Bulletin of the *Transilvania* University of Braşov
Series II: Forestry • Wood Industry • Agricultural Food Engineering • Vol. 6 (55) No.2 - 2013

THEORETICAL RESEARCH CONCERNING THE PROCESS OF CRUSHING WHEAT GRAINS USING THE FINITE ELEMENTS METHOD

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Abstract: *From the analysis of the working process executed by the technical equipments used for grain grinding, we concluded that the main forces that are applied to grains, refer to crushing and cutting. In this paper a mathematical model was performed by means of the finite element method for the crushing process of wheat, in order to establish the forces that appear to the first cracks of the grain, and also to determine the maximum strains from the grain that is being crushed; and the deformations of the crushing direction of the grain and the energy consumption during this process. For this simulation, the mechanical structural module in 3D space of the COMSOL Multiphysics software was used.*

Key words: *deformation, force, grain grinding, strain.*

1. Introduction

The behavior of solid materials subjected to the grinding operation is very different, due to the influence of many factors involved in achieving it. Experimental research has highlighted the main influence factors which can be taken into consideration in explaining how the grinding process is realized: the material nature, the initial state (form, particle size distribution (grading curve), etc.), structure, the way of application and the nature of force applied, value, speed and the duration of the applied effort. Due to the complex structure of cereal grains the latter can be considered "-capillary-porous colloidal" bodies; and from the rheological point of view they can display, at the same time, in certain proportions, three essential rheological properties: elasticity, plasticity and viscosity.

Considering the large number of factors that influence the process of grinding, in the theoretical study models, the following simplifying assumptions are made: the granules subjected to study have a spherical shape and from the macroscopic point of view it can be concluded that they are homogeneous and isotropic. Based on these theoretical approximations, the theoretical study of the phenomena taking place in their mass can be accomplished on the basis of mechanics laws under the action of external tasks, consequently the theory of tension and of plastic can be workable.

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2. The mechanism of grinding process produced by crushing

A number of research activities have dealt with the study of the behavior of solid particles, belonging to different materials, under the action of concentrated forces of compression, aiming to highlight the dependence of "force-deformation"[1].

Rumpf (1965), Schönert (1966) and May (1975) described in their works, the behavior of quartz particles, lime and clinker under the action of compressive force until crushing, and Stieß (1976) studied the influence of size and particle shape upon the process of grinding by crushing.

The systematic investigations performed by Rumpf (1958, 1962); Schubert (1975); Kendall (1987), on the resistance to compression of compound granules, have confirmed the correlation between the theoretical research and the experimental ones. The model developed by Rumpf (1958) describes the granules' resistance to compression, taking into account the forces of adhesion to the contact points of the spherical constituent particles. Xun et al. (2001) generalized the models put forward by Rumpf (1958) and Kendall (1987) and extended the studies to porous granules. The particles inside the granule are considered to be linked through a fluid, with a high viscosity and a high level of saturation, and the model developed by Schubert (1975) highlighted the dependence of resistance to compression besides the value of capillary pressure.

The works developed by Tomas et al., (1999); Khanal et al., (2004), and Salman et al (2003) on heterogeneous spherical particles, that are compressed, emphasized the formation of the force fan and of cracking zones.

The investigations carried out by Boccaccini (1994), Avar et al, (2003) on the resistance to compression of granules made of porous materials (ceramics, glass, cement clinker, polymers) and composites, show the reduction of the elasticity module and of Poisson's coefficient proportionally to the increase of porosity.

Experimental research, performed in the case of grains of regular shape, highlight the fact that in the granule mass, a spatial effort state is developed, and if those are compressed by a force (Figure 1), as a result, in a first phase, the granule will be elastically deformed and as the level of the exterior compression increases, the deformations pass in a plastic domain, and finally, it will disintegrate into particles with different sizes and shapes [4]. The force being applied in a single direction, in the particle mass, two areas that are stressed differently appear: the central zone (dashed) to compression respectively the external area to stretch, which is also highlighted by the experimental research carried out by means of photo elasticity.

The central area, that has the shape of two cones (truncated cones) and have the bases in the working points and centre (small base), the particle, which is compressed, is called force cone. The force cone crosses the particle, being centered on the force direction.

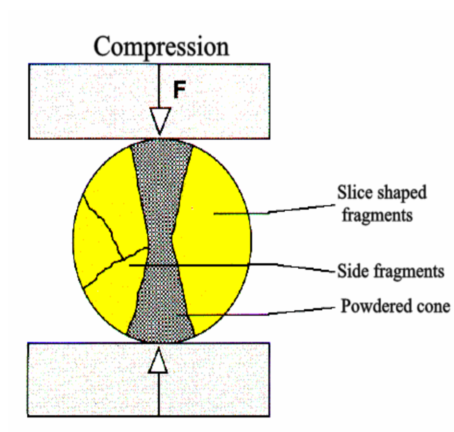

Fig. 1. *Model of a ferric grain stressed to compression [6]*

If the level of the effort state, generated in the particle mass by the external force, is below the limit of material elasticity, the consumed energy is transformed into heat energy which is completely lost.

If the flow limit is exceeded and we take into account the fact that in general the material resistance to compression σ_c is higher than the resistance to tension σ_t ($\sigma_c > \sigma_t$), in the lateral exterior sides, strained to compression, as a result of the action of stretching of unitary efforts, in the material mass, slides over the surface of the force cone can occur, and these result in the appearance of cracks and the fragile breakage of the material. From the particle mass, fragments of circular or of irregular shape fall off.

Depending on the level of force compression, the grinding process takes place in two stages:

- the first stage, where under the action of the compression force in the particle mass cracks appears;
- a second stage, in which the force overcomes the critical value and the cracks are rapidly conveyed, separated and from the material mass, fragments fall off and actually the breaking itself occurs. The value of the effort put up in the first stage depends on the initial state of the material (the number and the size of the existent cracks in the material), and for the second stage, it depends on the internal structure of the material.

In the case in which the material structure is not homogeneous, along the division surfaces slides occur, which lead to local development of some unitary efforts of stretching which produce fragile breaking [7].

The degree of energy usage would be at maximum level, if the material breakage took place at the value force that is applied at the onset of the breaking process.

3. The theoretical bases concerning the calculus of the grinding energy

For the theoretical research the MAXWELL-MOHR method was used in order to determine the motions of an elastic body. The generalized motion of an elastic body, under the action of a system of forces, is equal to the mechanical work produced by the system forces when it passes at full intensity [5]. This sentence is true only when one of the two systems is made up of a generalized force equal to the unit.

If we use $\sigma_x,...,\tau_{zx},\varepsilon_x,...,\gamma_{zx}$ and $\sigma_x^{(1)},...,\tau_{zx}^{(1)},\varepsilon_x^{(1)},...,\gamma_{zx}^{(1)}$ for the states of the unitary efforts and for deformations, and that corresponds to the force system and to the unitary generalized force, the motion δ has the following expression [8]:

$$\delta = \iiint\left(\sigma_x\varepsilon_x^{(1)} + \sigma_y\varepsilon_y^{(1)} + ... + \tau_{zx}\gamma_{zx}^{(1)}\right)dxdydz \quad (1)$$

Sometimes is much more easy to use the following expressed formula, exclusively depending on the states of the unitary efforts.

$$\delta = \frac{1}{E}\iiint\begin{bmatrix}\sigma_x\sigma_x^{(1)} + \sigma_y\sigma_y^{(1)} + \sigma_z\sigma_z^{(1)} - \mu\left(\sigma_x\sigma_y^{(1)} + \sigma_x^{(1)}\sigma_y + \sigma_y\sigma_z^{(1)} + \sigma_y^{(1)}\sigma_z + \sigma_z\sigma_x^{(1)} + \sigma_z^{(1)}\sigma_x\right) + \\ + 2(1+\mu)\left(\tau_{xy}\tau_{xy}^{(1)} + \tau_{yz}\tau_{yz}^{(1)} + \tau_{zx}\tau_{zx}^{(1)}\right)\end{bmatrix}dxdydz \quad (2)$$

4. The simulation of the grinding process using the finite elements method

On the market, different simulation programs using the finite element method are available. Usually, these programs have not been conceived for solving equations that describe the grinding process.

Because of that, for simulation, the COMSOL Multiphysics software was used, which is in fact a software package used to simulate the physical processes which can be described with the help of a system of differential equation (Maxwell).

The software package allows the solving of some difficult problems, the program for equations could be modified in order to allow the solving of some applications that are much more complex.

4.1. The main objectives and the simulation stages

The 3D simulation of the grinding system has as main objectives the simulation of the wheat grain behavior, during the crushing process. The first phase of this stage represents the generation of the geometrical model followed by the generation of the discredited model. Between the two phases the simplified hypothesis with the help of which the model can be run is applied.

In order to simplify the numerical calculation and to reduce the time of analysis, based on the longitudinal plane of symmetry of the analyzed grains, the geometry shall be reduced to half, and we suggest that the results be the same on both halves of the symmetry plane [2].

The simulation of individual wheat grains crushing using the finite element method, so that any program of computer-aided simulation can be used for the following steps: the pre-processing stage*;* the processing stage; the after processing stage.

The pre-processing stage. In order to achieve the grinding process it is necessary to know the values of the elasticity module of the material and of the Poisson coefficient, which were accepted in the case of wheat grain, of E = 50 MPa and of ν = 0.2. The crushing process of the wheat grain is realized between two plates. Thus the limit conditions will be: $Tx=Ty=Tz=0$, *and the rotations Rx, Ry* and *Rz* – free.

The wheat grains are compressed with an axial force, being placed upon two plates.

The geometry of the wheat grain is presented in Figure 2.

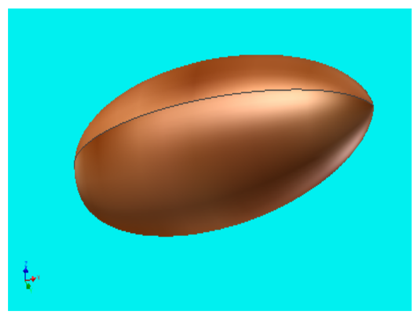

Fig. 2. *Geometry of the wheat grain*

The processing was done only on one half of the model, due to the geometrical symmetry and of the load of the system taken into consideration. The load module of the grain has been simulated by maintaining one of the working surfaces immobile, and the second surface being compressed with a surface force corresponding to each load case. The research made in the case of the wheat grain has a crushing force of 1000 N.

In the study conducted with finite elements, the basic concept is to analyze the structure of the geometric module, which is a set of discrete elements, connected together through a finite number of nodes. The operation of making such networks is known as meshing.

In the Comsol Multiphysics program, free, extruded and rotated meshing can be created, and also meshing on separation surfaces. Free meshing is the only method by means of which any type of geometric object can be meshed (Figure 3) [3].

The processing stage. During the processing stage we first chose the regime of the analysis used, thus being chosen an analysis of a transitory regime.

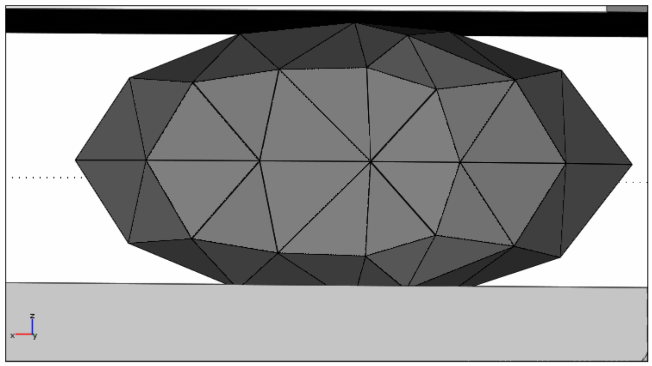

Fig. 3. *Digitations of a wheat grain in finite element*

The modeling process of the wheat grain crushing usually requires solving a full set of equations as well as those of Maxwell, which were theoretically described as complex interactions of the crushing force, the deformations resulted and the energy consumed in the crushing process.

The post processing stage. In the after processing stage the graphical representations of the selected sizes for storage from the previous phase are made as well as the listing of their values. The graphical presentation is made in the form of cut-outs. Each cut-out has a specific color and contains the region of geometric model where the specific size has the value defined in the chromatic legend, attached to the graphical representation.

The entire calculation has been realized with double precision by imposing a criterion of convergence of 10^{-6} of all residues to reduce the numerical errors.

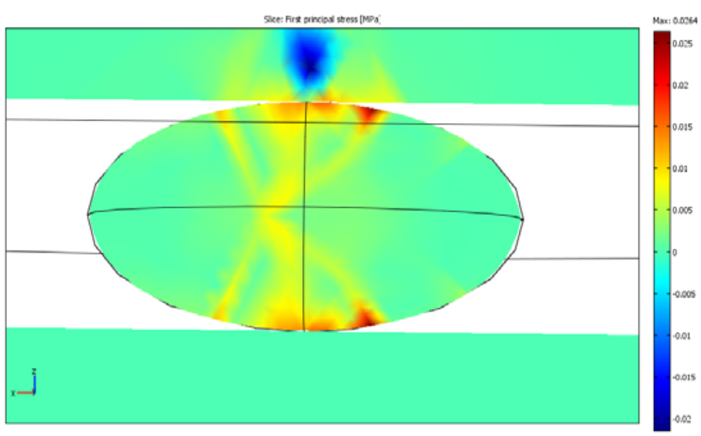

Fig. 4. *Values obtained during the first compressions to crushing of the wheat grain*

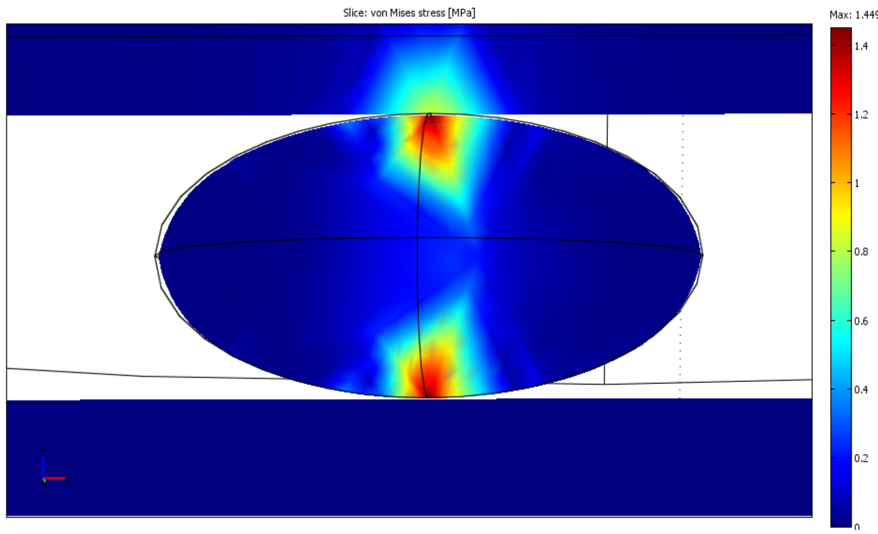

Fig. 5. *Compression values in the wheat grain [MPa]*

Analyzing Figure 4, we can see the first cracks that appeared in the wheat grain during the crushing process. We can also observe that the maximum values that are obtained are of approximately 0.0025 MPa.

In Figure 5 the compression values that appear in the wheat grain are presented. If we analyze these values we can see that the maximum compression that occurs in the wheat grain to a maximum strain of 1000 N is of approximately 1.5 MPa (the red color).

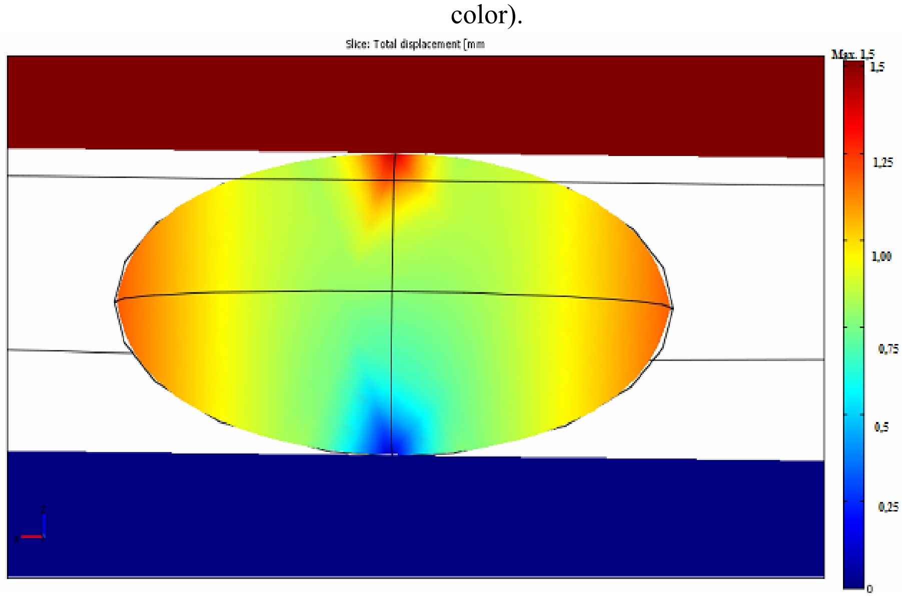

Fig. 6. *Grain deformations on crushing direction [mm]*

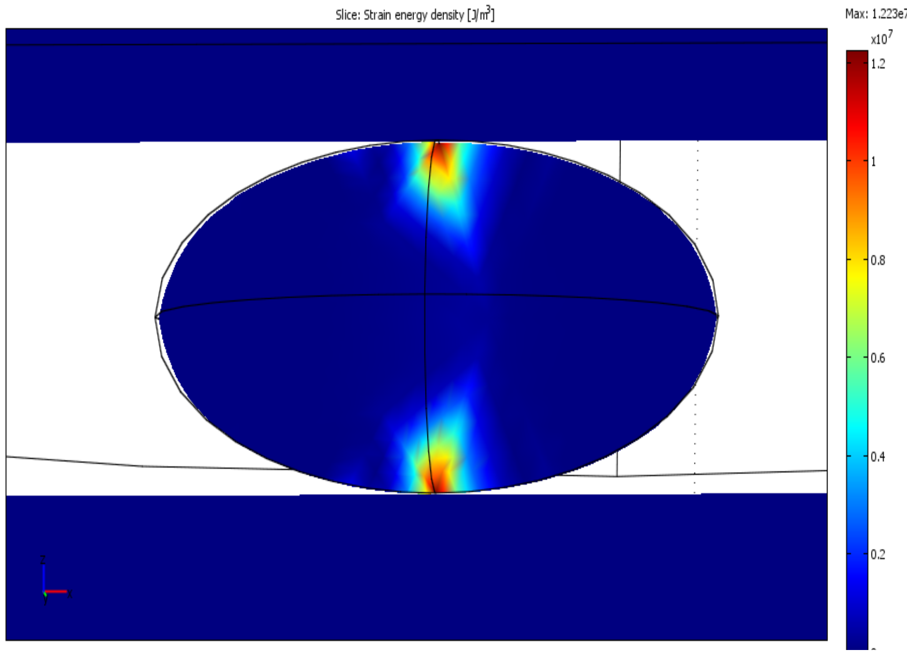

Fig. 7. *The energy values obtained as a consequence of the grinding process by wheat grain crushing [J/m^3]*

In Figure 6, the values regarding the deformations of the wheat grain crushing are presented. Analyzing these values, it was found that the maximum deformation of the grain is of approximately 1.5 mm.

Concerning the energy consumed during the crushing process, Figure 7 shows that the maximum power produced is of 1.25 • 107 J/m^3.

Conclusions

1. Although modern theories on grinding represent a real progress in understanding the grinding process, they have not completely managed to solve the problem of estimating the energy consumption. Also, these theories did not completely remove the classical assumptions.
2. During the simulation, we can see the first cracks and their maximum values which appear in the wheat grain and maize during the crushing process. We can determine the values of the tensions that arise in the wheat grain. By analyzing these values we can see that the maximum pressure that occurs in the wheat grain to a maximum compression of 1000 N is approximately 1.5 MPa.
3. Also as a consequence of simulation, the energy consumed during the crushing process and the deformations of the wheat grain on the crushing direction can be determined. Analyzing these values, we found that the maximum deformation of the grain is of approximately 1.5 mm.
4. Depending on the level of compression, the grinding process takes place in two stages: a first stage where under the action of compression force crack appear in the particle mass, and the second stage, where the force exceeds the critical value, and the cracks rapidly convey and split, and from the material mass fragments fall off, causing the crushing itself.

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