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Grinding Characteristics of Wheat in Industrial Mills

Gheorghe Voicu, Sorin-Stefan Biris,
Elena-Madalina Stefan,
Gabriel-Alexandru Constantin and
Nicoleta Ungureanu

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1. Introduction

Grinding of cereal seeds is due to the mechanical action of several forces: compression, shearing, crushing, cutting, friction and collision, to which seeds are subjected, depending on the design of the mill used for grinding (roller mill, hammer mill, stones mill or ball mill). By applying these forces, when the mechanical resistance of the particles is exceeded, their division happens in a number of smaller particles of different sizes, geometric shapes, masses and volumes.

An industrial wheat mill has several technological phases, starting with coarse grinding of seeds to fine grinding of the resulted milling products, after their sorting in fractions of different sizes. The first technological phase of grinding process, in wheat mills, is gristing or coarse grinding phase, which also consists of several technological passages.

A technological passage consists of a grinding machine (roller mill), a machine for sifting and sorting of the resulted milling fractions (plansifter compartment) and, eventually, a machine for the conditioning of semi-final product (semolina machine or bran finisher). In a technological passage, intermediate fractions are obtained, which, by a new grinding, lead to the obtaining of high-quality flour at milling passages (fine grinding).

Wheat processing requires a long and gradual transformation into flour. This process takes place after a gradual crushing schedule, from fine to finer, from machine to machine, of wheat seed, respectively of the crushed particles resulting from it. Each grinding operation is immediately followed by a sorting operation by sifting (fig.1) because during grinding, a wide variety of grinded seed particles is obtained.

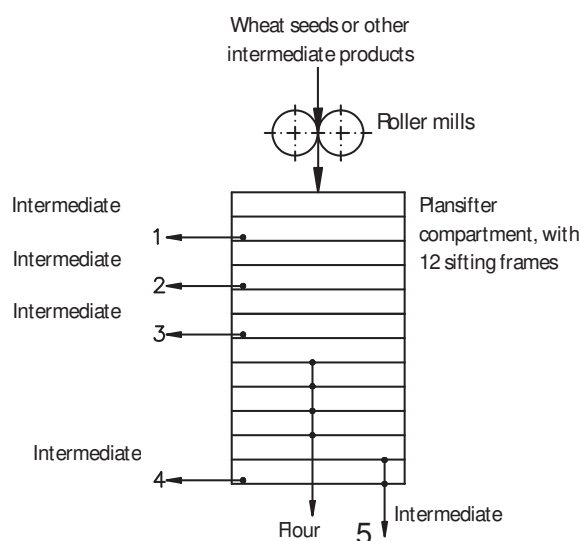


Figure 1. Schematic diagram of a grinding passage

Before the grinding process is started, grains must undergo the cleansing process. This is followed by a conditioning process that ensures a uniform moisture content for the entire lot of grains, helping endosperm softening and cover harshening, which improves the separation process.

One of the fractions resulting from a plansifter compartment is composed of flour particles (with sizes under $160\ \mu\text{m}$), in a higher or lower percentage of the total flour that can be withdrawn in the industrial mill. To extract the full amount of flour from the wheat berries, multiple passes (passages) are required. Some passages are part of coarse grinding phase (gristing), where the milling rollers have fluted surface, while other passages are part of milling phase (fine grinding), where the milling rollers have smooth surface.

Intermediate milling products are, mainly, grists (seed particles with various sizes), semolina (large, average and small) and dunsts (harsh and smooth). They all return in the grinding process for flour extraction, but the grists are grinded by mills with fluted rollers (gristing passages), while semolina and dunsts are grinded by mills with smooth rollers (milling passages). Semolina and dunsts, as intermediate milling products, are particles of clean endosperm or with a small percentage of cohesive coat.

Particles obtained by grinding have sizes in a fairly wide range ($1200\text{--}160\ \mu\text{m}$, within the mentioned fractions), average size of the particles of resulted fraction being determined by granulometric analysis using sieve classifier.

In roller mills, wheat seeds are grinded in the gristing phase by pairs of fluted rollers, thus being obtained a wide range of particles with sizes from $< 200\ \mu\text{m}$ to $> 2000\ \mu\text{m}$, [1], consisting in coat particles (of larger sizes) and endosperm particles (of smaller sizes), to be further separated with plansifters. The milling process aims to grind the endosperm into finer particles of flour and semolina, while the coating and the seed particles must remain in large sizes to be separated by sifting, [2]. In gristing passages, milling rollers with fluted surface are used, and in milling passages, rollers with smooth surface are used. The quality of wheat milling process

is influenced by the physical and mechanical properties of seeds and of the intermediate products (size distribution, seeds hardness, moisture content) and by the design and functional parameters of the roller mill (mutual arrangement of the rollers, differential speed, distance between the rollers, flutes profile, mutual position of the flutes), [3,4]. Effects of these factors are manifested in the size distribution of material particles, compositional distribution of the material, wear degree of the rollers, energy consumed for grinding, [4].

Fang, Campbell et al. (2002) showed that if the distance between rollers increases from 0.3 mm to 0.7 mm, wheat seeds breakage in the gristing phase has a lower intensity, resulting in more particles of large sizes and less particles of smaller sizes. Distance between rollers indirectly influences the specific surface and energy consumption per mass unit and directly influences the specific energy, [5]. Different flutes arrangements on the rollers lead to the obtaining of different size distributions. If the roller flutes are arranged in blade/blade position results in a relatively uniform size distribution, and back to back arrangement lead to a deep parabolic distribution, [1].

Differential speed of milling rollers has a significant effect on the grinding of semolina, flour and wheat bran. With the increase of differential speed of rollers, it also increases the amount of semolina and decreases the amount of flour and wheat bran, [6]. This is due to the difference between shearing and compression forces which are applied on the particles.

It is very important to know the size distribution of the material subjected to grinding, as well of the grist, so that appropriate adjustments can be made to roller mills, and also to choose the fabrics for the sieving frames of plansift compartments. Particles size distribution of the granular material can be determined using superposed sieve classifiers (sieve shakers), with different sizes of sieve holes. This can be assessed by various mathematical functions, from which, most used is the Rosin-Rammler function.

Experiments were performed on the material subjected to grinding (before and after grinding) and cumulative distribution curves were drawn for the sieved material, by computer aided regression analysis of the experimental data with Rosin-Rammler function. Based on the data obtained from particle size distribution were also determined other physical characteristics of the analyzed material: average particle size, grist modulus, specific surface of the granular material, surface increasement resulted from grinding within a passage (break), bulk density and specific mass.

Within this chapter are presented the flow diagrams for two wheat mills of different capacities, one of 100 tons / 24 hours and one of 220 tons / 24 hours, from which it can be estimated the movement of products within the mill.

There are also presented the experimental results obtained from the particles size distribution of the material subjected to grinding and of the resulted grist, in both technological phases, for the two mills, as well as particles size distribution of the material for various grinding machines of the analyzed mills.

Knowing of the mechanical characteristics of wheat seeds and of the grist particles, and also their size characteristics, volume and mass of the wheat seeds, is useful for estimating the energy required for crushing.

For this purpose, in this paper are presented the results of some experimental research on the behaviour of wheat seeds in uniaxial compression tests between parallel plates. There are also presented the curves of variation for the crushing force and energy absorbed until the crushing point of seeds.

The results presented and the obtained data are of real interest for the designers of roller mills, as well as for the manufacturers and users of such machines.

2. Technological diagrams for wheat grinding

The technological passage consists of one or two pairs of milling rollers, both processing the same product, combined with one or more plansifter compartments for sieving.

Gristing is the technological phase aiming to fragment the wheat seed in particles of different sizes and to remove the endosperm from the coating. Particles resulted from first, second and third grinding phase vary in size, from breakages like half seeds to flour particles with very fine granulometry. As gristing is repeated, particles will get increasingly finer, the amount of white flour decreases, and seeds coating reaches the penultimate and last phase as fine dust, [7]. Thus, grist is the intermediate product obtained in the milling industry, by grinding grains by mean of roller mills with fluted surface.

Fig. 2 presents the technological diagram of gristing phase of the wheat in an industrial mill with the capacity of 220 t/24 h.

Milling unit consists of 9 double roller mills, of which the first processes, in both sections, the same material (whole seeds), two plansifters, together amounting 14 compartments, three double semolina machines and five brushes and bran finishers. The three phases of the process (gristing, milling, sorting) can be observed in fig.3 – fig.5.

Gristing phase consists of six simple mills with fluted rollers, four full and two half's of plansifter compartments and four bran finishers which process the coatings resulted from multiple grinding operations. The seeds are processed in a mill with double rollers placed in horizontal plane, noted by B1–B2.

The first grist is processed in passage B3, and the fractions obtained here will follow different routes, to the milling passages, or to the semolina machines or bran finishers, passages B4gr and B5f being responsible for the processing of material particles with high coating content, and passage B4f processes the second refuse from gristing passage B3, with fractions having the same characteristics processed in plansifter compartments. The development of gristing phase is directly connected to the type of meal and the degree of flour extraction. Products resulted from gristing are named intermediate products and they consist of: big grist, fine grist, big semolina, middle semolina, fine semolina, big dunst, soft dunst, flour and bran, [7].

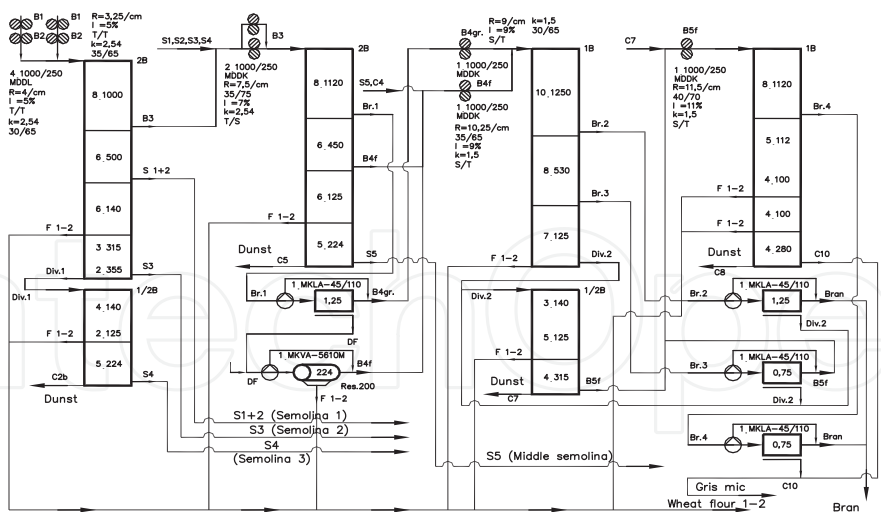


Figure 2. Technological diagram of gristing phase for a Bühler mill with capacity of 220 t / 24 h, [8]

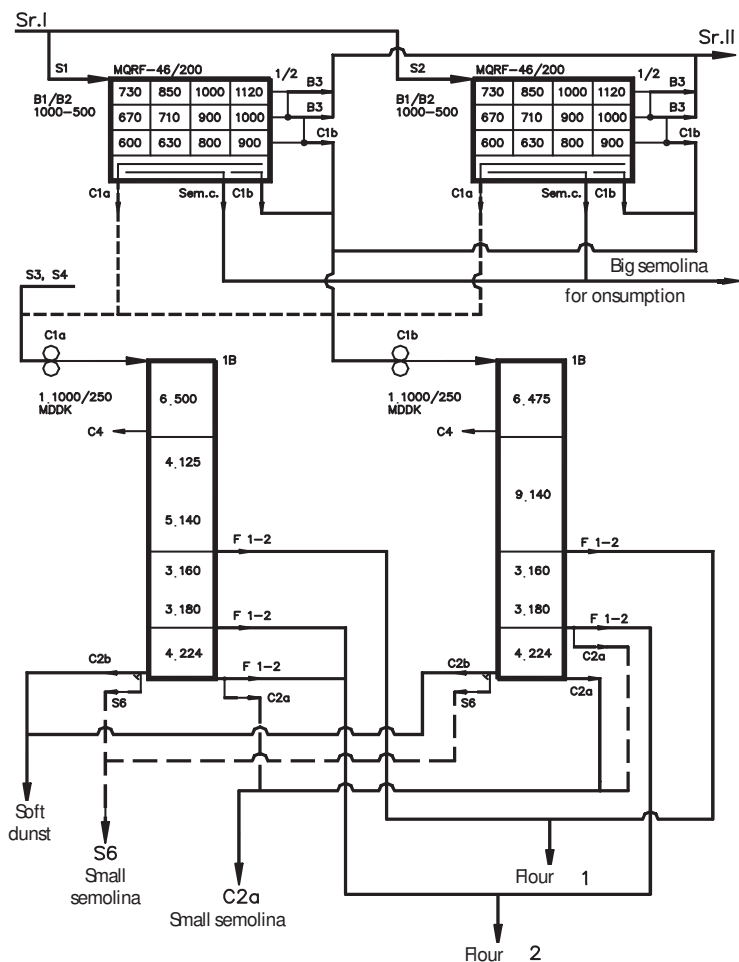


Figure 3. Technological diagram for sorting of big semolina in Bühler mill, [7]

Particles size of these components, resulted from sieving process, is determined by the size of the sieve holes used in sieving compartments. Depending on the particles size, semolina and dunsts can be classified as: big semolina with average size of 1200-630 μm ; middle semolina 630-400 μm ; fine semolina 400-310 μm ; big dunsts 310-245 μm ; soft dunsts 245-160 μm . Semolina sorting is done in sorting phase (fig.2.) A clear delineation between soft dunsts and flour can not be practically achieved, and therefore, are cases when soft dunsts ($d_m = 220 \mu\text{m}$) are considered to be flour (flours granulosity is given by the sieves, with mean equivalent size of the particles below 160 μm).

Particles of intermediate products can be highlighted not only by their size, but also by shape, volume, specific mass, aerodynamic properties. Particles with rich coating have irregular shape in the form of foils with rolled or folded edges. Particles of clean endosperm have polyhedral shape with sharp edges and convex lateral surfaces.

Semolina is an intermediate product obtained in percentage of 25...30% in industrial wheat milling, is found as small granules and after cleaning is further milled to obtain flour or a food product known as "kitchen semolina". This is obtained in percentage of 2...3 % at wheat milling and it is cleaned in special semolina machines in order to remove coating particles by the combined action of sieving and airflows. Dunst is a fine semolina obtained as intermediate product from the grinding of wheat or semolina.

After gristing phase it is important to sort the milling products using a wide range of sizes for sieve holes (1000...224 μm), followed by the cleaning of semolina and dunsts, the phase of semolina opening being no longer necessary, since most coating was already removed in the gristing phase (fig.3).

The unit is fully automated, all mill equipments starting and stopping from the computer, starting with the equipments from the final technological phases (bagging, flour homogenization, sieving with plansifters, semolina cleaning, bran finishers, etc.) from the circuit of flour or intermediate products, while stopping begins with the first pair of rollers, i.e. reverse of start up.

In fig.4 and fig.5 is presented the technological flow for a wheat mill with capacity of 100 t/24 h, in grinding phases (fig.4) and in the milling (breakage) phase of semolina (fig.5), [10].

The technological flow of wheat mill is ensured by 12 processing passages, with 12 pairs of milling rollers (6 double rollers of Buhler type) from which 5 gristing passages and 7 milling passages. In addition, the technological flow is fitted with a sorting passage (separate compartment of plansifter).

Apart from the 12 technological passages, each consisting in a pair of roller mills and one plansifter compartment, the mill also has a double machine for semolina, three bran finishers and other auxiliary equipments (detachers, wheat brushes, filters and cleaning cyclones, etc.), as well as the proper elements for the pneumatic transport system from one equipment to another, according to the technological flow.

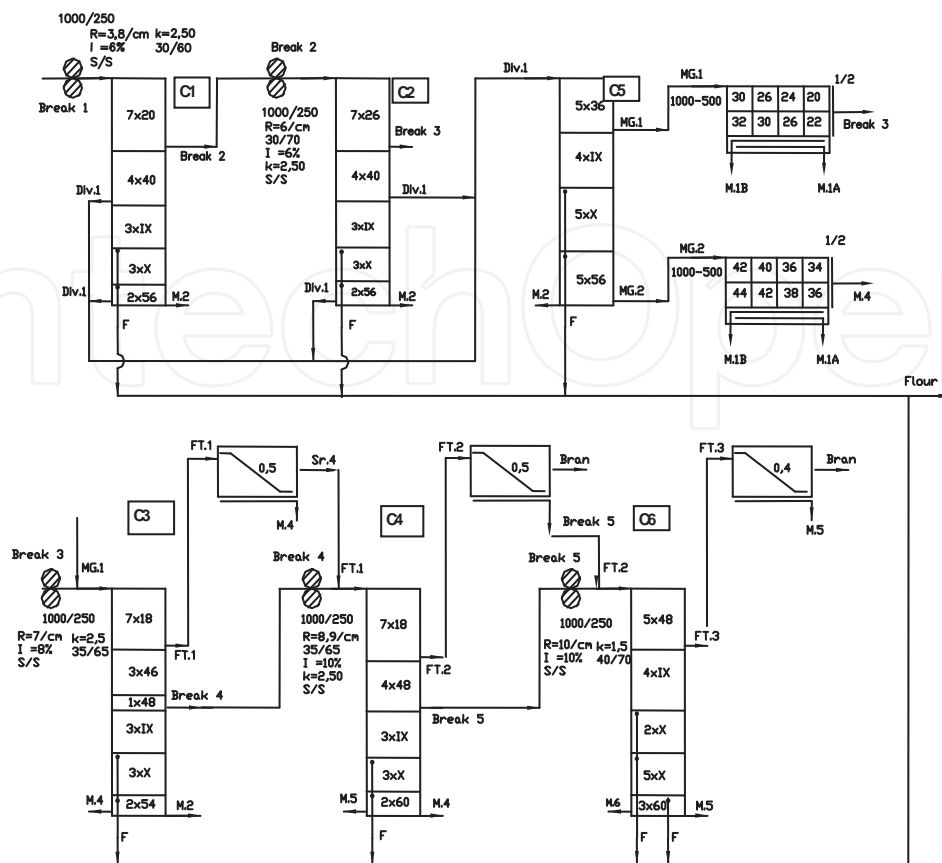


Figure 4. Technological flow of semolina grinding phase in wheat mill, capacity of 100 t/24 h, [11]

In breakage phase the technological diagram of mill contains five pairs of rolls, filled with one compartment of plane sieve, two semolina machines and three wheat bran finishers. The technological breakage phase is completed with one compartment of plane sieve without grinding machine, in which the material is sorted by fractions of different sizes as well as the other compartments of plane sieve.

The first grist, obtained from seeds processing with the pair of fluted rollers Sr.1, is processed in passage Sr.2, and from here the fractions follow various routes, to grinding passages, to semolina machines to wheat bran finishers. The sifting material from the second and the last set of gristing passage Sr.1, is send to a plansifter compartment for division in fractions (Div.1), which next reach the MG1 and MG2 semolina machines. The refuse from the last set of frames in the first passage is then sent to the M2 grinding passage.

The circulation of grist intermediate products in the technological diagram is shown in fig.4 and fig.5.

In the grinding phase (fig.5), the technological diagram of milling unit consists of seven simple roller mills, each fitted with one plansifter compartment for sorting in fractions of the grinded products and the extraction of flour from these products.

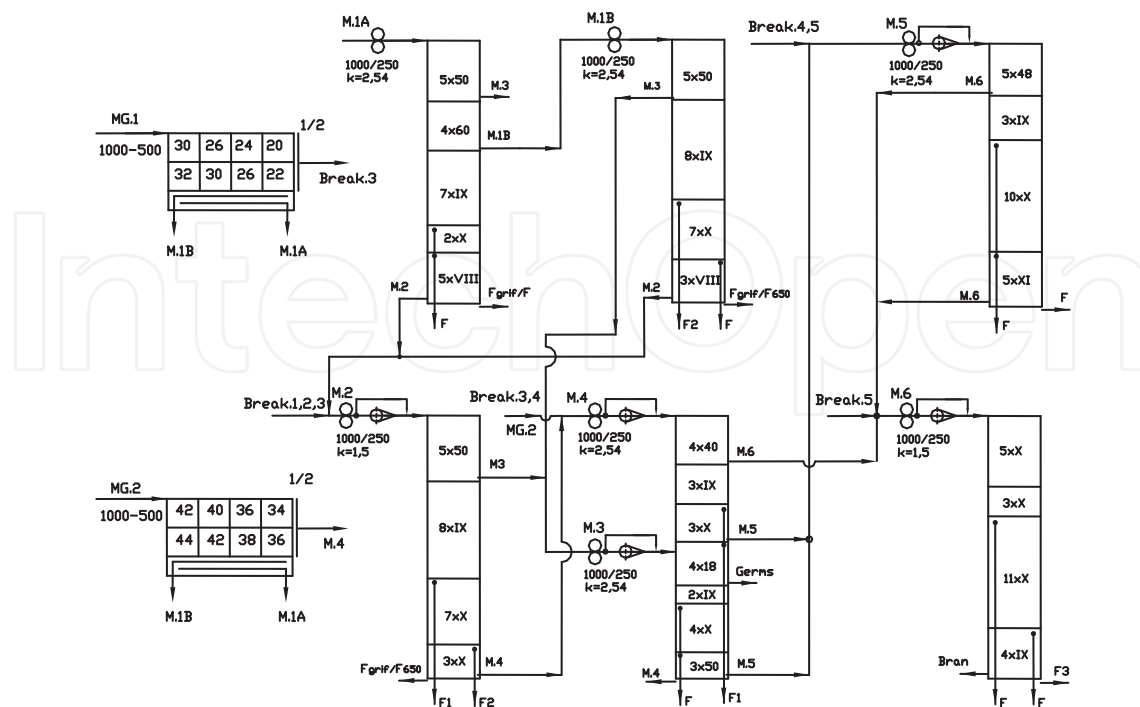


Figure 5. Technological flow of the semolina grinding phase in a wheat mill with 100 t/24 h, [9]

All roller mills of both technological phases have the length of 1000 mm and diameter of 250 mm, with fluted surface, in the gristing phase, respectively smooth surface without flutes in the grinding phase. In the gristing phase, the ratio of the tangential speeds of fluted rollers is $k=2.54$, and in the grinding phase, for five pairs of rollers, $k=2.54$, and for two pairs of rollers $k=1.5$.

As shown in fig.5, the products to be grinded into the grinding phase are products arriving from gristing phase (or breakage phase), inclusive from grists (Sr.1-6) or from semolina machines and bran finishers. The siftings from MG1 and MG2 semolina machines, which are semolinas with sizes below 0.8-1.0 mm, are grinded in the first technological passages M1A and M1B, while the siftings from FT1 and FT3 bran finishers go to the last two grinders M4 and M5, which processed products with higher content of bran. In diagram, the first refusal from M1A and M1B grinders is led to M3 grinder, working with half compartment of plane sieve. It is noted that to grinders which grinded smaller particles of endosperm (about 0.40 mm), after the mill rollers in technological flow are placed detached of material, due to agglomerations arising from the compression of smaller particles of endosperm in the action zone of grinding rolls.

In fig.6 is shown the arrangement of rollers to a mill with 100 t /24 h capacity, where the samples for our determinations were collected.

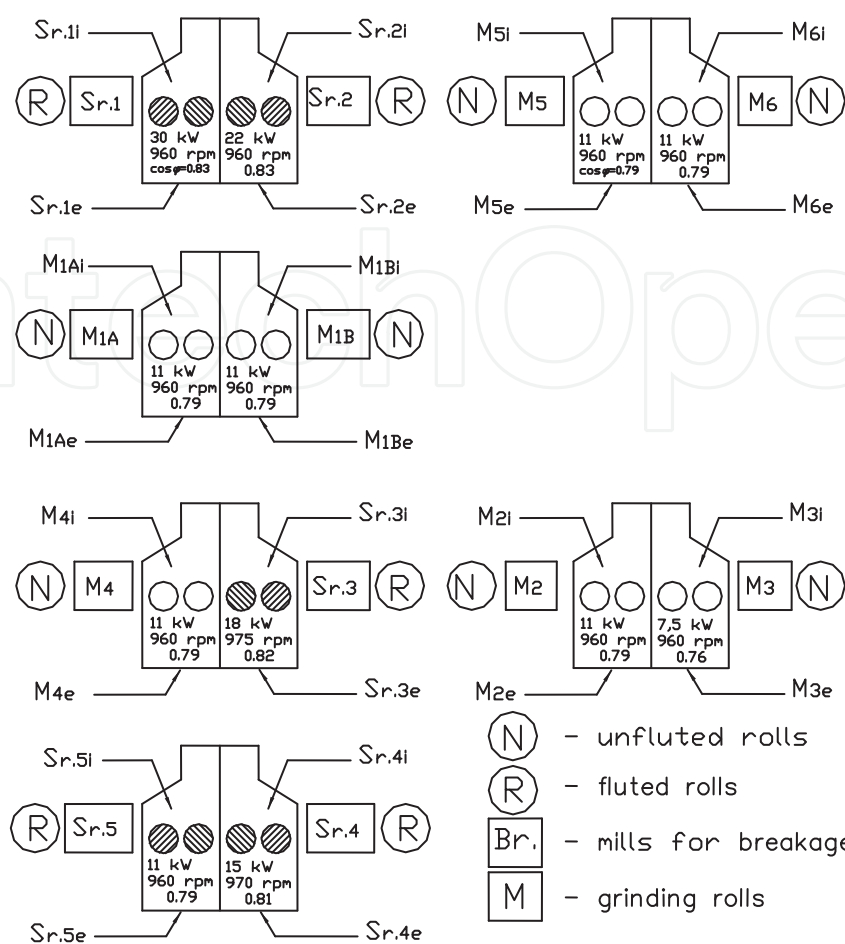


Figure 6. Arrangement of roller mills for the mill with capacity of 100 t / 24 h

Plansifters are driven by electric motors of 4 kW, $\cos \varphi = 0,81$ and speed of 960 rot/min. Double machine for semolina is driven by two moto-vibrators of 400 W and speed of 960 rpm. Characteristics of driving motors for mill rollers are given in table 1.

| Passage | I (A) | | P, kW | n, rpm | cos φ | Passage | I (A) | | P, kW | n, rpm | cos φ |
|---------|---------|------|-------|--------|-------|---------|---------|------|-------|--------|-------|
| | No-load | Load | | | | | No-load | Load | | | |
| Sr. 1 | 19 | 45 | 30 | 960 | 0.83 | M1 B | 10 | 15 | 11 | 960 | 0.79 |
| Sr. 2 | 21 | 37 | 22 | 960 | 0.83 | M2 | 11,9 | 16 | 11 | 960 | 0.79 |
| Sr. 3 | 23 | 32 | 18 | 975 | 0.82 | M3 | 10,9 | 18 | 7,5 | 960 | 0.76 |
| Sr. 4 | 13 | 30 | 15 | 970 | 0.81 | M4 | 10,9 | 15 | 11 | 960 | 0.79 |
| Sr. 5 | 13 | 17 | 11 | 960 | 0.79 | M5 | 12 | 16 | 11 | 960 | 0.79 |
| M1 A | 10 | 15 | 11 | 960 | 0.79 | M6 | 12 | 17 | 11 | 960 | 0.79 |

Table 1. Characteristics of electric motors for the drive of mill rollers, for wheat mill with capacity of 100 t/24 h [9]

According to relevant regulations, on the technological diagram (fig.4 or fig.5) should be written the characteristics of grinding rollers: length, diameter (ex.1000x250, in mm), number of flutes and their inclination (ex.7/cm, I=8%), flute angles (ex.35/65), mutual arrangement of the flutes (ex.S/S), speed ratio (ex.k=2.5), and the characteristics of fabrics used in plansifter frames (ex.3x46 – 3 frames with 46 wires per inch or 3xX for flour frames), at semolina machines (ex.42, which represents the number of wires per inch or 1000-500, which is frame size) or at bran finishers (ex.0.5 – size of fabric hole).

Sieve frames from top of compartments are fitted with metal mesh as they separate seed brokens of relatively large sizes (which would wear quite quickly the textile fabrics), while flour frames from the lower set are fitted with frames with plastic or textile fabrics.

Lately, textile fabrics have been replaced with sieve frames with meshes of plastic fabric. According to literature, for the technological diagram of the analyzed mill, the equivalence between the sieve number and the size of its holes, as they are specified in the diagram, is shown in table 2.

| | | | | | | | | | | | | | | | |
|----------------|------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|-----|-----|-----|
| Sieve no. | 18 | 20 | 26 | 36 | 40 | 46 | 48 | 50 | 54 | 56 | 60 | VIII | IX | X | XI |
| Hole size (µm) | 1170 | 1050 | 780 | 520 | 470 | 390 | 370 | 350 | 320 | 310 | 280 | 180 | 170 | 150 | 130 |

Table 2. Equivalence between sieve number and hole sizes

3. Physical and granulometric characteristics of seeds and grinding products

In the grinding process is necessary to know the physico-mechanical characteristics of the material at the entry and exit from a processing machine, in this case, roller mills.

Main factors influencing the process of grain grinding are the physico-mechanical properties of seeds and of the grinding products, the constructive and functional characteristics of the grinding machines as well as the technological regime, most of those factors having a random character.

As a result of grinding it is obtained a mass of particles with various smaller sizes and different geometrical shapes (grist).

Granulometric distribution of the grinded material and of the material leaving the grinding process can be assessed by the cumulative weight (%) of material passing through the sieve holes of classifier T(x) or which are refused by its sieves R(x), calculated on base of mass weight (%) of the fractions from the sieve. (R(x)+T(x)=100). The mathematical expression of granulometric distribution in case of grinded biological materials, is based on laws of mathematical statistical method of small particles, [11-14].

There will be defined three usual types of laws of cumulative granulometric distribution.

- The Rosin-Rammler distribution, for material particles with larger sizes than sieve holes, is expressed by the relation:

$$R(x) = 100 \cdot e^{-bx^n} \quad (1)$$

where: $R(x)$ is the mass percentage weight of fraction with larger particles than x (which remained on the sieve with meshes with size x); x – is the sieves meshes size by which the particles rest; b and n are the own coefficients of grinding material.

- The Schuhman distribution is defined by the relation:

$$R(x) = 100 \cdot \left\{ 1 - \left(x/k \right)^a \right\} \quad (2)$$

where: $R(x)$ and x have the significance from to relationship (1), k - the module product particles size (the size of sieve mesh through which, theoretical, pass all the sample particles (100%)), a - the distribution module.

- The logistics type distribution with two parameters is defined by the relation:

$$R(x) = 100 \cdot \frac{e^{\alpha + \beta x}}{1 + e^{\alpha + \beta x}} \quad (3)$$

where: $R(x)$ and x have the significance from relationships (1-3) α and β are logistical constants.

Of these characteristics are important: the bulk density, ρ_v (kg/m³), of the material to be processed, the density of the material, ρ (kg/m³); the equivalent sizes of material particle at entry and exit of the grinding machine, d_m (mm); angle of internal friction of particles appreciated by natural slope angle, ψ (°); angle of material friction with the surfaces working components, φ (°); material porosity, ε (%) and others.

Of particular importance is the equivalent size of seeds subjected to grinding in the first technological passage.

The density is the ratio between the sample mass and the volume of the particle in it. To determine the densities of wheat seeds, respectively the grinding products, the pycnometrical method was used (xylene 0.8254 kg/cm³).

The porosity is the property of granular materials, respectively of the grains, to not occupy the entire volume of storage, with an intergranular space. Knowing the values of bulk density and material density, the porosity was evaluated using the following relation, [15]:

$$\varepsilon(\%) = (1 - \rho_v / \rho) \cdot 100 (\%) \quad (4)$$

The static friction coefficient. The most common method for determining the coefficient of static friction is inclined plane method which was used in this paper. It was used a device with adjustable incline plane, [15]. Two sets of determinations were realized on three types of surfaces: glossy fiberglass, steel sheet and cotton canvas.

Assessing parameters of the grinding process are: grinding degree, grinding finesse and specific energy consumption at grinding.

Grinding degree and grinding finesse are determined by granulometric analysis, using a sieve overlay classifier with oscillatory movement.

Grinding degree is defined by the λ index and represents the ratio between equivalent sizes of particles before and after grinding, D_e , respectively d_m , or the ratio between the outer surface of the particles resulted in the grinding process and the initial surface of the particle subjected to grinding, S_f , respectively S_i :

$$\lambda = D_e / d_m = S_f / S_i \quad (5)$$

Absolute value of the increase of particles outer surface in the grinding process ΔS , is given by:

$$\Delta S = S_f - S_i = S_i(\lambda - 1) \quad (6)$$

The grinding finesse has been appreciated by the geometric mean diameter d_m of the grinding particles which was determined by the size distribution analysis, using the relation of weighted average:

$$d_m = (1 / 100) \cdot \sum_{i=0}^n p_i d_i, \quad (7)$$

where: p_i is mass weight of fraction remaining on the sieve i of the classifier, d_i is diameter (average value) of fractions particle on the sieve i , considered the arithmetic average of the sieves holes size that contain fraction i .

The surface area and the surface increase. Knowing the mean diameter of particles of a granular mixture, their specific surface $S_{e.m}$ is determined with the relation, [10,15]:

$$S_{e.m.} = 6 / \rho \cdot d_m \text{ (m}^2 \text{ / kg)}, \quad (8)$$

where: ρ is the density of the particles.

There are presented the results of some experimental research on the physical characteristics of grinding products on the technological flow of gristing phase of wheat from a mill with capacity of 100 t / 24 h (SC Spicul Rosiori de Vede, Teleorman, Romania).

The material tested in the experiments was taken from the entry, respectively from the exit of each pair of milling rollers (from the five pairs of the phase).

The experimental data characterizing the physical properties of the grist obtained are shown in table 3. Also, in table 4 and table 5 are presented the results of size distribution analysis on mixtures of material entering and leaving the rolls placed in the technological grinding phase.

| Break | | Static friction coefficient μ | | | Natural slope angle ψ |
|-------|---|-----------------------------------|-------------------|-------------|----------------------------|
| | | Cotton canvas | Glossy fiberglass | Steel sheet | |
| M1A | E | 1.74 - >1.76 | 68,7 | 0.61 – 0.85 | 39,43 |
| M1B | I | 1.24 – 1.82 | 56,4 | 0.45 – 0.67 | 30,19 |
| M2 | I | >1.76 | 61 | 0.6 – 0.86 | 43,97 |
| M3 | E | >1.76 | 72,4 | 0.58 – 0.82 | 38,35 |
| M4 | E | >1.76 | 67,5 | 0.58 – 0.73 | 41,96 |
| M5 | I | >1.76 | 64,3 | 0.60 – 0.88 | 46,62 |
| M6 | E | >1.76 | 69,5 | 0.54 – 0.71 | 40,17 |

Table 3. The values of static friction coefficient and natural slope angles [15]

From table 3 it is noted that the static coefficient values, on the glossy fiberglass and metal are within the limits set in various specialized papers, while the values obtained in the experiments on cotton canvas fall in broad limits, probably due to material fractions moisture, but also because of its granularity, this phenomenon is observed, especially, to flours and relatively small particle fractions of endosperm.

| l_i (mm) | M1A - I | | M1A - E | | l_i (mm) | M1B - I | | M1B - E | |
|-------------------|-----------|-------------------|-----------|-------------------|---------------|-------------------|-----------|-----------|-----------|
| | p_i (%) | T_i (%) | p_i (%) | T_i (%) | | p_i (%) | T_i (%) | p_i (%) | T_i (%) |
| 0,00 | 0,90 | 0,00 | 34,40 | 0,00 | 0,00 | 0,40 | 0,00 | 7,70 | 0,00 |
| 0,18 | 1,00 | 0,90 | 16,30 | 34,40 | 0,13 | 0,60 | 0,40 | 8,00 | 7,70 |
| 0,25 | 3,70 | 1,90 | 10,30 | 50,70 | 0,18 | 3,90 | 1,00 | 23,80 | 15,70 |
| 0,32 | 33,30 | 5,60 | 15,80 | 61,00 | 0,25 | 22,10 | 4,90 | 35,60 | 39,50 |
| 0,50 | 49,10 | 38,90 | 12,50 | 76,80 | 0,32 | 48,90 | 27,00 | 21,90 | 75,10 |
| 0,71 | 12,00 | 88,00 | 10,70 | 89,30 | 0,40 | 24,10 | 75,90 | 3,00 | 97,00 |
| $d_{M1AI} = 0,55$ | | $d_{M1AE} = 0,33$ | | $d_{M1BI} = 0,36$ | | $d_{M1BE} = 0,26$ | | | |

Table 4. The ponder values (p_i) of the fractions from the sieving machine classifier sieves and of the cumulative weights T_i (%) for the collected gritting, at entrance "I" and exit "E" from the mentioned rolls (only M1A, and M1B), [9]

| Break | Equivalent size(I/E) | Grinding degree | Bulk density | True density | Specific surface | Surface increase | Porosity |
|-------|----------------------|-----------------|-------------------|-------------------|-------------------------------------|-------------------------------------|-----------|
| | mm | λ | g/dm ³ | g/dm ³ | x10 ³ m ² /kg | x10 ³ m ² /kg | % |
| M1A | 0,55-0,33 | 1,68 | 560,0-389,5 | 1344,9-1247,1 | 8,13-14,72 | 6,595 | 58,3-68,7 |
| M1B | 0,36-0,26 | 1,385 | 583,5-499,0 | 1338,7-1372,0 | 12,34-16,72 | 4,38 | 56,4-63,6 |
| M2 | 0,19-0,17 | 1,113 | 480,5-437,5 | 1233,3-1313,4 | 26,04-27,55 | 1,513 | 61-66,7 |
| M3 | 0,35-0,45 | 0,788 | 363,5-308,5 | 1252,9-1119,8 | 13,55-11,95 | -1,605* | 71-72,4 |
| M4 | 0,22-0,24 | 0,940 | 452,5-419,5 | 1290,6-1290,6 | 21,02-19,76 | -1,252* | 64,9-67,5 |
| M5 | 0,22-0,24 | 0,924 | 430,5-419,5 | 1205,4-1210,2 | 22,74-20,89 | -1,854* | 64,3-65,3 |
| M6 | 0,24-0,27 | 0,903 | 416,0-373,0 | 1274,4-1224,5 | 19,40-18,23 | -1,164* | 67,4-69,5 |

The sign * in table 3, for negative values of specific surface increases, means that at the passage through milling rollers with smooth surface, agglomeration of gritting particles occurs.

Table 5. The values of grinding degree, specific surface, surface increase and porosity

Based on the data obtained from the experiments and presented in table 6, were mapped graphics, using MS Excel version 7.0 program (fig.6), the variations of mean diameter and bulk density to technological breakage passage of milling unit.

| Physical characteristic | Sr.1-I | Sr.1-E | Sr.2-I | Sr.2-E | Sr.3-I | Sr.3-E | Sr.4-I | Sr.4-E | Sr.5-I | Sr.5-E |
|---|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Bulk density, ρ_v (kg/m³) | 713.0 | 381.5 | 482.0 | 346.5 | 267.8 | 292.0 | 255.0 | 257.0 | 269.0 | 266.0 |
| Density, ρ (kg/m³) | 1239 | 1250 | 1219 | 1200 | 1100 | 1063 | 1016 | 1130 | 1100 | 1191 |
| Equivalent size, (mm) | 3.76 | 2.13 | 2.23 | 1.22 | 1.51 | 0.90 | 1.06 | 0.84 | 0.65 | 0.63 |
| Grinding degree, λ | 1.76 | | 1.83 | | 1.67 | | 1.26 | | 1.03 | |
| Specific surface, (m²/kg) | 1.29 | 2.25 | 2.21 | 4.10 | 3.61 | 6.27 | 5.57 | 6.32 | 8.39 | 8.00* |
| Surface increase, ΔS (m²/kg) | 0.96 | | 1.89 | | 2.66 | | 0.75 | | -0.39* | |
| Natural slope angle, ψ (gr.) | 21.8 | 37.8 | 37.1 | 37.5 | 44.6 | 39.0 | 41.1 | 39.2 | 42.6 | 44.4 |
| Porosity, ε (%) | 42.5 | 69.5 | 60.5 | 71.1 | 75.7 | 72.5 | 74.9 | 77.3 | 75.5 | 77.7 |

Table 6. Physico-mechanical characteristics of grinding products at gristing passages of wheat, from the mill with capacity of 100 t / 24 h, [10]

Correlation between individual volume of the seeds, calculated with the relation: $V = (1/6) \pi l w t$ (where: l, w, t represent the measured length, width, and thickness of each seed, and the seeds are assimilated with ellipsoid geometrical bodies) and their weight is presented in fig.7.

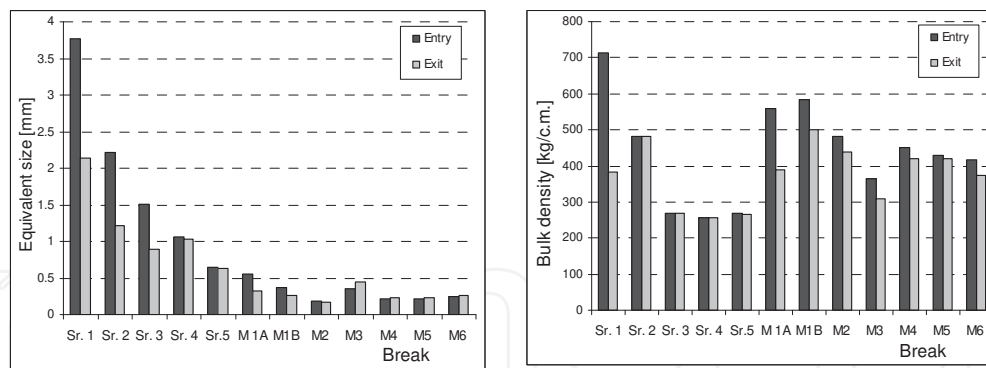


Figure 7. Variation of mean diameter and bulk density of grinding intermediate products on the grinding technological flow with grinding rollers [15]

Sieves used in granulometric analysis with sieve classifier and the results obtained by analysis are given in table 7, for each of the five technological passages, at the entry end exit from the respective mill rollers.

| l_i (mm) | Sr.1 - E | | l_i (mm) | Sr.2 - I | | Sr.2 - E | | l_i (mm) | Sr.3 - I | | Sr.3 - E | |
|--------------------|------------|-----------|--------------------|-----------|-----------|--------------------|-----------|--------------------|--------------------|-----------|--------------------|-----------|
| | p_i (%) | R_i (%) | | p_i (%) | R_i (%) | p_i (%) | R_i (%) | | p_i (%) | R_i (%) | p_i (%) | R_i (%) |
| 0.00 | 24.20 | 0.00 | 0.00 | 2.00 | 0.00 | 34.70 | 0.00 | 0.00 | 13.40 | 0.00 | 43.10 | 0.00 |
| 1.00 | 8.40 | 24.20 | 0.71 | 6.00 | 2.00 | 11.50 | 34.70 | 0.71 | 22.50 | 13.40 | 20.60 | 43.10 |
| 1.40 | 15.10 | 32.60 | 1.00 | 19.20 | 8.00 | 22.20 | 46.20 | 1.00 | 22.80 | 35.90 | 23.00 | 63.70 |
| 2.00 | 20.10 | 47.70 | 1.40 | 13.90 | 27.20 | 11.50 | 68.40 | 1.40 | 12.00 | 58.70 | 5.10 | 86.70 |
| 2.80 | 27.00 | 67.80 | 2.00 | 29.50 | 41.10 | 14.90 | 79.90 | 2.00 | 20.10 | 70.70 | 7.20 | 91.80 |
| 4.00 | 5.20 | 94.80 | 2.80 | 29.40 | 70.60 | 5.20 | 94.80 | 2.80 | 9.20 | 90.80 | 1.00 | 99.00 |
| $d_{1E} = 2.13$ mm | | | $d_{2I} = 2.23$ mm | | | $d_{2E} = 1.22$ mm | | $d_{3I} = 1.51$ mm | | | $d_{2E} = 0.90$ mm | |
| | l_i (mm) | Sr.4 - I | | Sr.4 - E | | l_i (mm) | Sr.5 - I | | Sr.5 - E | | | |
| | | p_i (%) | R_i (%) | p_i (%) | R_i (%) | | p_i (%) | R_i (%) | p_i (%) | R_i (%) | | |
| | 0.00 | 26.00 | 0.00 | 42.60 | 0.00 | 0.00 | 5.20 | 0.00 | 5.80 | 0.00 | | |
| | 0.71 | 25.20 | 26.00 | 27.50 | 42.60 | 0.25 | 3.90 | 5.20 | 3.90 | 5.80 | | |
| | 1.00 | 28.30 | 51.20 | 20.70 | 70.10 | 0.32 | 21.10 | 9.10 | 22.60 | 9.70 | | |
| | 1.40 | 11.90 | 79.50 | 3.60 | 90.80 | 0.50 | 28.20 | 30.20 | 29.70 | 32.30 | | |
| | 2.00 | 7.80 | 91.40 | 5.00 | 94.40 | 0.71 | 35.30 | 58.40 | 32.70 | 62.00 | | |
| | 2.80 | 0.80 | 99.20 | 0.60 | 99.40 | 1.00 | 6.30 | 93.70 | 5.30 | 94.70 | | |
| $d_{4I} = 1.06$ mm | | | $d_{4E} = 0.84$ mm | | | $d_{5I} = 0.65$ mm | | | $d_{5E} = 0.63$ mm | | | |

Table 7. Values of weights (%) p_i for the fractions on the shaker sieves of the sifter machine and of the cumulative percentages R_i (%) for the collected grinded products, at entry "I" and exit "E" from pairs of mentioned rollers (Sr.1... Sr.5), [10]

Based on the results obtained by granulometric analysis with the sieve classifier were tested by nonlinear regression analysis, the three laws of cumulative distribution for the refuse of the sieves $R(x)$ (Rosin-Rammler function, Schuhman function and two parameters logistical function), for products entering the process, and for the products leaving the pairs of rollers, in the gristing phase of the grinding process. Experimental points and the curves of cumulative distribution for the refuse of the sieves ($R(x)$), using the three functions (eq.1, eq.2, eq.3), for some grinding products are presented in fig.8.

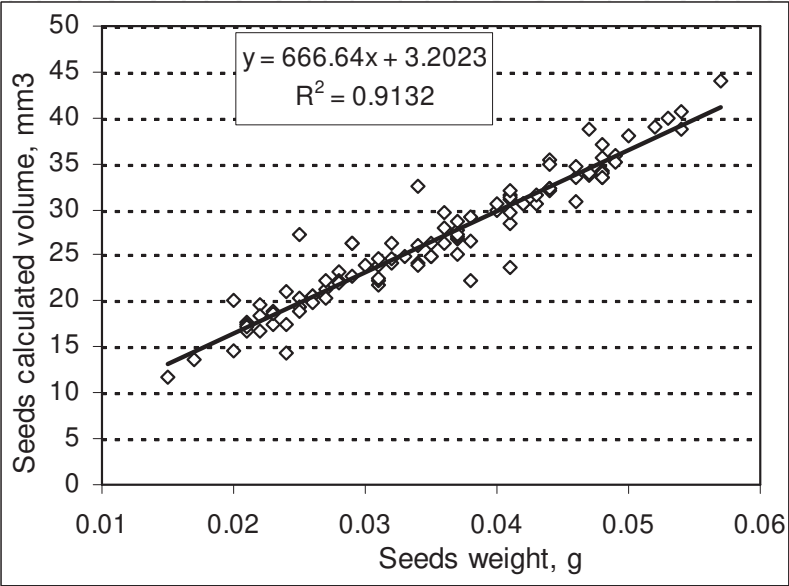


Figure 8. Correlation between volume and the mass of wheat seeds in an technological mixture (before grinding) [16]

The coefficient values k , a , b , n , α and β , from the cumulative distribution relations Rosin–Rammler, Schuhman and the two parameters logistical function, as well as the R^2 correlation coefficient values (which verifies the distribution adequacy degree expressed through the (1), (2), (3) relations), correspondent for the nine analyzed probes (from the five roll pairs) are presented in table 8.

From the analysis and interpretation of the obtained data for the 9 probes, which come from the mill rolls with rifles (for the coarse gritting in the breaking passages) (fig.9), following conclusions were found:

- For the vast analyzed material probes, from the mills flux, the best law of cumulative distribution is the Rosin-Rammler (1) with a correlation coefficient $R^2 \geq 0.982$, time in which the Schuhman type distribution law with a correlation coefficient $R^2 \geq 0.933$ (usually $R^2 \geq 0.956$) can be used with satisfactory results, in these cases;
- For the two parameter distribution law, the R^2 correlation coefficient presents close values from the ones obtained through the Rosin-Rammler function, $R^2 \geq 0.963$, at half the probes being very close;

- The total grinding degree of the wheat breakage phase at the analyzed mill is approximately $\lambda = 7$, correspondent to a coarse gritting (crushing);
- It is appreciated that, in all cases, at seeds wheat grinding in the complex roller mills, we can consider that the best law of distribution is the Rosin-Rammler (1), ($R^2 \geq 0,982$), but the other methods, Schuhman and two parameter logistic, also can be used with satisfactory results.

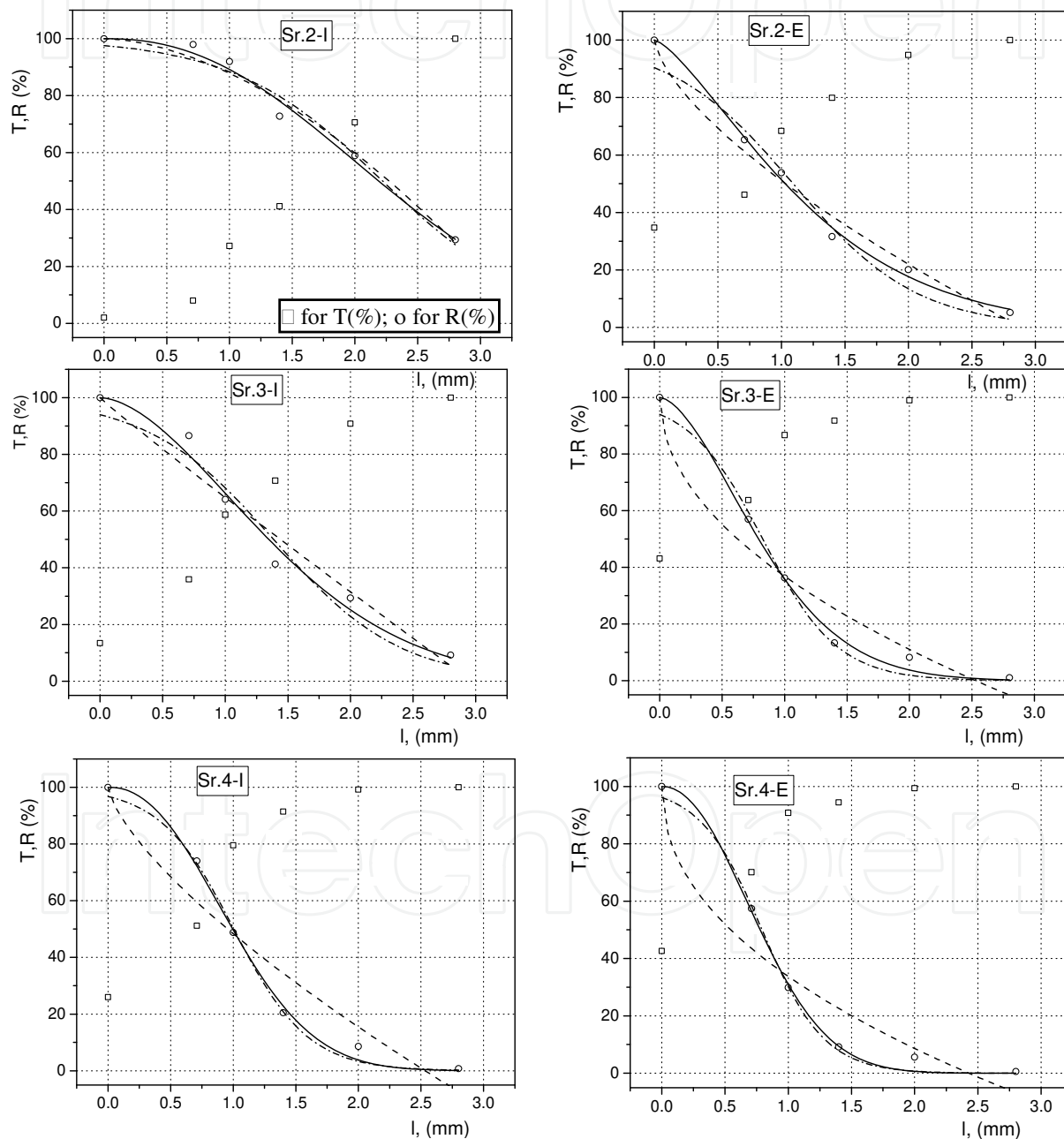


Figure 9. The curves described by the cumulative distribution laws (1), (2), (3) towards the experimental points R(%) for the gritting product from the five roll pairs (Sr.2...Sr.5) [10]; (I-entrance; E-exit); — Rosin-Rammler; - - - Schuhman; — · — · logistic function)

| Law type | Coeff. | Sr.1-E | Sr.2-I | Sr.2-E | Sr.3-I | Sr.3-E | Sr.4-I | Sr.4-E | Sr.5-I | Sr.5-E |
|--|----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Rosin-Rammler (eq.1) | b | 0.224 | 0.114 | 0.665 | 0.411 | 1.025 | 0.701 | 1.169 | 2.472 | 2.652 |
| | n | 1.659 | 2.302 | 1.382 | 1.747 | 1.682 | 2.220 | 2.093 | 2.852 | 2.817 |
| | R ² | 0,988 | 0,987 | 0,996 | 0,982 | 0,996 | 0,996 | 0,996 | 0,998 | 0,999 |
| Schuhman (eq.2) | k | 4.201 | 3.398 | 2.893 | 2.966 | 2.531 | 2.532 | 2.431 | 1.025 | 1.016 |
| | a | 0.996 | 1723 | 0.674 | 0.960 | 0.495 | 0.711 | 0.464 | 1.710 | 1.639 |
| | R ² | 0,999 | 0,981 | 0,985 | 0,956 | 0,958 | 0,933 | 0,940 | 0,991 | 0,987 |
| Logistic with two parameters (eq.3) | α | 2.573 | 3.701 | 2.243 | 2.744 | 2.760 | 3.397 | 3.216 | 4.347 | 4.303 |
| | β | -1.245 | -1.666 | -2.053 | -1.981 | -3.345 | -3.380 | -4.056 | -6.739 | -6.878 |
| | R ² | 0.984 | 0,974 | 0.972 | 0.963 | 0.988 | 0.995 | 0.994 | 0.997 | 0.997 |

Table 8. The coefficient values a, k, b, n, α and β and of the R² correlation coefficients, for the three size distribution laws tested, for the gritted products from the „I“ entry to the „E“ exit between the mentioned roll pairs (Sr.1...Sr.5), [10]

In plansifter compartments, material fractions are separated and sorted, as any granular material is made of particles with sizes between a minimum and a maximum value, in the interior of the mixture the size distribution being characterised by various distribution laws.

It must be mentioned that material particles, being extracted from various areas of the seed (from exterior to interior) have different mechanical characteristics and composition. This, and the different sizes of particles gives a different behaviour of the particles during grinding.

Thus is important to study and to know the size distribution of the particles of each fraction obtained in each frame set of the six plansifter compartments.

Size of sieve holes used for the experiments and the amount of material fractions on each sieve (individual and cumulative) for the separated material are presented in table 9.

In every fraction there is a percentage of material with sizes smaller than the size of the sieve hole, which means that sieving is incomplete, even if the number of frames is quite high. However, the average particle size of fraction C1–Break 2 is 2.27 mm, much larger than the opening of sieve holes of the package (1.05 mm). This shows that here are obtained the parts of seed with quite large sizes, which must be reintroduced in the grinding process at the passage Break 2.

At the second set of sieving frames of plansifter compartment C1, the opening of fabric holes is 470 μm (no. 40), but mean size of particles of fraction C1-DIV1' is 0.58 mm, slightly larger than the opening of the holes. It is noticed (Table 9) that there are particles with sizes smaller than the size of holes which remain unseparated (at least 8.4%). This phenomenon is valid for all sets of sieves in the plansifter with six compartments, as can be seen from the analysis of the results presented in table 9.

Composition of fraction C1-DIV1'' of plansifter compartment C1 consists of the refuse of sieve frames no. 56 (with holes opening 0.31 mm), after the sieved of the second set, consist-

ing of particles that passes through sieve no. 40 (with holes opening 0.47 mm) was extracted flour F (mean size of particles 0.08 mm). This fraction with fraction C1-DIV1' and with the two fractions C2-DIV1 of the second plansifter compartment are directed to the sorting-dividing compartment DIV1 (compartment C5). Mean particle sizes of fraction DIV1'', from compartment C1, are 0.31 mm (equal to the opening of sieve holes which refused them, proving that here also the sieving is incomplete).

| I_i (mm) | C1 Entrance | | I_i (mm) | C1 Break 2 | | I_i (mm) | C1 DIV1' | | I_i (mm) | C1 F | | I_i (mm) | C1 DIV1'' | | I_i (mm) | C1 M2 | |
|----------------------------|-------------|-------|---------------------------------|------------|-------|--------------------------------|----------|-------|----------------------------|-------|-------|---------------------------------|-----------|--------|---------------------------------|-----------|-------|
| | p_i | T_i | | p_i | T_i | | p_i | T_i | | p_i | T_i | | p_i | T_i | | p_i | T_i |
| | (%) | (%) | | (%) | (%) | | (%) | (%) | | (%) | (%) | | (%) | (%) | | (%) | (%) |
| 0.000 | 24.20 | 0.00 | 0.000 | 10.20 | 0.00 | 0.000 | 1.10 | 0.00 | 0.000 | 4.20 | 0.00 | 0.000 | 6.00 | 0.00 | 0.000 | 0.60 | 0.00 |
| 1.000 | 8.20 | 24.20 | 1.000 | 21.30 | 10.20 | 0.180 | 2.30 | 1.10 | 0.045 | 45.10 | 4.20 | 0.125 | 8.00 | 6.00 | 0.090 | 1.90 | 0.60 |
| 1.400 | 15.10 | 32.40 | 1.400 | 14.60 | 31.50 | 0.250 | 5.00 | 3.40 | 0.063 | 24.30 | 49.30 | 0.180 | 12.80 | 14.000 | 0.125 | 41.50 | 2.50 |
| 2.000 | 20.20 | 47.50 | 2.000 | 21.60 | 46.10 | 0.400 | 51.70 | 8.40 | 0.090 | 18.80 | 73.60 | 0.250 | 24.50 | 26.800 | 0.180 | 15.00 | 44.00 |
| 2.800 | 27.10 | 67.70 | 2.500 | 20.70 | 67.70 | 0.630 | 28.60 | 60.10 | 0.125 | 6.30 | 92.40 | 0.315 | 32.40 | 51.300 | 0.200 | 30.10 | 59.00 |
| 4.000 | 5.20 | 94.80 | 4.000 | 11.60 | 88.40 | 0.710 | 11.30 | 88.70 | 0.160 | 1.30 | 98.70 | 0.400 | 16.30 | 83.700 | 0.250 | 10.90 | 89.10 |
| $d_{1E} = 2.13 \text{ mm}$ | | | $d_{1Break2} = 2.27 \text{ mm}$ | | | $d_{1DIV1'} = 0.58 \text{ mm}$ | | | $d_{1F} = 0.08 \text{ mm}$ | | | $d_{1DIV1''} = 0.31 \text{ mm}$ | | | $d_{1M2} = 0.19 \text{ mm}$ | | |
| I_i (mm) | C2 Entrance | | I_i (mm) | C2 Break 3 | | I_i (mm) | C2 DIV1' | | I_i (mm) | C2 F | | I_i (mm) | C2 M2 | | I_i (mm) | C2 DIV1'' | |
| | p_i | T_i | | p_i | T_i | | p_i | T_i | | p_i | T_i | | p_i | T_i | | p_i | T_i |
| | (%) | (%) | | (%) | (%) | | (%) | (%) | | (%) | (%) | | (%) | (%) | | (%) | (%) |
| 0.000 | 34.40 | 0.00 | 0.000 | 23.50 | 0.00 | 0.000 | 5.60 | 0.00 | 0.000 | 19.10 | 0.00 | 0.000 | 17.70 | 0.00 | 0.000 | 0.30 | 0.00 |
| 0.710 | 11.50 | 34.40 | 1.000 | 30.10 | 23.50 | 0.180 | 4.00 | 5.60 | 0.045 | 34.90 | 19.10 | 0.090 | 9.40 | 17.70 | 0.125 | 1.60 | 0.30 |
| 1.000 | 22.20 | 45.90 | 1.400 | 13.50 | 53.60 | 0.250 | 7.70 | 9.60 | 0.063 | 21.60 | 54.00 | 0.125 | 22.30 | 27.10 | 0.180 | 5.60 | 1.90 |
| 1.400 | 11.60 | 68.10 | 2.000 | 17.60 | 67.10 | 0.400 | 26.10 | 17.30 | 0.090 | 16.10 | 75.60 | 0.180 | 9.60 | 49.40 | 0.250 | 19.20 | 7.50 |
| 2.000 | 15.00 | 79.70 | 2.500 | 12.40 | 84.70 | 0.500 | 49.20 | 43.70 | 0.125 | 6.70 | 91.70 | 0.200 | 25.10 | 59.00 | 0.315 | 44.50 | 26.70 |
| 2.800 | 5.30 | 94.70 | 3.150 | 2.90 | 97.10 | 0.710 | 7.40 | 92.60 | 0.160 | 1.60 | 98.40 | 0.250 | 15.90 | 84.10 | 0.400 | 28.80 | 71.20 |
| $d_{2E} = 1.22 \text{ mm}$ | | | $d_{2Break3} = 1.56 \text{ mm}$ | | | $d_{2DIV1'} = 0.52 \text{ mm}$ | | | $d_{2F} = 0.07 \text{ mm}$ | | | $d_{2M2} = 0.17 \text{ mm}$ | | | $d_{2DIV1''} = 0.37 \text{ mm}$ | | |

Table 9. Values of weights p_i (%) of sieved fractions and of the cumulative weights T_i (%) for products collected at the entrance, respectively exit of plansifter compartments, C1 and C2

The last components of plansifter compartments in gristing passage shave higher content of coating particles which are found in the upper layers of material on the frames, thus being recommended that they do not separate through the holes, even if their sizes are about the size of endosperm particles, to be further removed in semolina machines (sieving motion leads to the layering of mixture components by density). Flour particles have mean sizes under 0.18 mm in all plansifter compartments, while particles of last refuse from the five passages fitted with pairs of rollers have mean sizes over 0.37 mm (see Table 9). Values of

coefficients b and n in the equation of relationship Rosin–Rammler cumulative distribution law (eq.1), for the material which passed through sieve holes in granulometric analysis, and the correlation coefficients R^2 and χ^2 have high values which show the adequacy degree of the given function with the experimental data. In all cases, for all fractions obtained during gristing phase of wheat in the studied mill, the correlation is very good, appreciated by values of coefficient $R^2 \geq 0.926$.

As it can be noticed from fig.10, there are fractions having most particles of sizes close to the minim value of sieve classifier holes, but there are also components with particles with sizes from the mean size to the maximum size of the sieve holes used for granulometric analysis.

However, most components show mean profile (with central inflection point) of the separation curves which demonstrates the correct choosing of sieve classifier sizes (made from a set of 30 sieves by trying to take into consideration the arrangement in geometric distribution with holes ratio of $\sqrt{2}$).

From the analysis of coefficients b and n from Rosin–Rammler law (eq.1) it is noticed that values of coefficient b are $0.2\text{--}1.5 \cdot 10^3$ for most analyzed fractions, generally with high values, for the small size components of the particles (flour or dunsts), $1 \cdot 10^6\text{--}5 \cdot 10^7$, giving the size characteristics of such particles (Table 10).

| Plansifter compartment | | | | | | Plansifter compartment | | | | | |
|------------------------|-------------|----------------------|----------------|----------------|---------|------------------------|------------------------|----------------|----------------|--------|--|
| | b | n | R ² | χ ² | | b | n | R ² | χ ² | | |
| C1 | C1 Entrance | 0.222 | 1.663 | 0.988 | 17.039 | C4 Entrance | 0.621 | 1.958 | 0.988 | 21.914 | |
| | C1 Break 2 | 0.169 | 1.964 | 0.987 | 18.890 | C4 F | 2.06·10 ³ | 5.665 | 0.997 | 1.144 | |
| | C1 DIV1'' | 37.812 | 3.412 | 0.993 | 9.147 | C4 M4 | 1.15 · 10 ³ | 3.967 | 0.976 | 36.414 | |
| | C1 DIV1' | 15.782 | 6.033 | 0.997 | 6.245 | C4 FT2 | 0.027 | 4.557 | 0.996 | 9.071 | |
| | C1 F | 2.2·10 ³ | 3.051 | 0.938 | 142.827 | C4 Break 5 | 2.590 | 2.983 | 0.999 | 1.091 | |
| | C1 M2 | 2.86·10 ³ | 5.028 | 0.988 | 20.440 | C4 M5 | 1.6·10 ³ | 6.054 | 0.999 | 3.370 | |

Table 10. Values of coefficients b and n and correlation coefficient R^2 for Rosin – Rammler granulometric distribution, for the granulometric distribution law for fractions of the two plansifter compartments

Values of exponent n indicate the uniformity or the irregularity degree of particles from the analyzed fractions.

The analysis of this exponent values for the fractions of each plansifter compartment (Table 9) shows that they have a wide range of values, even for the same type of grinding product (for example flour – F), which shows the irregularity of particles, both for a given fraction and between fractions.

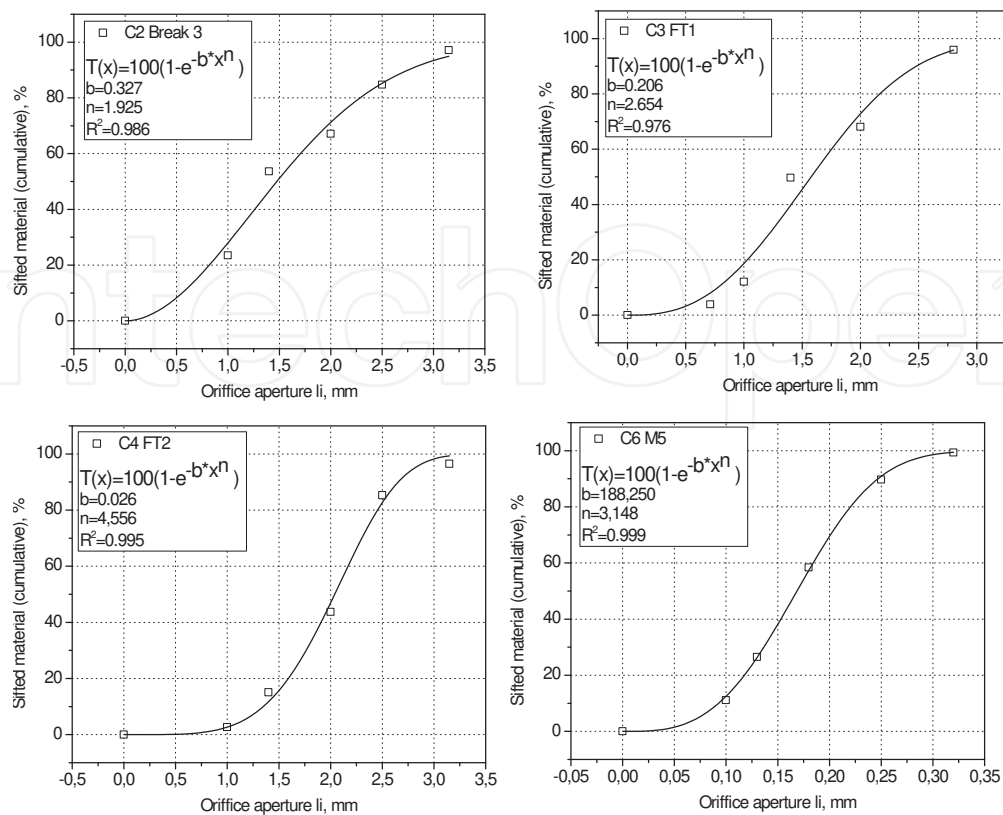


Figure 10. Curves of granulometric distribution given by eq. (1) in correlation with experimental data for grinding fractions in plansifter compartments during gristing phase of wheat in a mill with capacity of 100 t / 24 h

4. Some mechanical characteristics of wheat seeds in uniaxial compression tests

Main stress to which seeds are subjected, while passing through mill rollers, is given by the type of rollers surface, namely smooth or fluted. Regardless the surface type, one of the main stress during grinding is compression (or crushing), especially if the mill rollers have smooth surface. To estimate the behaviour of seeds while passing through the rollers, experimental research is required on the compression stress of seeds from various wheat varieties, knowing that not all varieties have similar mechanical characteristics. Even seeds from the same variety have different behaviour, due to the irregular development stage in the ear, and also from one ear to another.

The compression of wheat seeds is performed in three different stages: the first stage is elastically deformation, characterized by the proportionality between the compression force and the deformation; the second stage is plastic deformation, characterized by large increases of seed deformation at small increases of compression force; the last stage consists in cracking or rupture, being characterized by seed crushing when reaching a certain value of compression force, [17-20].

Compression test is an objective method for determining the mechanical properties of cereal seeds and also one of the best techniques for determining the modulus of elasticity by the study of their behaviour at compression stress, using force-deformation curve, [21,22].

By performing uniaxial compression tests on wheat seeds, force-deformation curve is obtained, giving the possibility to determine hardness, apparent modulus of elasticity, crushing resistance, force and deformation and energy consumption in various specific points of the curve (i.e. rupture point) and maximum stress in the material, [21,23].

Cereal seeds have a different behaviour under the action of compression forces, depending on their moisture content, [17,20], variety, development stage, geometric sizes, individual mass, glassiness, (soft cereals and hard cereals) etc.

In fig.1 is presented a typical force-deformation curve for compressed Flamura wheat seed.

The bioyield point is the point on the force – deformation curve at which the force decreases or remains constant with increasing deformation. Force in the rupture point (rupture force) is the minimum required force for the wheat seed to break (rupture). Deformation at bioyield and rupture points is the deformation at loading direction, [24,25]. Values of force and deformation to bioyield and rupture points are directly read from force-deformation curve and recorded by machine used for compression test, [21].

Energy absorbed in bioyield and rupture points could be determined from the area under the force-deformation curve between the initial point and the bioyield and rupture point, respectively, using equation [24,25]:

$$W = \frac{FD}{2} \text{ (mJ)} \quad (9)$$

where: W is energy absorbed (mJ), F is force in bioyield or rupture point (N), D is deformation in bioyield or rupture point (mm), (see fig.11).

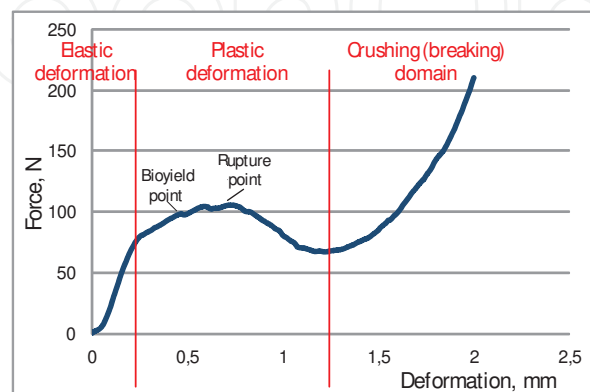


Figure 11. A typical force –deformation curve of wheat grain (type Flamura), [20]

Based on a standard method (ASAE 2008, [21]), for a seed placed between two parallel plates, the modulus of elasticity could be calculated with following equation, [20,21,21]:

$$E = \frac{0.338 k_u^{3/2} F (1 - \mu^2)}{D^{3/2}} \left[\frac{1}{R'} + \frac{1}{R_1'} \right]^{1/2} \quad (10)$$

where: E – modulus of elasticity for cereal seeds, (MPa); k_u – coefficient which depends on the geometrical properties of wheat seeds ($k_u = 1,303$ - adapted from calculus tables of Kozma and Cunningham, 1962); F – compression force, (N); D – seed deformation (m); μ - Poisson ratio, ($\mu = 0,3$ for wheat seeds); R' and R_1' – small and large radius of the curvature of convex surface seed in contact with the flat surface, (m), (see fig.12, left).

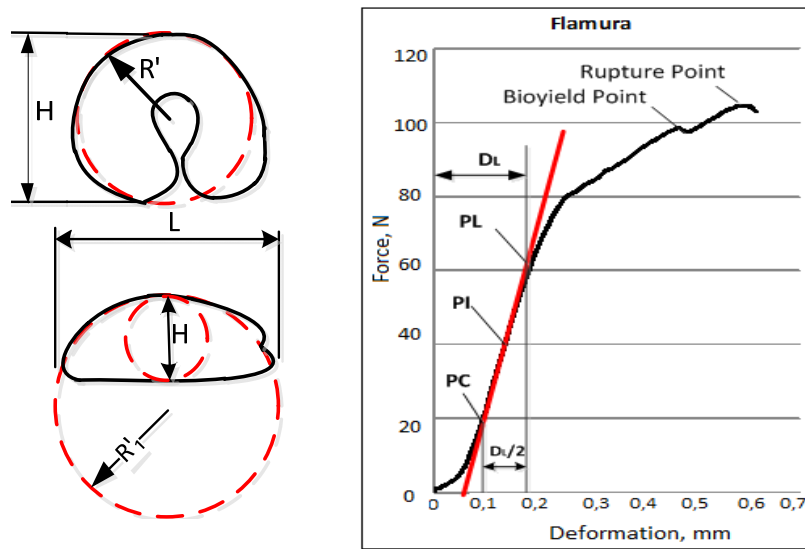


Figure 12. Estimation of curvature radius and force-deformation curve of wheat seed, (adapted from [25,26]) PL – proportional limit; PI – point of inflection; PC – point of calculation

According to the standard method (ASAE 2008, [21]), also presented by Mohsenin in [25,26], curvature radius of convex surface, R' and R_1' (fig.12) can be calculated using relations (11) and (12):

$$R' \cong \frac{H}{2} \quad (11)$$

$$R_1' \cong \frac{H + L^2/4}{2H} \quad (12)$$

where: H is seed thickness, (m), and L is seed length, (m), in undistorted state.

This method was used by many researchers to determine the modulus of elasticity for different agricultural products, [27-30].

According to the standard method (ASAE 2008), values of force F and deformation D , from equation (2) are calculated for the proportionality area of force-deformation curve in the point of calculation P_c (fig.12). The position of this point is estimated visually, as the point is located halfway between curve origin and proportionality limit P_L (fig.12, right). It was found that the point of calculation P_c is located lower than the point of inflection, also established visually, [21].

To determine the variation of mechanical resistance characteristics of wheat seeds from the same variety, compression tests were performed for sets of 100 seeds of three varieties of Romanian wheat (Flamura, Glosa and Trivale – soft wheat), using Hounsfield mechanical testing machine, at a constant speed of the crushing device of 5 mm min^{-1} , using a force cell of 1000 N. Were graphically plotted the force-deformation curves for each seed, and from each diagram were collected data about: force, deformation and energy absorbed in the bioyield point (F_1, ε_1, W_1), respectively in the final point (rupture), (F_2, ε_2, W_2).

The analysis of measured data showed that the seeds of Flamura variety were larger than Trivale variety, for all three main sizes, and for their volume. The same goes for seeds mass. Flamura variety seeds were more uniform as size and mass. Regarding the mechanical characteristics of wheat seeds, it was found that compression forces, for bioyield point and for final seeds crushing, were smaller for Trivale variety than Flamura. The same goes for energy absorbed to the bioyield point, respectively to crushing. Since the sizes of Trivale seeds were smaller than Flamura seeds, the deformations carried to the bioyield point, respectively to crushing, were smaller for Trivale than Flamura, but the standard deviation of the values was smaller for Flamura for deformations, showing that Flamura seeds were more regular in terms of deformations (until crushing).

In fig.13 are presented two examples of force-deformation curves for two varieties of wheat, and in fig.14 are presented the histograms of bioyield force and energy absorbed for seed crushing.

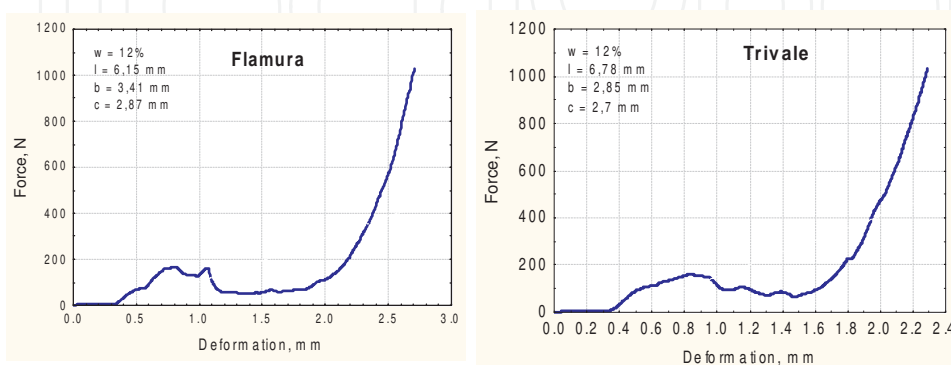


Figure 13. Examples of force-deformation curves for the two wheat varieties, [23]

On the histograms were traced the variation curves for the analyzed parameters by regression analysis of the values given by the histogram, using the normal function presented in equation (13), [23]:

$$p_x = 100a \frac{1}{\sqrt{2\pi}b} e^{-\frac{1}{2}\left(\frac{x-c}{b}\right)^2} \tag{13}$$

where: $p_x(\%)$ is the percentage weight of each class interval (number of seeds with values in the considered class interval); a – class interval for each analyzed parameter; b and c are regression coefficients of the analyzed function (b is the standard deviation, c is the values mean).

Values of coefficients for the regression function (eq.13) used in statistical analysis and values of correlation coefficient R^2 for data given by histograms are presented in Table 11.

| Measured parameters of wheat seeds | Flamura wheat variety | | | | Trivale wheat variety | | | |
|--------------------------------------|-----------------------|-------|--------|----------------|-----------------------|-------|--------|----------------|
| | a | b | c | R ² | a | b | c | R ² |
| Length l, (mm) | 0.20 | 0.404 | 6.443 | 0.989 | 0.20 | 0.501 | 6.186 | 0.971 |
| Width w, (mm) | 0.10 | 0.202 | 3.429 | 0.974 | 0.20 | 0.284 | 2.994 | 0.981 |
| Thickness t, (mm) | 0.20 | 0.248 | 3.058 | 0.975 | 0.20 | 0.315 | 2.664 | 0.983 |
| Mass m, (g) | 0.01 | 0.008 | 0.051 | 0.988 | 0.01 | 0.009 | 0.037 | 0.981 |
| Volume V, (mm ³) | 5.00 | 5.870 | 35.57 | 0.968 | 5.00 | 6.207 | 26.23 | 0.985 |
| Bioyield force F ₁ , (N) | 20.0 | 41.36 | 122.64 | 0.921 | 20.0 | 39.48 | 104.70 | 0.888 |
| Bioyield energy W ₁ , (J) | 0.01 | 0.024 | 0.036 | 0.923 | 0.01 | 0.017 | 0.026 | 0.884 |

Table 11. Values of coefficients for regression equation (eq.13) and its correlation with experimental data [20]

Analysis of histograms and variation curves, as well as of data in table 11, shows that all analyzed parameters have almost normal distribution, assessed by values of correlation coefficient R^2 .

Using standard method (ASAE 2008, [21]) and equations (10), (11) and (12) were determined the values of moduls of elasticity for wheat seeds of Flamura, Trivale and Glosa varieties, in this paper being presented their mean values, (table 12).

Fig.15 shows the machine used for uniaxial compression tests between parallel plates of weat seeds and their position.

From the sample of 100 determinations for each variety of wheat, were selected the 50 most representative determinations, being kept the values found for force and absolute deformation of the seed.

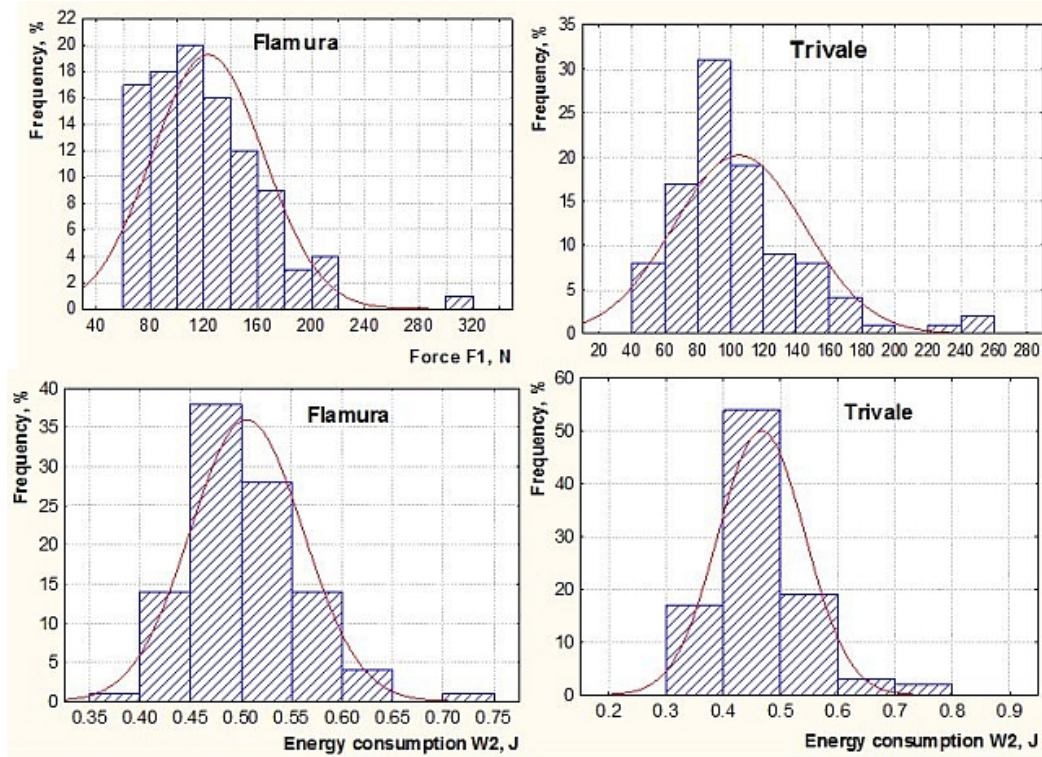


Figure 14. Histograms and variation curves for the force in bioyield point and the energy consumption in rupture point for wheat seeds [23]

Force-deformation curves, for each of the 50 determinations (of a variety) were processed so that each has the same origin (same starting point), and the intervals of reading (recorded) to be the same. Values for the parameter on the ordinate (forces in the mentioned points) were averaged (arithmetic average for the 50 determinations was calculated) for the same value of deformation (parameter on the abscissa), and these values were used to retrace the force-deformation curve, which represents the curve of mean values of compression force (fig.16). Using the approximately normal distribution, were statistically estimated the limits within which the mean force-deformation curve is found, for a confidence interval of 95%. For normal distribution, the confidence interval corresponding to 95% confidence level ranges between ± 1.96 , considered standard deviations. Thus, the confidence interval of mean curve was calculated using the following equation:

$$\mu = m \pm 1.96 \frac{\sigma}{\sqrt{n}} \quad (14)$$

where: μ is the confidence interval, and m is the mean value of the analyzed parameter (in this case, the compression force) and $\sigma / \sqrt{n} = S_m$ is the standard error of the mean, σ – standard deviation, and n – number of seeds from each variety of wheat (in this paper, $n = 50$).

On the curve of mean values (fig.16), were determined the values of mechanical characteristics mentioned before (forces and deformations in the characteristic points) and it was calculated the value of modulus of elasticity using the standard method (ASAE 2008, [21]), for mean curve (for the three varieties of wheat).

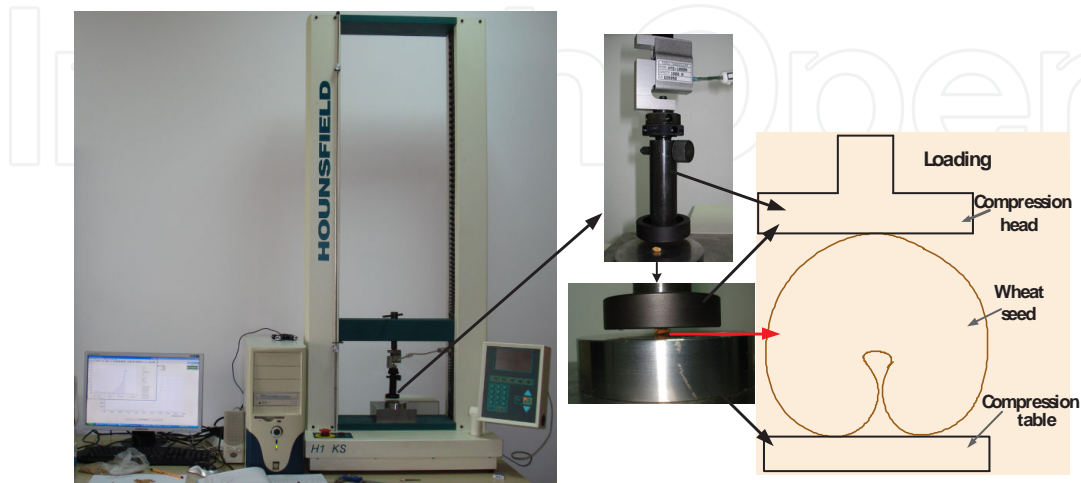


Figure 15. Hounsfield - Mechanical testing machine used in compression test [20]

Knowing the forces and deformations in the points of bioyield and rupture, from the area under the force-deformation curve between the initial point and the bioyield and rupture point, respectively, using equation (1), energy absorbed in bioyield and rupture point was determined.

| Measured parameters of wheat seeds | | Mean of parameters values | | | Values of parameters read from the mean curve | | |
|------------------------------------|----------------------------------|---------------------------|---------|-------|---|---------|-------|
| | | Flamura | Trivale | Glosa | Flamura | Trivale | Glosa |
| Bioyield force F_b , (N) | | 93.2 | 83.1 | 98.0 | 98.4 | 81.1 | 94.0 |
| Bioyield energy W_b , (J) | | - | - | - | 0.028 | 0.018 | 0.016 |
| Rupture force F_r , (N) | | 107.8 | 90.5 | 103.6 | 104.2 | 83.2 | 94.7 |
| Rupture energy W_r , (J) | | - | - | - | 0.038 | 0.018 | 0.016 |
| Bioyield deformation | Relative deformation, δ_b | 0.138 | 0.092 | 0.077 | - | - | - |
| | Absolute deformation, D_b (mm) | 0.304 | 0.267 | 0.260 | 0.464 | 0.348 | 0.292 |
| Rupture deformation | Relative deformation, δ_r | 0.099 | 0.109 | 0.086 | - | - | - |
| | Absolute deformation, D_r (mm) | 0.419 | 0.320 | 0.290 | 0.576 | 0.400 | 0.360 |
| Modulus of elasticity, (MPa) | | 313 | 364 | 486 | 298 | 369 | 468 |

Table 12. Values of measured and determined parameters in uniaxial compression test [20]

Analysis of data presented in table 12 showed that the values of bioyield force, respectively values of the force in the point of rupture of wheat seeds, determined from the mean curve are very close to the values of these forces obtained from the force-deformation curves for each particular seed.

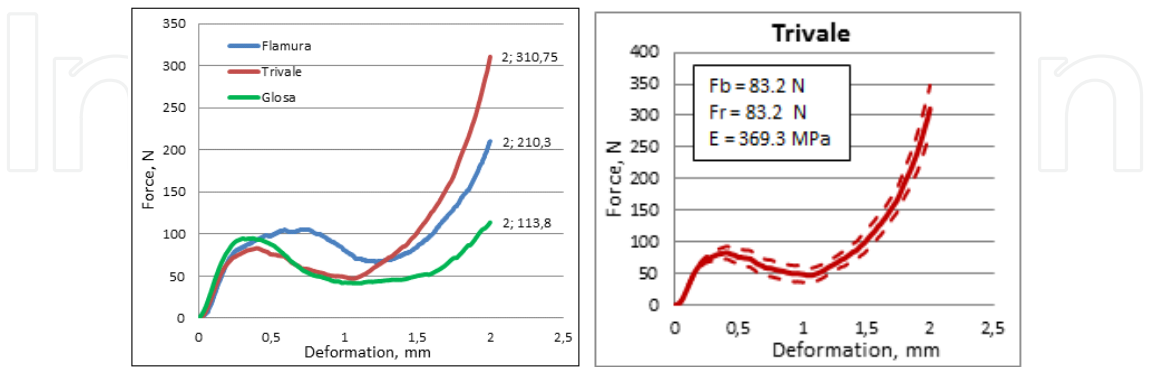


Figure 16. Mean curves force-deformation for three wheat varieties and 95 % confidence interval, [20]

Analysis of curves presented in figure 15 shows that they have similar shapes for the three varieties of wheat, and also within each of them and the force-deformation curves for each individual seed analyzed from each variety of wheat.

As absolute values of the force in the bioyield point, respectively in the rupture point, they are found in between 83.1 N for Trivale variety and 98.0 N for Glosa variety regarding the bioyield force, respectively 90.5 N for Trivale and 107.8 N for Flamura (values calculated with arithmetic average of the 50 determinations). These values are very close to the values presented in literature [31], where is stated that crushing force (rupture) of wheat seeds is of approximately 100 N.

On the relative deformation of seeds, during the compression tests, for the force in the bioyield point (bioyield force), respectively rupture, data in table 12 also show relatively close values for the wheat seeds of the three varieties.

5. Conclusions

Development of technological gristing process of the wheat in a mill is very important for the entire technological flow of the mill, having a great influence on the degree of flour extraction, without excessive grinding of seed coating.

Based on material samples taken from the entrance and exit of each pair of milling rollers it can be determined, by laboratory analysis, the equivalent average sizes of the material, grinding degree in the passage, and the specific surface of material particles.

Granulometric analysis of the material to be grinded or of the grinded material at mill rollers, and of the sorted fractions in plansifter compartments show a distribution after multiple

known laws, from which most used is Rosin-Rammler distribution function, with high correlation coefficient R^2 .

However, it is shown that there can also be used with good results the Schuhman and logistical two parameters distribution laws, the finding suggest that the type of granulometric distribution law which best describes the size of grinded biological materials depends on material nature and the place and role of roller mill used for grinding in the general technological flow. Knowledge of adequate mathematical models describing the size distribution of grinded materials is useful in all engineering activities related to the processes on the flow of complex roller mills of last generation.

Values of mechanical characteristics of wheat seeds (regardless the variety) are necessary to estimate the energy consumed for their grinding in grain mills. A great influence on the grinding energy is given by the crushing force and their relative and absolute deformation, determined by experimental research of uniaxial compression.

For some wheat varieties presented in this chapter, compression force in the rupture point, determined from force-deformation curves has values of 100-110 N, for seed moisture content of about 12%.

Crushing energy has values of 0.02-0.04 J, for each wheat seed, but it is influenced by the moisture of seeds and by seed arrangement during compression: on width "sideways" or on thickness "laying flat".

Regarding the modulus of elasticity, its values are between 313-487 MPa, being greater as moisture is lower. It was found that lower moisture content resulted in higher values of modulus of elasticity and to lower values of rupture energy, which confirm that wetter seeds have greater plasticity than dry seeds, so they have higher energy consumption.

Author details

Gheorghe Voicu, Sorin-Stefan Biris, Elena-Madalina Stefan,
Gabriel-Alexandru Constantin and Nicoleta Ungureanu

"Politehnica" University of Bucharest, Romania

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