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Effect of twin-screw extrusion parameters on mechanical hardness of direct-expanded extrudates

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Abstract. Mechanical properties of cereal (starch-based) extrudates are perceived by the final consumer as criteria of quality. We investigate one of the important characteristics of extrudates, mechanical hardness, which is one of the main texture parameters. Texture quality has an influence on taste sensory evaluation, and thus on the acceptability of the product. Characteristics that have great influence on acceptability are crispness, elasticity, hardness and softness.

These attributes are narrowly related to, and affected by, the process parameters. A 2-level–4-factor factorial experimental design was used to investigate the influence of temperature of expansion, screw speed, feed moisture content and feed rate, and their interactions, on the mechanical hardness of extrudates. Feed moisture content, screw speed and temperature are found to influence, while feed rate does not have significant effect on extrudate hardness.

Mechanical properties of specimens were measured by means of compression testing, based on the concept of nominal stress, using a universal testing machine and special grips that were constructed for this purpose.

Keywords. Expansion temperature; cereal extrudates; extrusion parameters; feed moisture content; mechanical hardness; screw speed; texture.

1. Introduction

Extrusion cooking is a modern high-temperature short-time (HTST) processing technology, gaining ground in certain industries for various reasons. It offers several advantages over other types of cooking processes, such as faster processing times and significant reduction in energy consumed, which consequently results in lower prices for the final products. The products of extrusion are of major importance in the food and feed industries today. Extruders can be used for a wide range of traditional (conventional) food products, as well as in the production of numerous new products (cereal baby food, confectionery, breakfast cereals, snack foods, bakery products, flavours, pastas, pet food and meat products) (Wiedemann & Strobel 1987).

An extruder represents a very complex bioreactor in which, various types of food raw materials with different moisture contents and viscosities are treated, , under high temperatures, short residence times, high pressures and very strong shear forces.

During any extrusion process, the treatment of the material consists of mixing, mass kneading, heating and shearing, and finally extrusion through a die appropriately designed to form and dry the product under expansion and rapid fall in pressure (Akdogan 1999).

In the food industry, the following operations take place during raw-material processing by extrusion: gelation, extrusion cooking, molecular disintegration, sterilization, mixing, shaping and expansional drying. In the course of conveying the raw material through the extruder by screw-turning, mechanical energy is created and turned into heat, which is transmitted to the raw material. The raw material is thus converted to a highly elastic mass which is extruded through a die (Chinnaswamy 1993).

In warm extrusion, cooking temperatures lie within 120–180°C, and pressures are between 12 and 25 MPa. The barrel and dies are cooled or heated as required to maintain the desired temperature. A (high temperature, short time) (HTST) procedure is one which uses raw material short residence time, high temperature, high pressure, large shear forces and intensive mixing for the (Zheng & Wang 1994).

Under these conditions, the dipolymers in the raw material are subject to protein denaturization, starch glue formation and plasticization of the complete volume. The evolved plasticized volume expands through the die due to a rapid fall in pressure, to form an extrudate with characteristic properties. These properties are very different from those of the starting raw material (Cai *et al* 1995).

HTST extrusion makes it possible to manufacture a wide variety of new products. In addition, well-known food products already on the market can also be improved. Breakfast cereals, "ready to eat" food, flat breads, soluble dietary fibres (Ježek *et al* 1996), modified powders, starch syrups (Ćurić *et al* 1998), and pet food are just some of the products in the wide range that can be manufactured or improved using this extrusion processing method.

However, when they are produced by modern extrusion technology, the various types of extrudate are produced in very different shapes. These depend not only on processing conditions, but also on the size and shape of the die, and the speed of the final cutting device. Also, extrudates are manufactured with a wide range of various additives to improve aroma, taste and smell, and to achieve higher quality, taste and unique characteristic of the product.

The quality of extrudate produced can be determined using different methods according to their applicability in a variety of food-industry sectors. Sensory qualities include aspects of the food product that can be adequately evaluated by the consumer. These include colour, size, shape, taste, odour and structure. Such qualities vary considerably among products, significantly affecting their status and success. Evaluation of sensory characteristics is a difficult task, and some of the characteristics are very hard to estimate.

However, there are many research methods capable of presenting relevant data about the structure. If force is used on food material, it is in the form of compression, shear or cutting, or a combination of shear and compression (Lucas *et al* 1986). Out teeth 'work' in a simultaneous combination of compression and shear, first in kneading and crashing, and then in the chewing process (Ostry *et al* 1996; Takada *et al* 1996).

Shear compression can be measured with a food texture analyzer (Friedman *et al* 1963), Kramer's tearing press (Kramer & Twigg 1970), Instron's universal testing machine (Bourne 1978) and Charpy's pendulum (Bauman & Tripalo 1992). The time duration of the force activity is represented by the shape of the curve on the instrument, and the complete procedure of deformation, compression, cutting or kneading can be observed.

Relevant information about the structure, i.e. texture, may be determined in a subjective way using different sensory methods (methods of difference, preference tests, quantitative descriptive analysis, scoring systems). The tests used most commonly are sensory panel tests. In these tests, an examiner subjectively evaluates the structure of a food product, usually in the form of acceptability and preference.

In the ideal case, an objectively determined physical parameter of structure, such as hardness, is evaluated in relation to the final consumer's acceptability or preference, and proves very useful in predicting the final reaction.

The objectives of this study are to determine the effect of process parameters (feed moisture content, feed rate, expansion temperature and screw speed) on the mechanical properties of whole wheat starch-based extrudates.

In accordance with how mechanical properties of solid food extrudates are usually determined, a new method was introduced for this particular type of food extrudate. The cross-section of the extrudate is basically circular, and hence the method of nominal stress is appropriate because the load is distributed over the entire surface of the sample. So far this method has not been used for the determination of the mechanical properties of extrudates, or in food technology generally. In addition, the object grating method is applied for visual monitoring of sample behaviour during compression.

2. Materials and methods

Experiments were performed on extruded products manufactured from wheat flour (provided by "Zagrebaèke pekarne – Klara", Zagreb, Croatia), water and emulsifier.

The perception of food texture is through the sensation of touch or feeling by the hand or the mouth. Some characteristics, such as cell size, cell wall thickness, physical properties of the biopolymers, and the influence of moisture at the moment of expansion, are what primarily determine the texture of a product.

Instrumental methods for measuring food texture are based on mechanical tests, which include detecting the resistance of the food to the applied force. Most foods have a heterogeneous structure, which makes determination of the material's mechanical properties difficult.

The main purpose of this research was to experimentally determine certain mechanical properties of extrudates, produced by a twin-screw extruder (APV Baker MPF 50:15) and, on the basis of the achieved results, to draw conclusions on the effects of processing parameters on the mechanical hardness of the extrudates. Mechanical and geometrical properties of food, such as hardness and thickness, are the main factors that affect its texture. The concept of the research method presented here is based on real-time simulation of a bite, from the mechanical point of view.

A 2-level–4-factor factorial experimental design was used to investigate the influence of temperature, screw speed, feed moisture content and feed rate, and the effect of their interaction. In addition, two central points were added to evaluate the curvature effect. Table 1 shows the factors, levels and experimental design in terms of coded and uncoded values. Screw speeds of 150, 225 and 300 rpm were used, temperatures in the last extruder section were 120°, 145° and 170°C, feed moisture contents were 24·5, 21·4 and 18·3%, and feed rates were 20, 30 and 40 kg/h. Barrel temperature zone profiles were set to 28°/51°/75°/120°/120°, 28°/67°/106°/145°/145° and 28°/72°/120°/170°/170°C.

Table 1. Experimental design and observed experimental data[a].

n	T [°C]	MC [%]	r [kg/h]	Hardness [N/mm^2]	SD
150 (−1)[b]	120 (−1)	24·5(1)	40 (1)	1·5890	0·2240
150 (−1)	170 (1)	24·5 (1)	40 (1)	0·7925	0·1932
150 (−1)	120 (−1)	24·5 (1)	20 (−1)	1·1000	0·1193
150 (−1)	170 (1)	24·5 (1)	20 (−1)	0·7330	0·1408
300 (1)	120 (−1)	24·5 (1)	40 (1)	0·5360	0·2208
300 (1)	170 (1)	24·5 (1)	40 (1)	0·4740	0·0771
300 (1)	120 (−1)	24·5 (1)	20 (−1)	0·7660	0.1015
300 (1)	170 (1)	24·5 (1)	20 (−1)	0·6070	0·1522
150 (−1)	120 (−1)	18.3 (−1)	40 (1)	0·2800	0·0363
150 (−1)	170 (1)	18·3 (−1)	40 (1)	0·1400	0·0173
150 (−1)	120 (−1)	18·3 (−1)	20 (−1)	0·2400	0·0272
150 (−1)	170 (1)	18·3 (−1)	20 (−1)	0·1330	0·0170
300 (1)	120 (−1)	18·3 (−1)	40 (1)	0·2073	0·0306
300 (1)	170 (1)	18.3 (−1)	40 (1)	0·0985	0·0159
300 (1)	120 (−1)	18.3 (−1)	20 (−1)	0·1436	0·0201
300 (1)	170 (1)	18·3 (−1)	20 (−1)	0·1018	0·0168
225 (0)	145 (0)	21·4 (0)	30 (0)	0·3799	0·0586
225 (0)	145 (0)	21·4 (0)	30 (0)	0·4030	0·1016

[a] n – screw speed, T – temperature, MC – moisture content, r – feed rate, SD – standard deviation
[b] The values (−1), (0) and (1) are coded levels

2.1 *Manufacture of extrudate*

When solids and liquids are fed into the extruder, shear and kneading energy is imparted by specifically designed screws. On passing through the extrusion die, a drop in pressure causes vaporization of water, leading to product expansion. The shaped material foams and a porous structure is formed. A rotating knife cuts the shaped product. Using the extruder, raw materials can be converted, as required, into semi-cooked or finished products in 30–60 seconds.

After expansion, the extrudates are cut into pieces and dried at about 60°C overnight in an oven drier. Immediately after drying, the samples are stored in air-tight containers. We determined the mechanical properties of 18 material types after manufacture by this process. Specimens were classified by the temperature applied in the final extruder section. Tests were performed on at least 10 samples for each extruded sample.

2.2 *Determination of hardness*

Edible extrudate material has a porous, non-homogeneous structure that makes the production of standard-shaped specimens for material testing virtually impossible. In order to overcome the unknown stress distribution owing to the non-homogeneous specimen structure, it was convenient to introduce the concept of nominal stress. We introduce an experimental method for specimen compression testing (figure 1) that is also suitable for *in situ* specimen quality testing. The results of these experiments influence extrudate structure and material porosity, directly affecting the nutritional qualities of the product.

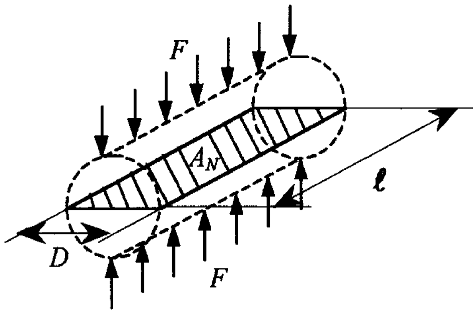

Figure 1. Nominal stress method.

During the compression tests, the specimens were held in special grips of the universal testing machine, Messphysik Beta 50–5 (figure 2). The curvature of the grip lines is variable in this method and should be adapted to the diameter of the tested specimens. Measurements were conducted in the laboratory under strictly controlled conditions. During experiments, the prevailing conditions were measured on the laboratory "Hygroskop DT" by "Rotronic AG" Switzerland. Measured data were: temperature 27°C, relative humidity 48%. The specimens were loaded at a constant speed of 40 mm/min that was determined experimentally by investigation of speed variation on the consumable specimens (Brnčić *et al* 2001).

The experimental investigation of the influence of non-homogeneous specimen structure was realized by the actual deformation distribution analysis during the conventional time-controlled compression tests. Measurements were carried out at the specimen surface by the object grating method (Gomerčić 1999). The deformation is obtained by the displacement registration of the attached grating (figure 3).

Therefore, the area-based image-matching algorithm is applied to the image analysis of the reference unloaded stage and to several loaded stages. Actual surface deformation is shown as a series of prints.

The automatically captured force and grip displacements were analysed. A typical stress/strain response diagram obtained from these data is shown (figure 4).

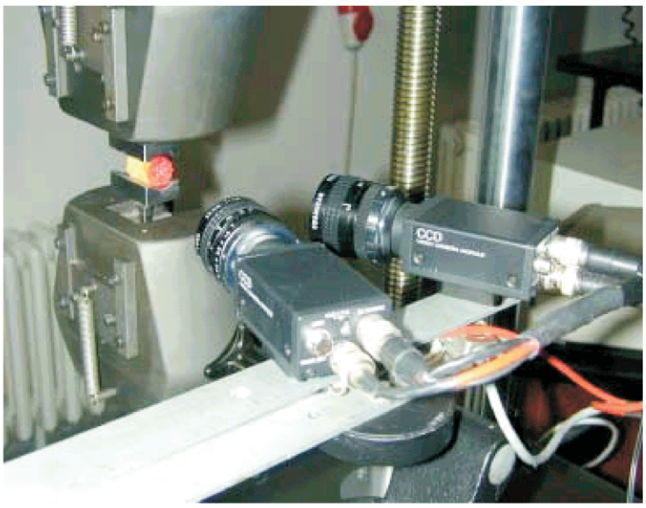

Figure 2. Universal testing machine Messphysik Beta 50–5.

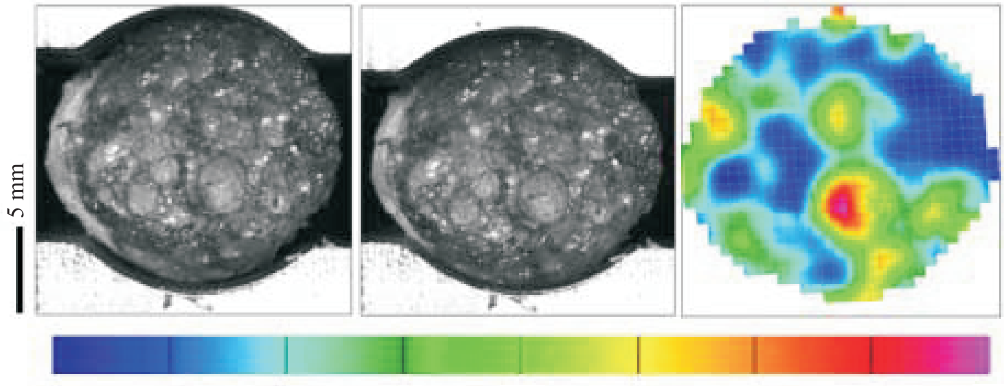

Figure 3. Actual surface deformation.

The characteristics of the stress/strain curves are:

- The first part of the curve is linear; i.e. the sample at the beginning of the experiment withstands the force.
- The small collapses are accompanied by evident hardening of the sample.
- The major specimen collapse occurs immediately after the peak point is reached.

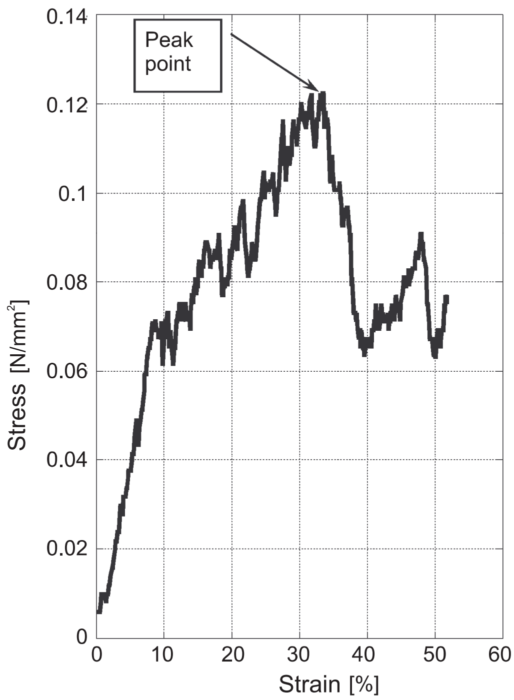

Figure 4. Stress/strain response diagram.

2.3 *Data analysis*

The experimental data (table 1) were analysed using MINITAB Statistical Software, Release 14 for Windows to fit the following model:

$$Y = \beta_0 + \sum_{i=1}^{4} \beta_i x_i + \sum_{i=1}^{3} \sum_{j=i+1}^{4} \beta_{ij} x_i x_j + \sum_{i=1}^{2} \sum_{j=i+1}^{3} \sum_{k=j+1}^{4} \beta_{ijk} x_i x_j x_k + \beta_{1234} \prod_{i=1}^{4} x_i \quad (1)$$

where Y is response (hardness); β_0, β_i, β_{ij} and β_{ijk} are constant coefficients; and x_i are the coded factors. The significance of the effect is given as a p-value. In this study, the effect is considered significant if the p-value for each factor or interaction is less than 0·05.

3. Results and discussion

It is well known that the pressure drop at the end of the die causes the plasticized starch, at temperatures usually above 100°C, to expand by water evaporation, creating foam-like expanded extrudates. The temperature of the extrudates drops during water evaporation, the cooling rate depending on the initial heat content of the extruded material and the difference between its temperature at the die exit and the ambient temperature (Brummer *et al* 2002). At the moment of expansion the material becomes an extrudate, and its properties change. From the textural and mechanical point of view it become plasticized.

Optimal grip speed for specimen deformation of 40 mm/min was chosen, based upon preliminary measurements on 30 specimens (figure 5). The dotted curve was obtained with a grip speed of 20 mm/min, the dashed curve with 30 mm/min and the solid line with 40 mm/min,

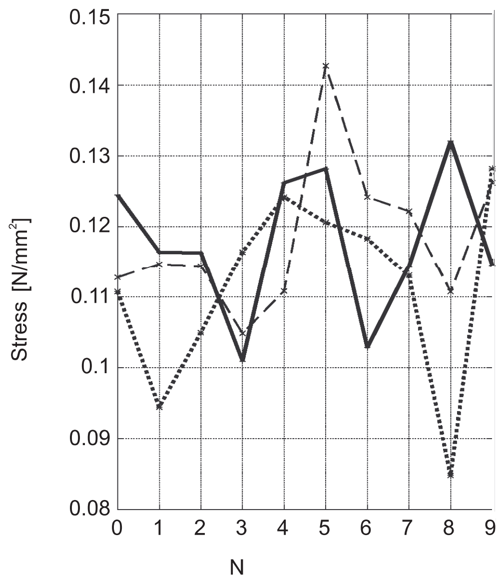

Figure 5. Preliminary determination of grip speed.

Table 2. Analysis of variance.

Source	p-Value
Main effects	0·018*
2-Way interactions	0·153
3-Way interactions	0·269
4-Way interaction	0·295
Curvature	0·074

*Significant, $p < 0.05$

which showing minimal dissipation of the stress results in such a heterogeneous material as criterion for choosing optimal grip speed.

The extrudates used for this experiment are characterized by non-homogeneous, foam-like structures with randomly distributed air holes (bubbles). Therefore, the deformation distribution will not comply with the laws of the mechanics of homogeneous solids. This was clearly confirmed by measuring actual strain distribution on the specimen surface by the grating method. From the results in figure 3, the actual surface deformation after the load application is shown as the strain expressed in percentage of the nominal dimension in real time. It can be seen that the strain distribution of the extruded specimen under the compression test is distributed on a substantially random basis.

A significant distribution of mechanical properties occurs due to a non-uniform displacement of the remaining water within the samples (table 1).

The analysis of the variance for main and interaction effects, together with the curvature check, is shown in table 2. It can be seen that the main effects are significant, but interaction and curvature are not. This result indicates the validity of the pure factorial design in the experimental range analysed, thus second-order models are not necessary.

The estimated effects, coefficients and p-values are shown in table 3. The screw speed, temperature and moisture content are found to have significant effect on the hardness. β-coefficients show that feed moisture content has a positive effect on extrudate hardness, while screw speed and temperature have negative effects. Feed moisture content is found to have the most significant effect on extrudate hardness, with relative effect strength of 0·6567. Screw speed and temperature have the relative effect strength of −0·2592 and −0·2228 respectively. Feed rate is found to have no significant effect. The resulting model, after removing the non-significant terms, is evaluated in terms of dimensional (uncoded) factors and is presented below:

$$\text{Hardness} = 0.747 - 0.001728\, n - 0.004455\, T + 0.1059 MC. \quad (2)$$

The effects of extrusion conditions on extrudate hardness can also seen found in the 3D surface plot (figure 6). The feed rate term is left out since it gives a poorer model (no significant values). The factors are represented in dimensional coordinates (uncoded).

Previous studies have also reported that the hardness of extrudate increases as the feed moisture content increases (Badrie & Mellowes 1991). This might be due to the reduced expansion caused by the increase in moisture content (Liu *et al* 2000).

This use of the innovative procedure of stress-deformation analysis represents its initial application within the food industry for the investigation of the mechanical properties of extruded products.

Table 3. Estimated effects, coefficients and p-values[a].

Factor or interaction	Effect	Coefficient β	p-value
Constant		0·4847	0·002*
n	−0·2592	−0·1296	0·035*
T	−0·2228	−0·1114	0·046*
MC	0·6567	0·3283	0·006*
r	0·0366	0·0183	0·539
$n \times T$	0·1299	0·0649	0·121
$n \times$ MC	−0·1987	−0·0994	0·057
$n \times r$	−0·1123	−0·0561	0·153
$T \times$ MC	−0·1234	−0·0617	0·131
$T \times r$	−0·0541	−0·027	0·391
MC $\times r$	0,0098	0·0049	0·863
$n \times T \times$ MC	0·1058	0·0529	0·168
$n \times T \times r$	0·0616	0·0308	0·342
$n \times$ MC $\times r$	−0·1156	−0·0578	0·146
$T \times$ MC $\times r$	−0·0291	−0·0145	0·618
$n \times T \times$ MC $\times r$	0·0701	0·035	0·295
$SD = 0.09955 R^2 = 99{\cdot}27\%$			

[a] R^2 – coefficient of determination, see table 1 for other abbreviations. *significant, $p < 0.05$.

4. Conclusions

Screw speed, temperature and moisture content are found to have significant effect on the hardness of extrudates. Feed moisture content has a positive effect on extrudate hardness, and screw speed and temperature have negative effects. Feed moisture content is found to have the most significant effect on extrudate hardness. Feed rate has no significant effect.

The object grating method enables visual investigation during compression of the sample, observation of the point of collapse of the sample's structure, and demonstration of the 'plastic' nature of the sample, as opposed to the elastic nature of the mixture inside the extruder. Unfortunately, because of the non-homogeneous nature of that food extrudates, results show non-uniformity. Therefore, this method is recommended for confirming the results of monitoring procedures.

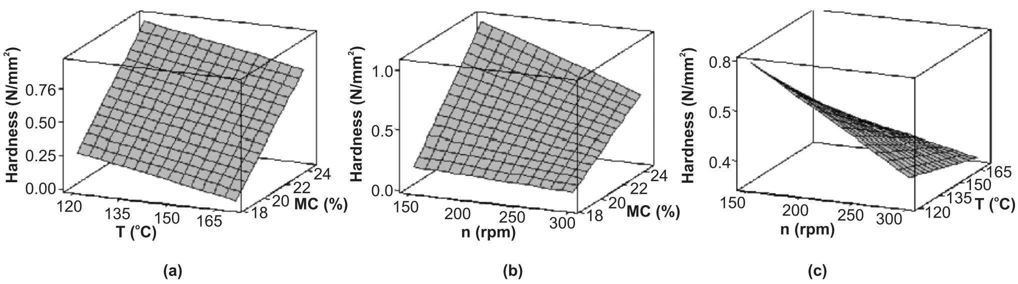

Figure 6. (**a**) Influence of T and MC on hardness of extrudate at screw speed 225 rpm. (**a**) Influence of n and MC on hardness of extrudate at temperature 145°C. (**c**) Influence of n and T on hardness of extrudate at moisture content 21.4%. For abbreviations see table 1.

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