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UTILIZATION OF PLASTIC MATERIALS FOR PRODUCTION OF LOADED ELEMENTS OF PNEUMATIC SERVOS

Summary: The advantages of plastic materials applied for the production of vehicles and devices meant that they are used increasingly common also for production of loaded structural elements. In this work, we studied the possibility of replacing the aluminium housing of a pneumatic servo with fibre-reinforced plastic materials. The studies in question were conducted using the methods of coupled elements under the MOLDFLOW and ABAQUS system.
Keywords: polymers, injection moulding simulation, MOLDFLOW, ABAQUS.

INTRODUCTION

In construction of new machines and devices, elements or sub-assemblies made from plastic materials are used increasingly frequently. Availability of new materials with much better mechanical and thermal properties provide further possibility to extend the application of plastic materials in the development of machines and devices. Their application for development of mechanically loaded structure elements is a non-trivial task, since typical plastic materials have very low volumetric elasticity, simultaneously with much lower mechanical resistance, lower resistance to high temperatures and potential dynamic fatigue with long-term mechanical loads. In order to prevent such phenomena, plastic materials are reinforced with doping materials, such as fibres or glass balls, or even through chemical and thermal processing. In order to prevent such phenomena, plastic materials are reinforced with doping materials, such as fibres or glass balls, or even through chemical and thermal processing. In this work, we conducted simulation analysis of a design of a pneumatic servo made from plastic materials using fibre reinforcement.

FLOW MODEL

In order to examine the potential for proper injection of the designed element, computer-aided systems are used, employing appropriate flow models for the given plastic material. For example, in the Moldflow system, it was assumed that the injection mold is filled according to the fountain flow model. Individual parti-

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cles of the plastic material flow faster in the core region of the mould, while in the area adjacent to the stream front they are directed towards the surface. When the particles reach the surface, the solidification process takes place. The flow of the plastic material within the mould is presented in Figure 1. The speed of the plastic material particles moving around in the mould has a parabolic distribution. The highest speed value is observed in the core region, and diminishes gradually moving outwards. The solidification velocity changes in a similar manner, i.e. it has the highest value at the border of the liquid and solid material. The viscosity of the plastic material depends proportionally from the solidification velocity and temperature, and it reaches the highest value when both the parameters have their minimum, i.e. at the contact point between the liquid plastic material and the mould wall.

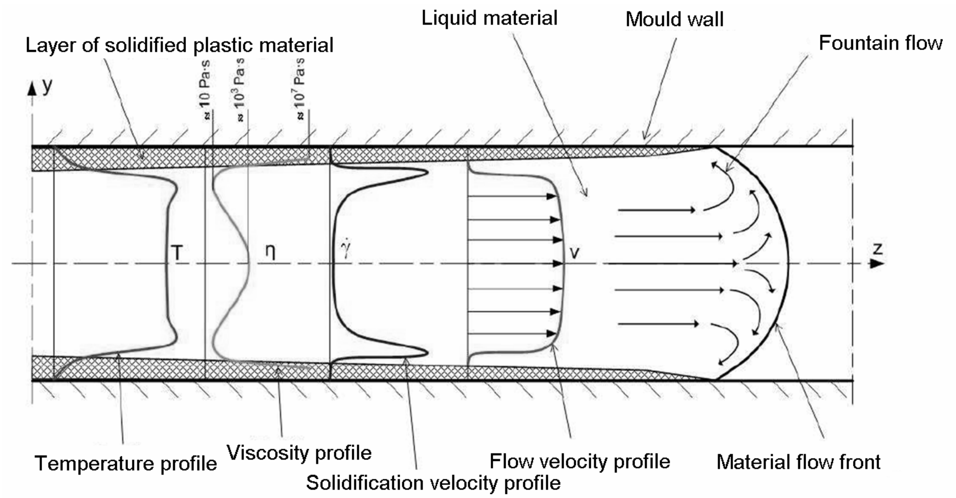

Fig. 1. The process of plastic material flow covering the flow speed, solidification velocity, viscosity and temperature characteristics [4]

The flow of plastic materials is complex in terms of liquid mechanics. Liquid plastic materials are considered non-Newtonian liquids, creating non-isothermal material injection model. The Moldflow system solves preservation equations for continuous media mechanics for the target material models under the strictly defined flow conditions. These equations represent the principle of preservation of motion, mass and energy and create the following set of equations [5]:

(mass) continuity equation
$$\frac{D\rho}{Dt} + \rho \; div \; \vec{v} = 0 \tag{1}$$

motion equation
$$\rho \frac{D\vec{v}}{Dt} = -grad \;\; p + div \vec{\tau} + \rho \; \vec{g} \tag{2}$$

Energy equation	$\rho\, c_p \dfrac{DT}{Dt} = k\nabla^2 T + \vec{\tau} : grad\ \vec{v}$	(3)
Definition of the material model, under specific flow conditions	$\vec{\tau} = F(D)$	(4)

Where:

$\dfrac{d\rho}{dT}$	- complete derivative of density against time,
ρ	- density,
$div\ \vec{v}$	- divergence of the velocity vector,
$\dfrac{D\vec{v}}{Dt}$	- complete derivative of the velocity vector against time,
$gradp$	- gradient of the hydrostatic pressure (the isotropic part of the stress tensor $\vec{\sigma}$,
$div\vec{\tau}$	- divergence of the extra-stress tensor (the deviator part of the stress tensor $\vec{\sigma}$,
g	- acceleration components,
$c_p \dfrac{DT}{Dt}$	- complete derivative of the internal energy, where c_p represents the specific heat capacity under constant pressure,
k	- thermal conductivity coefficient,
T	- temperature,,
$\vec{\tau}$	- extra-stress tensor,
$grad\ \vec{v}$	- tensor of the gradient of the velocity field.

These equations represent a set of six scalar equations, which results from the fact that the motion equation is of vector type. In this set, there are twelve unknown values: scalar functions of the hydrostatic pressure p and temperature T, function of the velocity vector $\vec{v}$, function of a symmetric stress tensor $\vec{\tau}$ and density ρ.

Currently, the Moldflow system is based on Jeffrey's equations and assumptions, who was the forerunner in research on mathematical model describing orientation of plastic materials within manufactured elements. A few improvements were introduced though, improving the precision of calculations when compared to the real distribution. Jeffrey reduced a single fibre to a non-deformed body with the shape of an ellipsoid (see Figure 2) [6]. The orientation tensor for this ellipsoid can be described as follows:

$$a_{ij} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \rightarrow \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}; \begin{bmatrix} e_1 & e_2 & e_3 \end{bmatrix} \tag{5}$$

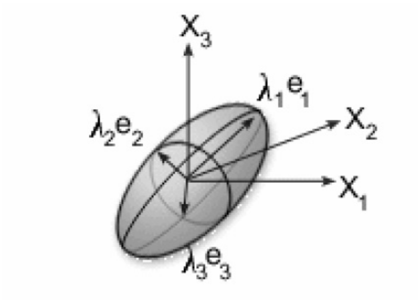

Fig. 2. Fibre model according to Jeffrey [6]

The verified version of the Jeffrey's equations is used by the Folgar-Trucker models, later employed within the Moldflow system.

These models assume the possibility of interaction between individual fibres, introducing possible random location of fibres in the core [1, 2]. This model is described with the following equation:

$$\frac{DA_{ij}}{Dt} + \frac{1}{2}\left(\omega_{ik} A_{kj} - A_{ik}\omega_{kj}\right) = \frac{1}{2}\kappa\left(\dot{\gamma}_{ik} A_{kj} + A_{ik}\dot{\gamma}_{kj} - 2\dot{\gamma}_{kl} A_{ijkl}\right) + 2C_1\dot{\gamma}\left(\delta_{ij} - 3A_{ij}\right) \tag{6}$$

Where:

A_{ij} and A_{ijkl}	– tensors of the second and fourth order orientation vectors,
ω_{ij}	– rotation tensor,
$\dot{\gamma}_{ij}$	– velocity and deformation tensor,
κ	– material constant, depending on the ratio between the fibre length L and its radius r $\kappa = \frac{\left(\frac{L}{r}\right)^2 - 1}{\left(\frac{L}{r}\right)^2 + 1}$,
C_1	– material constant, representing fibre interaction coefficient depending on the volumetric share of the fibres in the plastic material,
δ_{ij}	– deformation.

INFLUENCE OF MANUFACTURING PROCESS ON MATERIAL STRUCTURE

Changes in the thickness of the element walls, manufactured from plastic materials reinforced with glass fibres, generates automatically changes in the fibre distribution, which become oriented in the flow direction only next to the mould walls. This happens because when increasing the wall thickness, the thickness of cross-section where glass fibres are distributed in a random manner also increases, while the thickness of the layer with fibre oriented along the flow direction virtually does not change. This relationship is illustrated in Figure 3 [1].

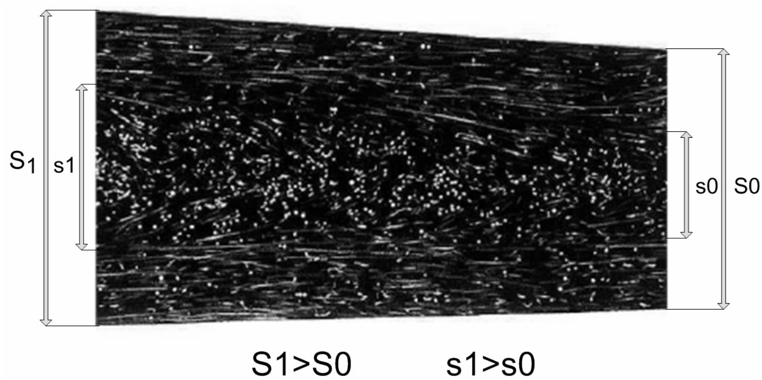

Fig. 3. Orientation of glass fibres in the core and edge regions S1-s1=So-so

When examining Figure 3, it is possible to note then when increasing the wall thickness, the share of the edge region in the wall cross-section decreases, while in the case of plastic materials reinforced with glass fibres, this particular edge region defines the overall element stiffness [7].

COUPLING LINES

During the injection of plastic materials, two of more flows can come across each other, creating thus the coupling lines. Varied wall thickness can also cause such coupling lines. Figure 4 presents results obtained under the Moldflow system, depicting the distribution of coupling lines for the edge injection process (injection - left side of the image).

Deterioration of the mould properties in vicinity of the coupling lines clearly depends on the type and number of injectors or reinforcing additives. This makes evaluation of the degree to which the mechanical resistance deteriorates in these locations more challenging. In the area of coupling lines, which are characterized with sufficiently good resistance to stretching, resistance to lateral mechanical load is not necessarily that good [3].

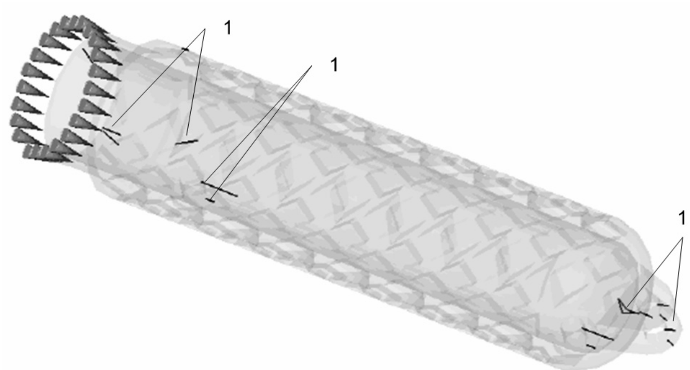

Fig. 4. Injection locations for a model of a servo body and coupling lines - 1

When using reinforcing materials, fibres are typically located transversely in the area of the coupling lines, causing deterioration in the mechanical properties of this particular element area, as depicted in Figure 5 [1, 2].

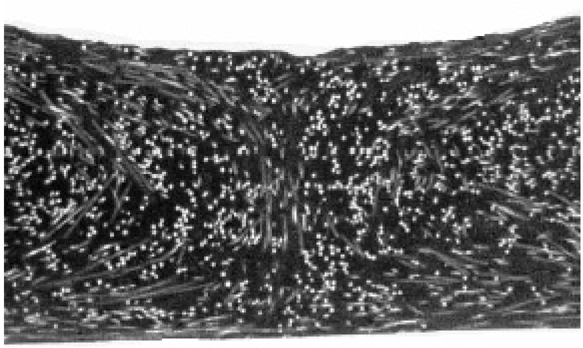

Fig. 5. Orientation of glass fibres in the vicinity of coupling lines

ANALYSIS OF MECHANICAL RESISTANCE OF PLASTIC MATERIALS ACCOUNTING FOR ORTHOTROPIC PROPERTIES

In components with orthotropic structure, anisotropy occurs in three, reciprocally perpendicular axes of symmetry. The schematic describing the procedure of analysis of mechanical resistance, accounting for orthotropic properties of the examined material, was presented in Figure 6.

Based on the above-referred schematic, it is clear that the work must be divided into two independent phases. In the first phase, it is necessary to simulate the process of injecting the plastic material in the servo body, based on which it is possible to observe the coupling lines for the plastic material (see Figure 4) as well as distribution of glass fibres in the core and surface layers of the element (see Figure 7).

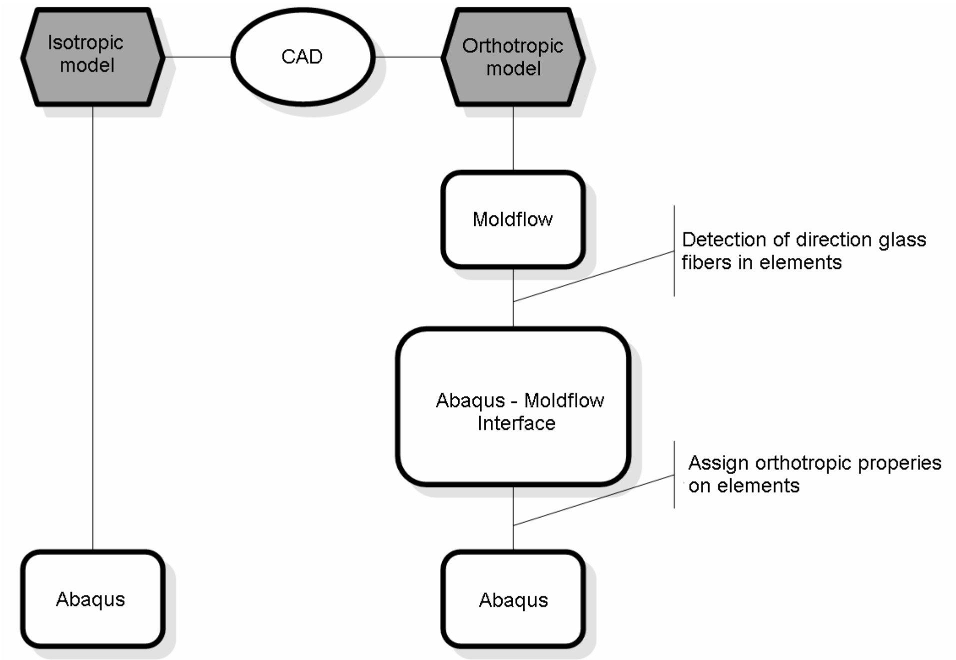

Fig. 6. Schematic representation of mechanical resistance analysis for a pneumatic servo body, accounting for orthotropic properties of the used materials.

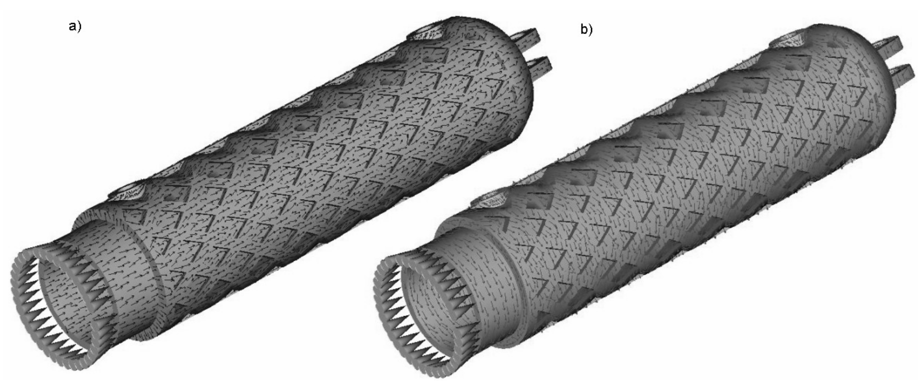

Fig. 7. Orientation of glass fibres in a) core layers of the servo body, b) surface layers of the servo body.

In the subsequent phase, special macros were created in the Python language, which examine the simulation results for the plastic material injection process obtained from the MoldFlow system and assign appropriate material properties to individual finite elements. The interface requires the appropriate location of the 3D model both in the Moldflow system and the Abaqus system, which was used to carry out the remainder of the mechanical resistance calculations. In this way, the mechanical properties of the plastic material were made dependent on the orientation of the fibres in the mould, achieving in this way the orthotropic structure of the examined component (see Figure 8) [8]. During the simulation of the plastic material injection process and mechanical resistance analysis carried out in the Abaqus system, material data was used as presented in Table 1.

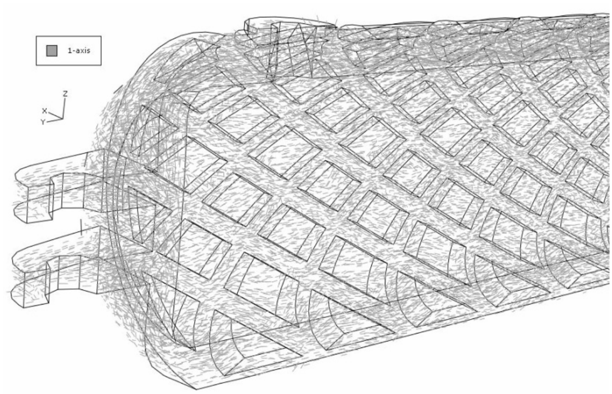

Fig. 8. Orthotropic structure of the examined component

Table 1. Information about PBT GF20

Material model	Young module	Poisson coefficient	Kirchhoff module	Density
Isotropic	E = 4200 [MPa]	ν = 0,3	-	1460 [kg/m3]
Orthotropic	E1 = 4200 [MPa] E2 = 2700 [MPa] E3 = 2700 [MPa]	ν12 = 0,3 ν13 = 0,35 ν23 = 0,35	G12 = 2300 [MPa] G13 = 2300 [MPa] G23 = 2600 [MPa]	1460 [kg/m3]

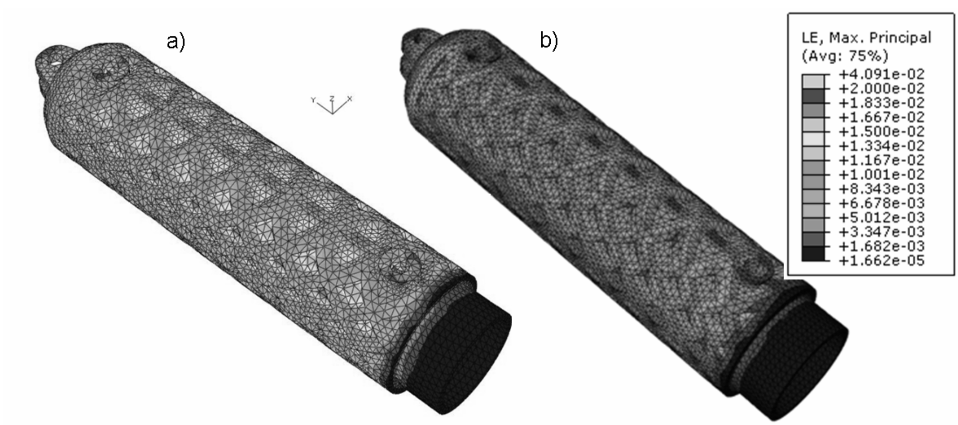

Fig. 9. Deformation maps for a pneumatic servo body:
a) orthotropic model, b) isotropic model

Figure 9 presents deformation maps for the servo body made from PBT GF20 material, for the orthotropic and isotropic models. Comparing both results, it is clear that using the isotropic material properties, the maximum deformation caused by exerting pressure to the internal walls of the servo body do not exceed 2%, which might indicate that the design was properly optimized. Examining the deformation map using the orthotropic material properties, substantial increase in the deformation along the body circumference is observed.

CONCLUSIONS

In this article, we address the topic of modelling elements of mechanically loaded bodies of pneumatic servos made from plastic materials. The process of designing elements made from plastic materials is a complex process, apart from problems related with modelling objects, includes also problems with selection of proper materials. Non-Newtonian parameters of material flow, varied pressure fields and statistical estimation of distribution of glass fibres are just some of the problems that need to be tackled when designing such elements. The developed models in connection with the analysis using such systems as Moldflow, Abaqus and custom-designed software, allowed for manufacturing a prototype servo body with the expected parameters.

In the next step author is planning to run an experiment with real parts. After this activity there will be a possibility to compare results from performed simulations and real world.

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WYKORZYSTANIE TWORZYW SZTUCZNYCH NA OBCIĄŻONE ELEMENTY SIŁOWNIKÓW PNEUMATYCZNYCH

Streszczenie
Zalety tworzyw polimerowych stosowanych w konstrukcji maszyn i urządzeń sprawiły, że coraz częściej wykorzystywane są one również na obciążone elementy konstrukcji. W pracy zbadano możliwość zastąpienia aluminiowego korpusu siłownika pneumatycznego tworzywem polimerowym wzmacnianym włóknami szklanymi. Badania przeprowadzono metodą elementów skończonych z wykorzystaniem systemów MOLDFLOW i ABAQUS.
Słowa kluczowe: polimery, symulacja wtryskiwania, MOLDFLOW, ABAQUS.