STRUCTURAL ANALYSIS OF A PROFILED TUMBLER USED WITHIN A MACHINE FOR MODELLING BAGELS DOUGH

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In the literature, there are few studies on the structural analysis of bagels and pasta dough modelling machines. This paper presents the structural analysis of the profiled tumbler of such a machine. The purpose of the study was to obtain the reactions from bearings, equivalent stress, displacement, equivalent deformation, safety factor, as well as the power required to operate.

Keywords: profiled tumbler, FEM analysis, dough modelling

1. Introduction

The modelling process follows the final shape of the product, which develops evenly when baked. The modelling operation is a deformation obtained by the action of external forces and it is done in order to even out the structure of the dough [1]. The action can be achieved by passing the dough mass between two tumblers that rotate in the opposite direction or a rotating tumbler and a hard surface [2]. The tumblers pull the sheet of dough between them, reducing its thickness to one given by the distance between them. The tumblers can have different diameters or the same diameter [3]. Rolling and drawing dough is a common process in the food industry for bread, pizza, noodles or biscuits doughs [4-6]. There are many studies that address the formation of dough sheets by passing it through a pair of cylinders and the impact that this process has on its behaviour during the baking stage, as well as on the properties of the finished product. Instead there are few studies on the structural analysis of modelling machines [7]. Studies focusing on

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the structural analysis of modelling machines, are mainly machines that are used in other industries, such as plastic or steel. The rolling process is considered similar to calendering [1, 7-8].

For this reason, a structural analysis of a profiled tumbler of a bagels dough modelling machine using finite element 3D numerical simulation was proposed in this paper.

2. Material and method

The purpose of this finite element 3D numerical simulation study was to simulate the behaviour of the structure of a profiled tumbler of a GR 15 MINI dough modelling machine, manufactured by Italpan, Italy [9].

In the first stage of this study, the simplified three-dimensional geometric model of a profiled tumbler and the simplified frame of the modelling machine were made. It should be noted that the dough is shaped between two profiled tumblers, actuated in a rotating motion, with the same speed and different directions of rotation. The two profiled tumblers are symmetrical in terms of execution. The dough is initially fed manually by an operator. After the dough comes in contact with the two tumblers, it is pulled by the tumblers, the intervention of the operator being no longer necessary. After modelling, the dough wicks are removed from the machine using a belt conveyor. It should be noted that throughout the modelling process the two profiled tumblers rotate at a constant speed.

The 3D modelling was performed using the parameterized design program Solid Works Premium 2016 S.P. 0.0.

The modelling of the components was done in the “Parts” module of the design program, Fig. 1a and Fig. 1b showing different views of a profiled tumbler, as well as the Solid Works program interface. Fig. 2 presents the assembly (in a simplified representation), containing the two profiled tumblers, the machine housing and the piece of dough considered for modelling.

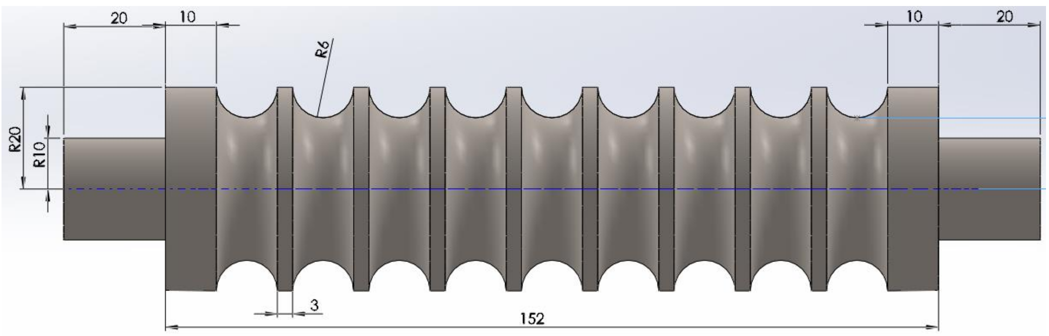

Fig. 1a. Profiled tumbler view

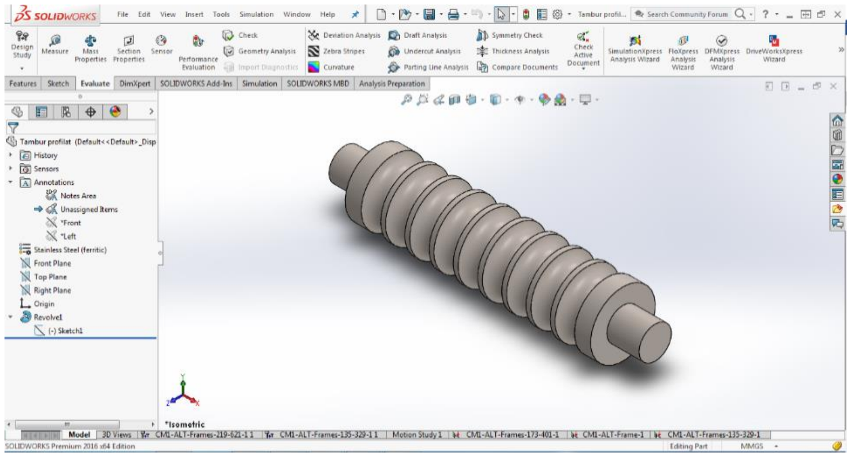

Fig. 1b. Profiled tumbler view

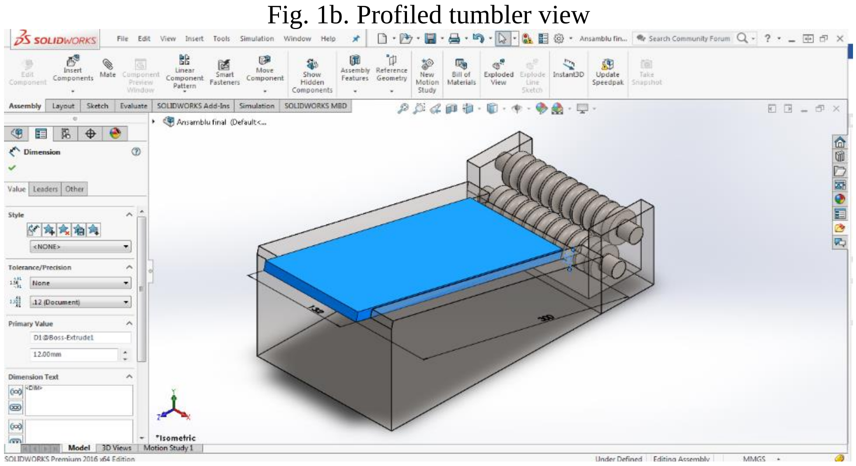

Fig. 2. Isometric view of the assembly as well as the interface of the software used

After making the parts in the ”Parts” module, it were introduced in the ”Assembly” module of the program where it were positioned by adding geometric relationships between their entities (constraints of concentricity, coincidence and parallelism between edges and faces). The machine frame was considered a fixed part, the two tumblers each have a degree of freedom (rotation about the OX axis) and the piece of dough has a degree of freedom (translation on the OZ axis). The piece of dough has the dimensions 300x132x12 mm (see Fig. 2).

Before performing the actual dynamic simulation, to each component of the assembly was assigned the material characteristics. So, according to the execution sheet of the machine the frame is made of an alloy steel [9], the profiled tumblers are made of stainless steel [9], and the dough characteristics were taken from several sources in the literature [10-16]. The values of the material characteristics are presented in Table 1, it should be noted that for the dough were used 55% water and 10% oil reported to the amount of flour.

Table 1

Mechanical properties of the materials used in the study [10 -16]

Material / Property	Alloy steel (for machine frame)	Stainless steel (for tumblers)	Bagels dough
Modulus of elasticity, N/mm^2	210000	200000	0.123
Poisson's ratio, -	0,8	0.28	0.49
Shear Modulus, N/mm^2	79000	77000	0.00345
Mass Density, kg/m^3	7700	7800	1200
Tensile Strength, N/mm^2	723.23	516.61	0.081
Yield Strength, N/mm^2	620.422	172.34	3.5
Thermal Expansion Coefficient, 1/K	1.3e-005	1.1e-005	1.12e-004
Thermal Conductivity, W/(m·K)	50	18	0.42
Specific Heat, J/(kg·K)	460	460	1682

After entering the material characteristics for each component, the whole assembly of Fig. 2 was introduced in the "Motion Study" module to perform the dynamic simulation of the bagels dough modelling process. The contacts were first established: on the one hand between the profiled tumblers and the machine frame, and on the other hand, between the dough and all the components of the assembly.

A rotary motor with a speed of 29 rpm was attached to the two profiled tumblers (speed measured right on the modelling machine) and with opposite directions of rotation, see Fig. 3.

Instead, to piece of dough was attached a linear motor with a speed of 60.2 mm/s, see Fig. 4. It was considered that immediately after contact with the two profiled tumblers, the speed of advance of the piece of dough is equal to the peripheral speed of the tumblers. Knowing $v_p = \omega \cdot R$, where $\omega = (\pi \cdot n)/30$, n = 29 rpm and R=20 mm (maximum radius of the profiled tumblers), resulted in the value of 60.7 mm/s for the feed speed of the dough piece.

The dynamic simulation was made assuming that the piece of dough is homogeneous in any section of it.

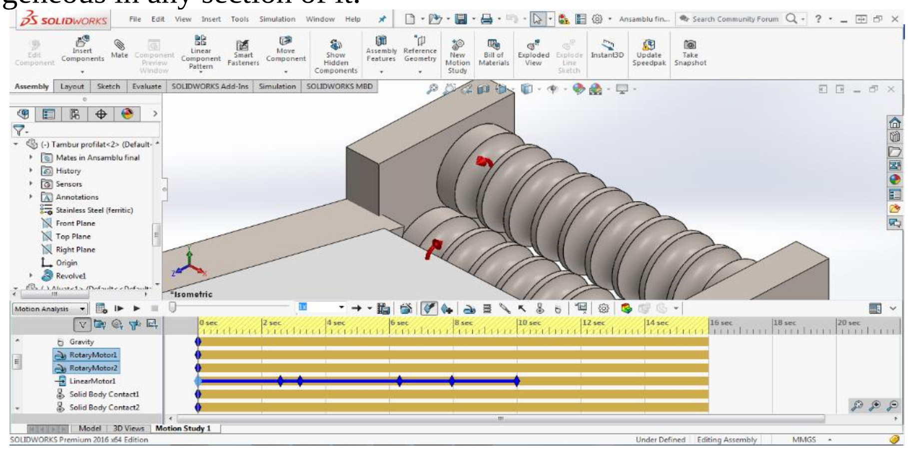

Fig. 3. Rotary motors attached to the two profiled tumblers

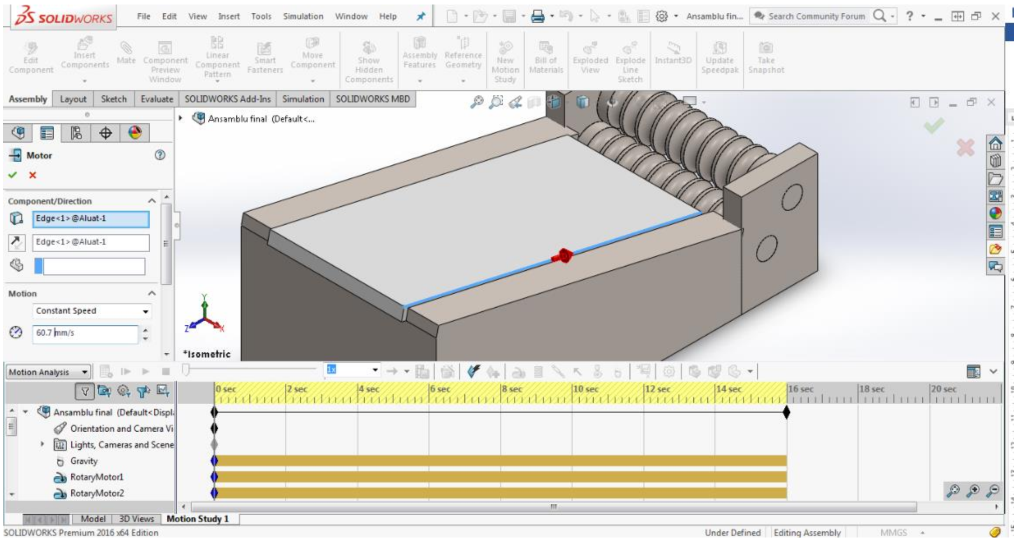

Fig. 4. Linear motor attached to the dough piece

It should also be mentioned that the calculation period (dynamic simulation) was 16 s, below is presented only the time between the feeding of the dough between the two profiled tumblers (t=3.47 s) and the moment of evacuation of the dough between the two profiled tumblers (t=8.79 s).

Following the dynamic simulation, the values of the stresses in the profiled tumblers were obtained. So, in Fig. 5 the curve of variation of the reaction force in the right bearing for the upper profiled tumbler is shown, and in Fig. 6 – the reaction force variation curve in the left bearing for the same tumbler. For the following analysis only the upper tumbler was considered, because the stresses are similar for the two profiled tumblers.

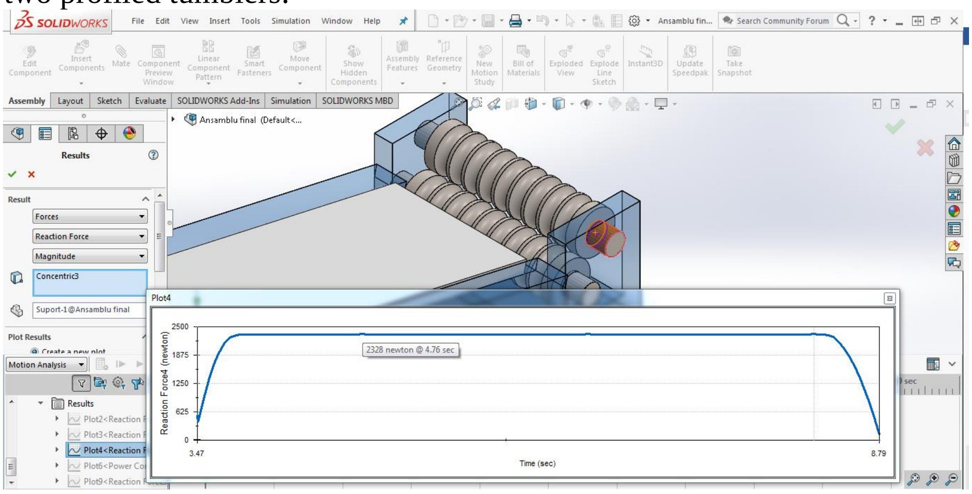

Fig. 5. Variation curve of the reaction force in the right bearing for the upper profiled tumbler

It can be seen from figure 5 that the maximum reaction force in the right bearing is 2328 N and is reached at the time of 4.76 seconds from the beginning of the simulation, or at time t = 1.02 seconds when the dough is fed between the profiled tumblers. For the left bearing the maximum reaction value is less than 5 N (2323N), but it is reached a little faster, at t = 3.96 s from the beginning of the simulation or at 0.49 s from the moment when the dough is fed between the two profiled tumblers.

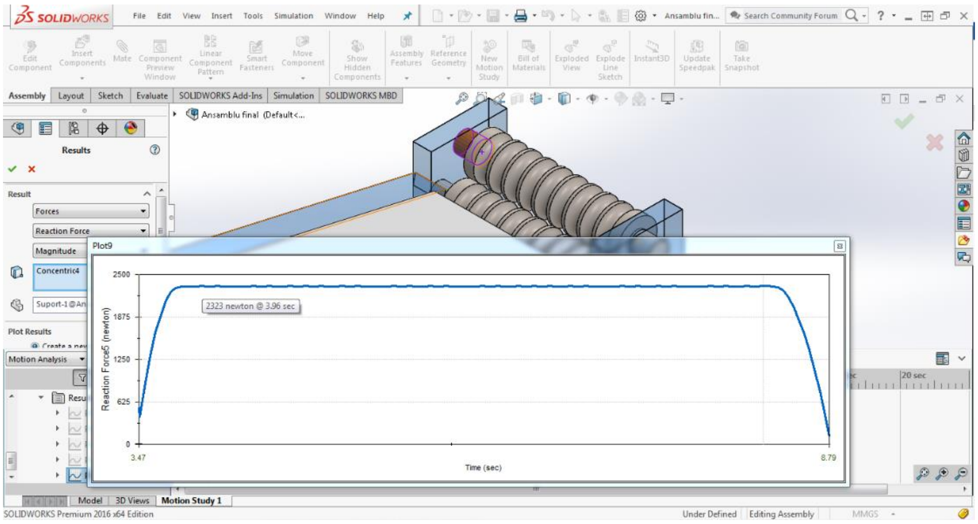

Fig. 6. Variation curve of the reaction force in the left bearing for the upper profiled tumbler

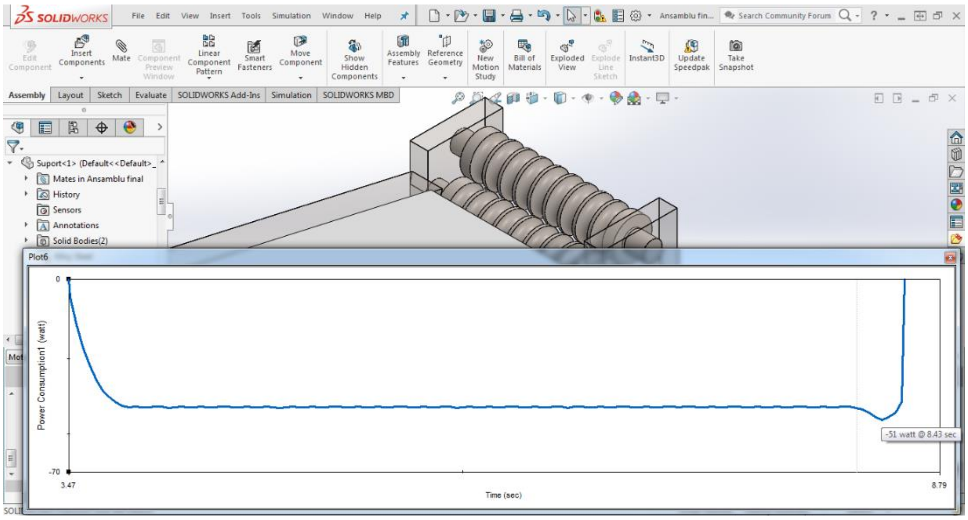

Fig. 7. The variation curve of the power requirement

In Fig. 7 the variation curve of the power requirement is represented. It can be seen that the power required for the modelling process is a maximum of 51 W. It must be specified that the actuating power from the technical book of the dough modelling machine is 144 W. The bagels dough can be considered to be a dough with a lower stiffness as opposed to some pasta doughs that have a lower water content and, therefore, greater stiffness, thus leading to a higher power requirement. Still, it can be concluded that the engine is slightly oversized for this working process.

After completing this step, proceeded to the next stage which consisted in importing the stresses for the 3D geometric model of the upper profiled tumbler in the “Simulation” module of the Solid Works design program.

To validate the results obtained from the numerical calculation, by the finite element method, an analytical calculation was performed for the calculation of the maximum stress and the maximum displacement for the upper profiled tumbler. Both the maximum stress and displacement were calculated for the median area of the tumbler.

The tumbler was considered to have a constant section, with a diameter of 28 mm, that the pressure is evenly distributed along the entire length of the tumbler and that the reactions in the bearings are equal (being calculated the arithmetic mean of the reactions obtained from the dynamic simulation). In Fig. 8 the bending moment variation diagram for the upper profiled tumbler is shown. The analytical calculation was made on the assumption that the profiled drum is similar to a simple bar supported at the ends and loaded with a uniformly distributed load [17].

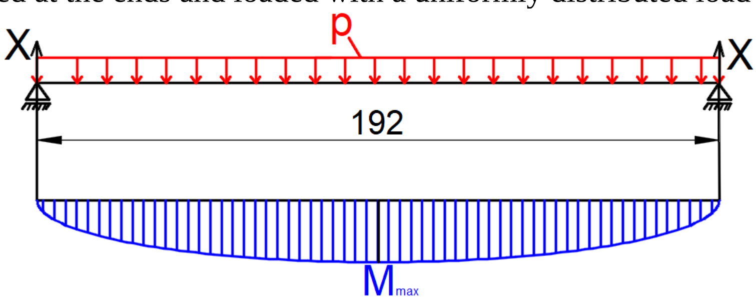

Fig. 8. Bending moment variation diagram

As previously mentioned, the maximum reaction in the right bearing is 2328N, and in the left bearing is 2323 N. So, the value taken into account for the analytical calculation was the average of the two reactions, noted X.

Knowing the value of the reactions in the bearings, it was possible to determine the value of the pressure with the following relation:

$$p \cdot l - 2X = 0 \Rightarrow p = \frac{2X}{l} \quad \text{[N/mm]} \tag{1}$$

Using the pressure value, the maximum moment could be calculated and its diagram was drawn:

$$M_{max} = \frac{p \cdot l^2}{8} \quad \text{[N/mm]} \tag{2}$$

The maximum bending stress will be:

$$\sigma_{max}^{inc} = \frac{M_{max}}{W_y} \quad \text{[N/mm}^2\text{]} \tag{3}$$

where W_y is the modulus of bending strength and is calculated with:

$$W_y = \frac{\pi \cdot d^3}{32} = \frac{\pi \cdot 28^3}{32} \quad \text{[mm}^3\text{]} \tag{4}$$

The maximum arrow in the middle of the profiled tumbler will be:

$$\delta_{max} = \frac{5 \cdot p \cdot l^4}{384 \cdot E \cdot I_y} \quad \text{[mm]} \tag{5}$$

where E – the modulus of elasticity for the material from which the profiled tumbler is made (shown in Table 1 and equal to 200000 MPa), and I_y – the moment of inertia that can be calculated with the relation:

$$I_y = \frac{\pi \cdot d^4}{64} \quad \text{[mm}^4\text{]} \tag{6}$$

3. Results and discussions

Below are the results obtained from the finite element analysis and the results of the analytical calculation.

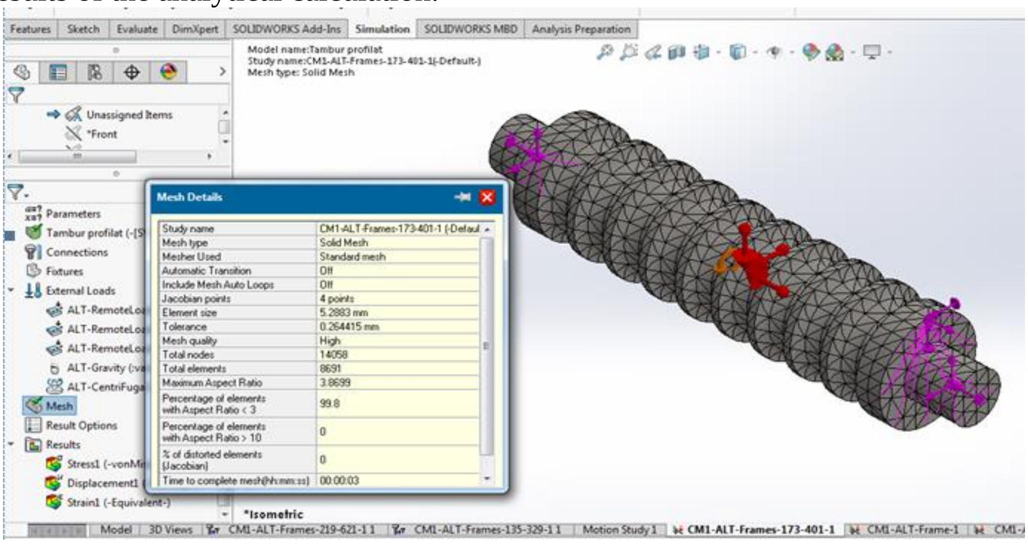

Fig. 9. Finite element discretization of the geometric model

In Fig. 9 the discretized model with finite element of the profiled tumbler is presented. For mesh was set up an adaptive method with a target refinement off 98%.

Following the simulation, the design program provided the results obtained in graphical form; the geometric model is divided into areas of a certain colour, each area comprising the region of the geometric model in which the analysed size has the value specified in the colour legend on the right side of the screen. The results have a maximum error of 10^{-5}. The "Simulation" module of the program used It has this implicit default value. The iterative calculation will end when the value of 10^{-5} for residual values.

For the profiled tumbler model that has been modelled and analysed, the results obtained after the simulation in Solid Works are presented. Therefore, Fig. 10 shows the displacement values that appear in the profiled tumbler during the previously defined stresses.

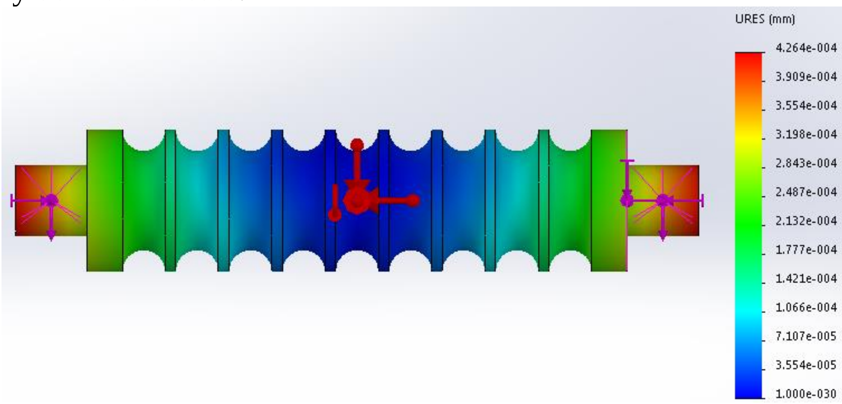

Fig.10. Displacement values in the profiled tumbler

It is observed that the value of the displacement under the simulation conditions is extremely small (0.4 μm) as opposed to the calculated maximum displacement (70 μm). It should be noted that the displacement is for the centre of the profiled tumbler towards the ends and it can also be mentioned that those rings with a diameter of 40 mm stiffen the tumbler.

In Fig. 11 the values of the equivalent stresses in the profiled tumbler are presented, stresses calculated according to the von Mises criterion.

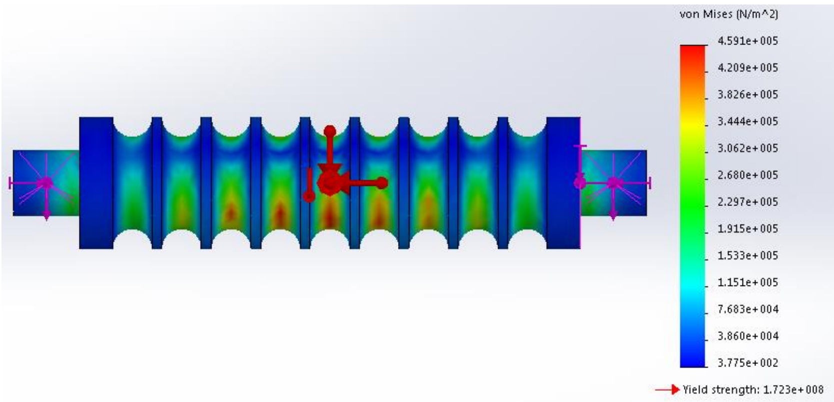

Fig.11. Equivalent stresses values according to the von Mises criterion

Analysing the figure it can be seen that the highest equivalent stresses (0.46 MPa) appear in areas of minimum diameter (28 mm), and their values are well below the breaking stresses (172.3 MPa) for the specific material applied to this part.

In Fig. 12 the equivalent deformations in the profiled tumbler are shown. Analysing this figure it can be seen that these equivalent deformations occur in the same areas of minimum diameter (28 mm).

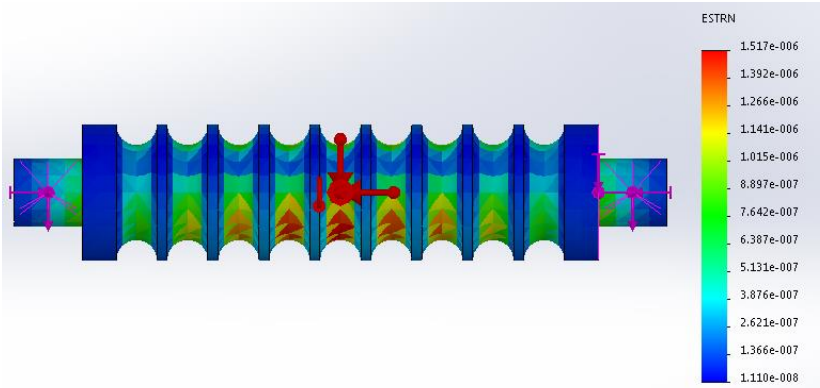

Fig.12. The equivalent deformations in the profiled tumbler

In Fig.13 the oscillation of the safety factor in the profiled tumbler is shown.

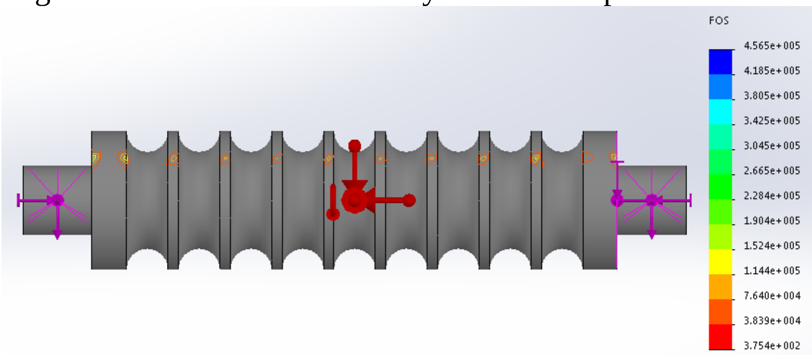

Fig.13. The oscillation of the safety factor in the profiled tumbler

The minimum value of the safety factor is reached in the areas where the longitudinal cutting of the dough is carried out, as expected, because these areas are the most requested. Regarding the distribution of the graph, it can be recommended that the cutting areas are no longer executed with double edges but with a single edge. This will increase the pressure on the piece of dough when cutting longitudinally, thus reducing the stresses in the profiled tumbler.

Using relations (1-6), were obtained: the value of 24.22 N/mm for pressure (p), 111605.76 Nmm ≈ 111.6 Nm for the maximum moment (M_{max}), 2154.04 mm^3

for the bending strength module (W_y), 5.38 N/mm^2 for maximum bending stress (σ_{max}^{inc}), and for the maximum arrow in the middle of the profiled tumbler (δ_{max}) and the moment of inertia (I_y), were obtained 0.07 mm, respective 30156.56 mm^4.

4. Conclusions

In the paper was performed a structural analysis of a profiled tumbler of a bagels dough modelling machine.

Thus, regarding the distribution of the graph for the safety coefficient, it can be recommended that the cutting areas to be no longer executed with double edges but with a single edge. This will increase the pressure on the dough piece when cutting longitudinally, thus reducing the stresses in the profiled tumbler.

Also, the dynamic simulation showed that for a bagels dough with a water content of 55%, the power consumed at modelling the dough will be 51 W, well below the installed power of the modelling machine (144 W). In order to reduce the energy consumption of such machines, it is recommended that the engines to be no longer oversized. Even if it would reduce the water content of the dough, thus increasing its rigidity, the authors believe that a 100 W electric motor was sufficient for the modelling machine to operate in good condition.

The article can be helpful to both technological engineers on bakery or technological flows, as well as for machine manufacturers in the two industries.

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