cell debonding is dominant mode when adhesion decreases as a result of maceration or when low intracellular pressure decreases force between cells.

REFERENCES

Alvarez M.D., Canet W., and Lopez M.E., 2002. Influence of deformation rate and degree of compression on textural parameters of potato and apple tissues in texture profile analysis. European Food Res. Technol., 215, 13-20.

Alvarez M.D., Saunders D.E.J., Vincent J.F.V., and Jeronimidis G., 2000. An engineering method to evaluate the crisp texture of fruit and vegetables. J. Texture Stud., 31, 457-473.

Bateman D.F., 1968. The enzymatic maceration of plant tissue. Neth. J. Plant Pathology, 74, 67-90

Christensen C.M. and Vickers Z.M., 1981. Relationships of chewing sounds to judgments of food crispness. J. Food Sci., 46, 574-578.

Dacremont C., 1995. Spectral composition of eating sound generated by crispy, crunchy and crackly foods. J. Texture Stud., 26, 27-43.

Drake B.K., 1963. Food crushing sounds. An introductory study. J. Food Sci., 28, 233-241.

Fillion L. and Kilcast D., 2000. Concept and measurements of freshness of fruits and vegetables. Leatherhead Food RA Research Reports No. 770.

Fillion L. and Kilcast D., 2001. Consumer perception of crispness and crunchiness in fruits and vegetables. Food Quality Pref., 13, 23-29.

Gross K.C., Wang C.Y. and Saltveit M., 2002. The Commercial Storage of Fruits, Vegetables and Florist and Nursery Stocks. Agricultural Handbook, No. 66, doi: http://ba.ars.usda.gov.hb66/.

Harker F.R., Redgwell R.J., Hallet I.C., and Murray S.H., 1997. Texture of fresh fruit. Horticulture Reviews, 20, 121-224.

Harker F.R., White A., Gunson F.A., Hallett I.C., and De Silva H.N., 2006. Instrumental measurement of apple texture: A comparison of the single-edge notched bend and penetrometer. Postharvest Biol. Technol., 39, 185-192.

Ilker R. and Szczesniak A.S., 1990. Review paper structural and chemical bases for texture of plant foodstuffs. J. Texture Stud., 21, 1-36.

Lapsley K.G., Escher F.E., and Hoehn E., 1992. The cellular structure of selected apples varieties. Food Structure, 11, 339-349.

Lin T.T. and Pitt R.E., 1986. Rheology of apple and potato tissue as affected by cell turgor pressure. J. Texture Stud., 17, 291-313.

Ng A. and Waldron W.K., 1997. Effect of steaming on cell chemistry of potatoes (*Solanum tuberosum* cv. Bintje) in relation to firmness. J. Agric. Food Chem., 45, 3411-3418.

Niklas K.J., 1982. Plant Biomechanics, an Engineering Approach to Plant form and Function. Chicago Univ. Press, Chicago, IL, USA.

Pitt R.E. and Chen H.L., 1983. Time-dependent aspects of the strength and rheology of vegetative tissue. Transaction of ASAE, 26(6), 1275-1280.

Ranachowski Z., 1997. Methods of measurements and analysis of acoustic emission signal (in Polish). IPPT Studies, Monography, 6.

Van Buren J.P., 1979. The chemistry of texture in fruits and vegetables. J. Texture Stud., 10, 1-23.

Vincent J.F.V., 2004. Application of fracture mechanics to the texture of food. Eng. Failure Analysis, 11, 695-704.

Vincent J.F.V., Saunders D.E.J., and Beyts P., 2002. The use of stress intensity factor to quantify 'Hardness' and 'Crunchiness' objectively. J. Texture Stud., 33, 149-59.

Waldron K.W., Parker M.L., and Smith A.C., 2003. Plant cell walls and food quality. Comprehensive Reviews. Food Sci. and Food Safety, 2, 101-119.

Waldron K.W., Smith A.C., Parr A.J., Ng A. and Parker M.L., 1997. New approaches to understanding and controlling cell separation in relation to fruit and vegetable texture. Trends in Food Sci. Technol., 8, 213-221.

Williams J.G. and Cawood M.J., 1990. European Group on Fracture: K_c and G_c Methods for Polymer. Polymer Testing, 9, 15-26.

Zdunek A. and Bednarczyk J., 2006. Effect of mannitol treatment on ultrasound emission during texture profile analysis of potato and apple tissue. J. Texture Stud., 37, 339-359.

Zdunek A. and Konstankiewicz K., 2004. Acoustic emission in investigation of plant tissue micro-cracking. Transactions of ASAE, 47, 4, 1171-1177.

Zdunek A. and Ranachowski Z., 2006. Acoustic emission in puncture test of apples during shelf-life. Electronic J. Polish Agric. Univ., Agricultural Engineering, 9, 4. doi: http://www.ejpau.media.pl.