# Numerical analysis of the coupled thermal-stress strength of the active grooved feed zone in an innovative extruder for polymeric plastics

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# Numerical analysis of the coupled thermal-stress strength of the active grooved feed zone in an innovative extruder for polymeric plastics

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**Summary**

The article presents a new concept of active grooved feed zone in an extruder for granular polymer plastics.The innovation of this concept lies in the use of a properly shaped sleeve with a set of grooves and a closing element moved by the actuator so that it is possible to change the length of the grooves during the extrusion process.Numerical calculations using finite element method are presented. They were a temperature-displacement coupled analysis, which was a geometrically and physically non-linear issue. The obtained results of calculations confirmed the sufficient strength of the structure of this extruder zone. The professional ABAQUS® software was used for the computations.

***Keywords***: *active grooved feed zone of the extruder, polymeric materials, finite element method.*

## 1. Introduction

The development of modern extruders for the production of polymeric elements is focused on the appropriate selection of geometric parameters of the device elements, ensuring the achievement of optimal parameters of the manufacturing process. In the literature there are many examples describing the influence of geometric features of the feeding zone on the performance and pressure of plastics in the plasticizing system of an extruder[1,2,3]. In this respect, the best extruders were those with a grooved zone, which allows for an increase in productivity and pressure by several dozen percent[4,5].

Moreover, the quality of the extrudate obtained is confirmed by the degree of mechanical and thermal homogenization of the material. In order to obtain it in a satisfactory degree, it is necessary to use additional devices - static mixers in the process line. This is particularly important in the case of filled plastics, including nanofillers, which can be agglomerated in many cases, reducing the quality of the resulting products. Glogowska and Sikora[6] stated that, the modification of polymers by a wide variety of fillers causes numerous changes in processing, mechanical properties and morphology of product structure, and, like others, admitted that the properties depend primarily on good mixing.

The adjustable grooved feed section, which has been known for thirty-five years now, cannot boast a large number of design solutions, with most existing designs coming from the United States[7-10]. Unlike its non-adjustable counterpart, the adjustable grooved feed section has not yet been used in industrial processing machines. Only a few original designs of the adjustable grooved feed section have been proposed so far and their characteristics have been evaluated using specially built laboratory extruder prototypes. The adjustable grooved feed section differs from the non-adjustable section in that its design parameters can be changed during extrusion without the need to interrupt the process. The parameters in question include the number of grooves, their inclination angle, handedness, depth, and cross sectional shape. The adjustable grooved feed section was invented by Meyer, who first described his invention in 1983 in US Patent No. 4462692[6]. There are also several later Polish patents for this part of the extruder[11÷13].

The grooved zone is a very important structural element of the extruder, which significantly influences the effectiveness of mixing the plastic and the efficiency of the device.

The main aim of this work is to present an innovative concept in which the grooved zone can change its geometrical parameters during the operation of the machine. We will also provide numerical calculations in which the presented solution will be evaluated in terms of strength. The analyzed conceptual model is a fully functional solution, tested in terms of strength and temperature, and therefore ready for further commercialization.

## 2. The concept of active grooved feed zone with the possibility of changing the length of grooves during the extruder operation

The most important characteristic of this solution is the possibility to change the length of the grooves while maintaining their other geometrical features. The main element of the presented grooved section is an appropriately shaped sleeve with grooves and openings, through which goes a specially shaped and well fitted element with a group of inlets. It is put into motion by two pneumatic or hydraulic cylinders. The axonometric view of this grooved section is shown in assembly Figure 1 (in a fully open and closed position), while in Fig. 2 an exploded view is shown.

a) b)

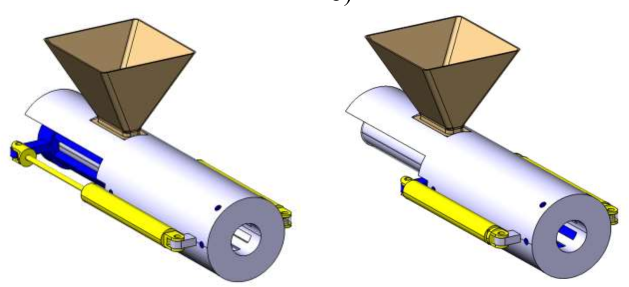

Fig.1.Grooved feed section with:
a) fully open grooves b) completely closed grooves

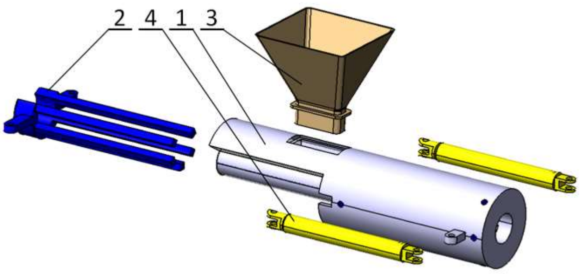


Fig.2.Exploded view of a concept model: 1 – main sleeve, 2 – closing element with a group of inlets, 3 – polymer hopper, 4 – pneumatic cylinder

Main sleeve 1 is a crucial element of the conceptual model. Inside, it contains six irregularly arranged grooves, and in the rear part, in a way, under the polymer hopper 3, there is a semi-circular guide along which, in a sliding motion, the closing element 2 with a set of tightly fitting inlets can move. This element is driven by pneumatic cylinders 4. The irregular arrangement of the grooves results from structural conditions (collision with the hopper).

The feeding zone is cooled with water by a set of channels running along the extruder, which are led out radially. The arrangement of the cooling channels is shown in Figure 3.

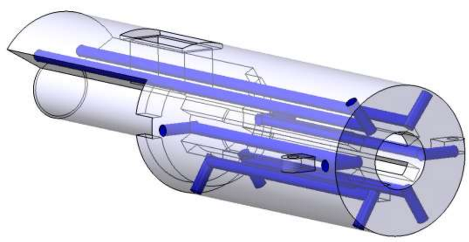

Fig.3. Cooling channels in the main sleeve

## 3. Numerical FEM calculations

### *a. Numerical calculation methodology*

Numerical calculations were carried out using the finite element method. The scope of numerical simulations included the analysis coupled with temperature and displacement, which is a combination of static strength analysis with thermal analysis, enabling the determination of stress distributions and temperature distribution within the area of the analyzed structure[14÷17]. In this case, the basic fully coupled thermal-stress analysis equation takes the form:

$$\begin{bmatrix} K_{uu} & K_{u\theta} \\ K_{\theta u} & K_{\theta\theta} \end{bmatrix} \begin{Bmatrix} \Delta_u \\ \Delta_\theta \end{Bmatrix} = \begin{Bmatrix} R_u \\ R_\theta \end{Bmatrix} \tag{1}$$

where:
$\Delta u$ i $\Delta\theta$ are the respective corrections to the incremental displacement and temperature, Kij are submatrices of the fully coupled Jacobian matrix, and Ru and Rθ are the mechanical and thermal residual vectors, respectively. Solving this system of equations requires the use of the unsymmetric matrix storage and solution scheme. Furthermore, the mechanical and thermal equations must be solved simultaneously. The method provides quadratic convergence when the solution estimate is within the radius of convergence of the algorithm.

Numerical calculations were a geometrically and physically nonlinear issue, which was solved using Newton-Raphson's incremental-iteration method[18÷21]. For modelling and calculation, the commercial FEM package, ABAQUS®, was used.

### *b. Discretization of construction*

The discretization of the geometric model was made with the use of tetragonal fixed elements, type C3D10, which constitute 10-nodal elements with the shape function of the second order and full integration. Additionally, in thermal analysis, tetragonal elements, type C3D10MT were used to enable to take into account in a numerical analysis a thermal degree of freedom. The FE model is shown in Fig. 4.

The elements of the extruder analyzed in the paper were made of steel marked 40HM, for which the following material and thermal properties were accepted (table 1).

a) b)

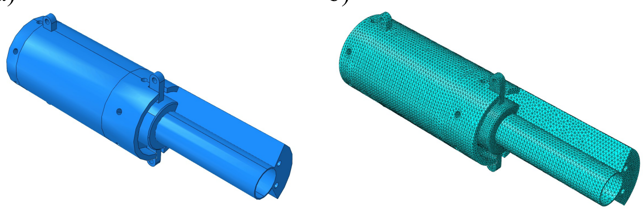

Fig.4. FE model of the adjustable grooved section: a) the assembly of the main components b) discretized model with generated mesh

Table 1. Mechanical and thermal properties of steel 40HM

| **Material property – steel 40HM** | |
|---|---|
| Young modulus E [Pa] | $2.1\cdot10^{11}$ |
| Poisson number [ - ] | 0.3 |
| Yield strength $R_e$ [Pa] | $8.8\cdot10^{+11}$ |
| Strength limit $R_m$ [Pa] | $1.03\cdot10^{12}$ |
| Elongation at break [%] | 10 |
| Density ρ [kg/m$^3$] | 7860 |
| Linear expansion coefficient [1/K ] | $1.2\cdot10^{-5}$ |
| Heat conduction coefficient λ [W/(m·K)] | 58 |
| Specific heat [J/(kg·K] | 450 |

In order to imitate the cooperation of joint elements of the model, interactions of type *Tie* were defined - they ensure a constant connection of elements through joining all degrees of freedom on contacting surfaces of construction elements. In this way it was possible to model the possibility of constant transfer of loads and displacements between the joint construction elements. In the case of cooperation of construction elements consisting in taking into account mutual mechanical and thermal influences, contact interactions were used, which enable to model mechanical influence at the normal and tangential direction of the cooperating elements of the model as well as take into account the possibility of heat transfer on the surfaces of cooperation.

*c. Boundary conditions and loading of the discreet model.*

The definition of boundary conditions in numerical model was carried out by fixing nodes placed in the specified mounting surfaces of the actuators, blocking the possibility of their displacement in all directions. Boundary conditions with marked fixing surfaces, defined in the openings of mounting holders, are presented in Fig. 5a (orange cones).

In strength analysis, the loading of the model was constituted by the pressure caused by the transfer of polymer pellets in the extruder screw. In this case, the exponential pressure distribution along the grooved section equalling $L_R = 100$ mm, whose maximum value (at the end of the section, counting from the feed opening zone) equalled p = 10MPa. The scheme of introducing pressure into the construction of the grooved section is presented in Fig. 5a-5b (purple arrows).

a) b)

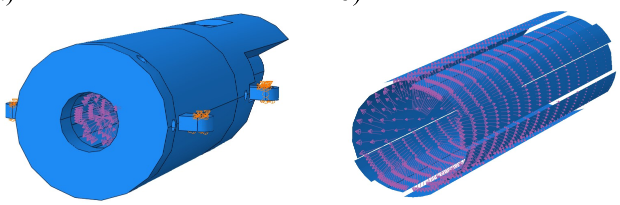

Fig.5. a) Boundary conditions and loading of the pressure b)exponential pressure distribution along the grooved section.

In thermal analysis, loading was constituted by temperature produced by friction of polymer pellets transported by the screw. Temperature was applied to the surface of the grooved section in an analogical way as pressure, e.i. exponential distribution was accepted along the grooved section equalling $L_R = 100$ mm, whose maximum value (at the end of the section, counting from the feed opening zone) equalled T = 120$^0$C. The initial temperature of the numerical model was accepted as $T_0 = 22^0$C. The scheme of introducing temperature load into the construction of the grooved section is presented in Fig. 6. Additionally, systems of cooling with liquid of temperature $T_c = 10^o$C were used. The arrangement of the cooling channels is shown in the Fig. 3. In thermal calculations, it was accepted that the time of duration of numerical analysis was equivalent to the time of constant extruder operation equalling t = 5 hours.

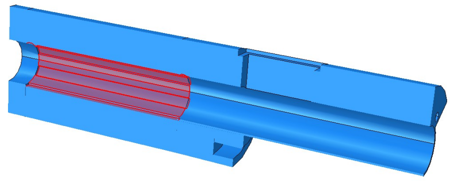

Fig.6. Loading the grooved section with temperature.

## 4. Results of numerical calculations

A strength and stiffness analysis of particular construction elements was conducted on the basis of the distributions of reduced tension, determined in accordance with Huber-Mises-Hencky strength hypothesis in the area of analysed construction and displacement of nodes of its particular elements. Distributions of tension, displacements and temperature are presented in the form of colourful contour maps against the background of the deflected model, in which the red colour indicates maximum values, while the blue colour minimum values.A general view of reduced tension against the background of the deflected model is presented in Fig. 7. The presented values of tension are expressed in [Pa].

a) b)

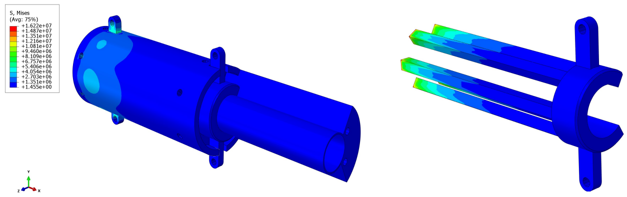

Fig.7. Distribution of reduced tension H-M-H in the elements of the grooved section (a), in the closing element (b).

Maximum reduced tension in the elements of the grooved section in the case of mechanical load equal approximately $\sigma_z \approx 16$ MPa and appear in the material of the elements which adjust the length of the grooves. The value of the received tension does not exceed the yield point, which, according to accepted material properties for steel 40HM equals $R_e = 880$ MPa. It means that the level of reduced tension appearing in the construction for the considered case of load does not threaten a safe operation of the construction.

Fig.8 presents total displacement of nodes of the numerical model closing element with a group of inlets expressed in [m].

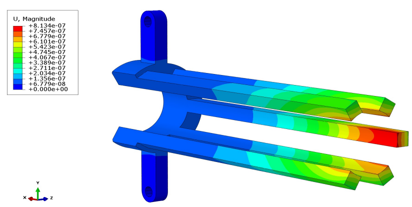

Fig.8.Map of nodes displacements of the closing element model.

Analysing the values of nodes displacement, the maximum values of deflection were located in inlets which adjust the length of grooves. It equals 0.0008 mm, which constitutes a very small value, not threatening the correct operation of the construction.

Fig. 9 presents maps of temperature distribution in the elements of the grooved section, corresponding to 5 hours of constant operation of the plasticizing system of the extruder. The presented temperature values are expressed in [$^0$C].

a) b)

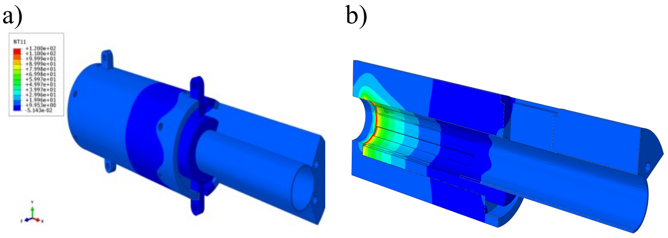

Fig.9. Distribution of reduced tension H-M-H in the elements of the grooved feed section (a), in the closing element (b).

Analysing the obtained temperature distributions in the area of the grooved section it can be stated that the applied cooling system was designed in a correct way. This is confirmed by temperature maps in the material of the inner body (Fig. 9a), directly exposed to the temperature action caused by the friction of pellets against the inner walls of the grooved section. The received temperature distribution shows that its high values equalling T = 120$^0$C persist only on the inner wall, while almost in the whole area of the inner body the level of temperature is low (light blue and light green colour) of values approximately T = 20 – 40$^0$C. The above temperature distribution in the area of the grooved section ensures a stable operation of the grooved section.

## 5. Conclusions

The conducted numerical analysis using the method of finished elements allows to formulate conclusions concerning the strength and thermal evaluation of the analysed variants of the extruder grooved section. On the basis of the received results of numerical calculations it was stated that for the analysed load case, the designed structures work in a safe range. This is confirmed by very low values of tension in the elements of construction, which do not exceed 17 MPa. Additionally, the received temperature distributions in the area of construction, corresponding to 5 hours of continuous work of the machine, confirm the proper cooling of the body of the machine, preventing from the distribution of high temperature values into the material of the grooved section of the extruder.

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