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# 9. METHODS OF EFFECTIVELY FORMING FIBER COMPOSITES IN FUSED DEPOSITION MODELING

The chapter presents methods of forming fiber composites in the extrusion head used in the Fused Deposition Modeling printing technique. Designs of two printhead layout solutions were presented. In both cases, the numerical simulations showed the correctness of the construction and compliance with the assumptions. A method for estimating the effective content of reinforcements in composites obtained by these methods was presented. The influence of process variables on the geometrical properties of composites has been demonstrated. Materials reinforced with carbon fibers - regardless of their percentage content - showed elastic nature in a static tensile test. The tensile strength of the tested composites increases in direct proportion to the percentage of fiber content in the composite.

## 9.1. INTRODUCTION

Along with the growing interest in rapid prototyping with the help of the technique of Fused Deposition Modeling - FDM, the demand for specialized composite materials has also increased. Natural steps were attempts to transfer methods for the preparation of composite materials for 3D printing techniques. The methods of obtaining this type of composites can be divided into three groups:

- adding reinforcements at the stage of filament forming in a screw extruder [1],
- using prefabricated mass-produced composite [2],
- feeding continuous reinforcement directly to the head of a production machine working in the FDM technique [3,4].

The work focuses on the third method that allows strict controlling of the amount of composite produced and simple changing of matrix material depending on the application.

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The numerical simulations of heat transport of the first version of the head with symmetrical feeding of matrix material allowed the identification of particularly vulnerable parts of the system [5]. Analysis of PLA polymer extrusion with variable amounts of material fed to the head made it possible to determine the optimal work program for filament feeders. Comparative research on the results of numerical simulation of the flow with experimental research was carried out [6].

Existing methods for determining the percentage of composite components used in conventional manufacturing methods may not be sufficiently accurate for Additive Manufacturing methods due to the properties of laying materials and process variables not found in other methods.

## 9.2. METHODS OF FORMING FIBROUS COMPOSITES

### 9.2.1. EXTRUSION HEADS DESIGNS

Each of the methods for forming polymer composites reinforced with appropriately directed carbon fibers must meet a number of criteria relating to the technology itself, the materials used and the structure. It was assumed that the reinforcing fibers could be oriented in relation to the surrounding matrix material and the surface of the element, the possibility of applying the method to 3D FDM printing technology, ensuring the possibility of interference in the technological parameters of the process, that allowed obtaining the desired physical properties of materials and obtaining even distribution of the reinforcing material, no excessive fiber concentration in the composite.

After analyzing the assumptions regarding the technology for forming fiber composite, mixing of components in a specially constructed extrusion head adapted to a 3D printing machine using FDM technology was adopted as the appropriate method of obtaining the composite material.

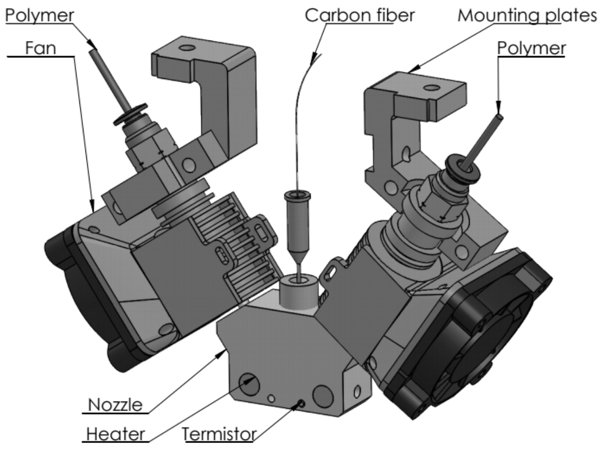


Fig. 9.1. Head with symmetrical feeding of matrix material

Two designs of extrusion heads have been developed that allowed the formation of fiber composites at the stage of fabrication of the detail in the FDM technique. In the first system (Fig. 9.1) matrix material is fed symmetrically to the extrusion axis through two transport channels, while the continuous fiber is transported through the center of the system. The central position is occupied by the base detail, which is the frame of the entire structure and is responsible for the transport of heat generated by a heating resistor located on the rear wall of the detail. The thermistor is responsible for the continuous reading of the operating temperature and is coupled to the heating element via the machine control software. The extrusion nozzle is a replaceable part of the head and can be adjusted to obtain the correct diameter of the extruded composite. In the upper part of the system, there are two filament feeders, which were designed as roller systems. Two plastic transport channels - 3 - simultaneously act as system heat sinks with mounted fans on each of them. It counteracts plasticizing the material too far from the outlet opening and reduces the possibility of stepper motors heating up.

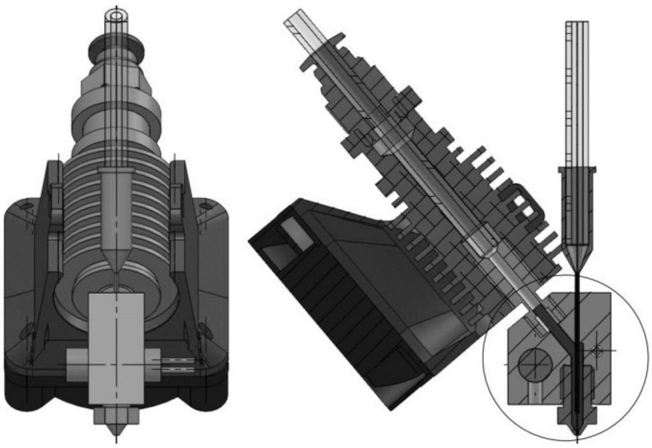

Fig. 9.2. Head with asymmetrical feeding of matrix material

The second head, shown in Fig. 9.2, is based on feeding matrix material from one side only. This allows you to simplify the entire system and its control. Each of the presented methods allow us to obtain the proper orientation of the reinforcing fibers in relation to the surrounding matrix material and ensures a simple change of the components of the composite depending on current research and manufacturing needs.

### 9.2.2. NUMERICAL SIMULATION OF MATERIAL FLOW IN THE HEAD

The next stage of the work was to perform numerical simulations of the flow of matrix material and short carbon fibers through the designed extrusion nozzle. A two-phase material flow was assumed, in which the polymer was presented as the liquid phase and the carbon fiber as the solid phase. ANSYS software with the FLUENT module was used for calculations. Carbon fibers have been modeled as a discrete phase of the DPM model and simplified to spheres of the same volume and density as a fiber with a length of 1 mm and diameter 7μm. The deformation and rotation of the solid phase were taken into account that allowed us to obtain close to real flows. All these treatments allowed us to obtain a two-phase material flow through the system.

The flow of matrix material through the system was adopted as the liquid phase of the simulation. The simulated polymer was ABS, which is a frequently used material in this type of heads. The adopted model of a non-Newtonian fluid being an approximation of the polymer flow taking into account its viscosity was chosen the Bird - Carreau model [7]

$$\eta = \eta_\infty + (\eta_0 - \eta_\infty)(1 + \lambda^2\dot{\gamma}^2)^{\frac{n-1}{2}}, \tag{9.1}$$

where $\eta_\infty$- coefficient of maximum shear viscosity [Pa·s]; $\eta_0$- zero shear viscosity coefficient [Pa·s]; $\lambda$ - times [s]; $n$ - power law index; $\dot{\gamma}$ - shear rate [$s^{-1}$].

The material data for the simulation were determined on the basis of tests carried out while extruding ABS through a technologically convergent head used for a given work [8]. Table 9.1 shows the data included in the simulation.

Table 9.1. ABS material data adopted for simulation [8]

| Parameter | Value |
|---|---|
| density | 944 |
| zero shear viscosity coefficient [Pa·s] | 2404 |
| coefficient of maximum shear viscosity[Pa·s] | 0 |
| time [s] | 0.07 |
| Power law index | 0.037 |

One of the stages of the research was to conduct a quantitative analysis of thermoplastic and carbon fiber flows at various volumetric and mass material expenditure. Quantitative distribution tests of the extruded composite from the nozzle were carried out with a constant volume flow of matrix material and variable flow of reinforcing fiber. Table 9.2 shows the input data adopted for the simulation.

Table 9.2. Data for simulation

| Parameter | Flow value | | | | |
|---|---|---|---|---|---|
| | 80% | 90% | 100% | 110% | 120% |
| Plastic volumetric capacity [$m^3/s$] | $4.811 \cdot 10^{-9}$ | | | | |
| Mass flow rate of carbon fiber [kg/s] | $6.414 \cdot 10^{-6}$ | $7.216 \cdot 10^{-6}$ | $8.018 \cdot 10^{-6}$ | $8.82 \cdot 10^{-6}$ | $9.622 \cdot 10^{-6}$ |

An analysis of the calculated standard deviations of the obtained courses of the distribution of reinforcing fibers in the extruded material depending on the mass expenditure of carbon fiber fed to the system was performed. Fig. 9.3 shows the standard deviation of the amount of fiber at the exit of the nozzle at different amounts of fiber being fed.

The graph shows small deviations in the significant range of the extrusion head output hole - the same amount of fiber is given in the range. An increase in the value of the standard deviation at the walls can be observed, which may be due to certain errors in the numerical analysis and the distribution of the finite element mesh. All deviation values differ by a maximum of 0.03%. The fiber distribution does not change significantly depending on the mass expenditure of the reinforcing material at a constant value of the volumetric expenditure of the matrix material.

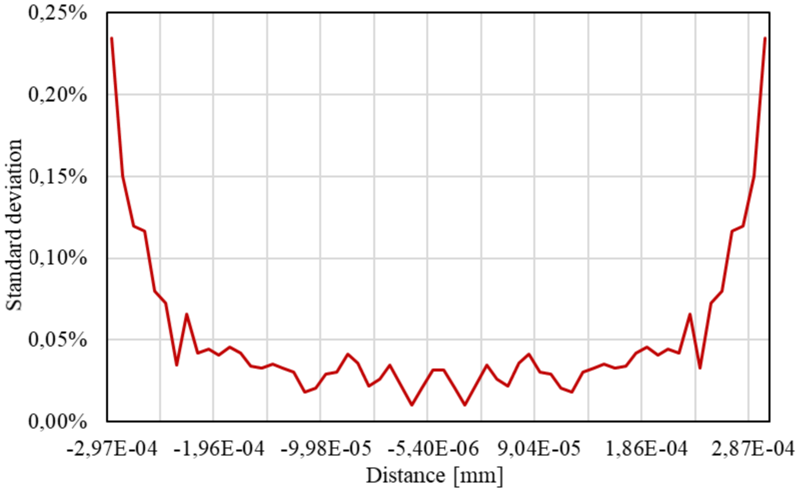


Fig. 9.3. Graph of the standard deviation of the amount of carbon fibers at the exit of the nozzle with different amounts of fiber fed

Numerical simulations carried out as part of research on the flow of material in the system showed mixing of matrix and reinforcing material streams as they passed through the extrusion nozzle and the concentration of fibers in the center of the hole at the exit of the system. Changes in the value of the mass expenditure of the reinforcing material and the volume expenditure of the material in the examined range do not significantly affect the operation of the system, the obtained flows and the distribution of composite components at the outlet of the system.

## 9.3. METHOD OF ESTIMATING THE EFFECTIVE CONTENT OF FIBERS IN DETAILS

Elements formed from fibrous composites using the FDM technique can significantly differ in terms of macroscopic internal structure from similar geometrical elements made using classical techniques of forming composite details. Additive manufacturing techniques enable precise control of arrangement of a single material path and place it as intended.

To the proposed method for estimating the effective content of reinforcements, the following initial assumptions were adopted:

- the detail is made using the FDM technique,
- the composite consists of one type of matrix material and one type of reinforcing material,
- composite material paths are applied in layers, i.e. on a two-dimensional plane,
- the height of the applied material layer and the width of a single track is constant.

The coefficient of the effective content of fibers in the details of fiber composites made using the FDM technique was determined by the following

$$W_F = \frac{\sum_{i=1}^{N} L_{Fi} \cdot d^2 \cdot \pi \cdot f \cdot sin\,(\alpha)}{\sum_{i=1}^{N} L_{Ci} \cdot 4 \cdot h \cdot s}, \tag{9.2}$$

where: $h$ - height of a single layer, $s$ - path width, $L_{Fi}$ - number of reinforced paths in the layer, $L_{Ci}$ - total number of paths in the layer, $N$ – number of model layers, $d$ – diameter of the reinforcing fiber, $f$ – number of fibers in a single path, $sin(\alpha)$ – deviation of the fiber axis from the reference plane.

Using the presented method, it is possible to determine the effect of track height and width on the gain content factor. Fig. 9.4 shows a graph made on the basis of calculations in which a fixed number of layers and paths in the model, a constant angle of deviation of the composite paths as well as an equal amount of reinforcing material were adopted.

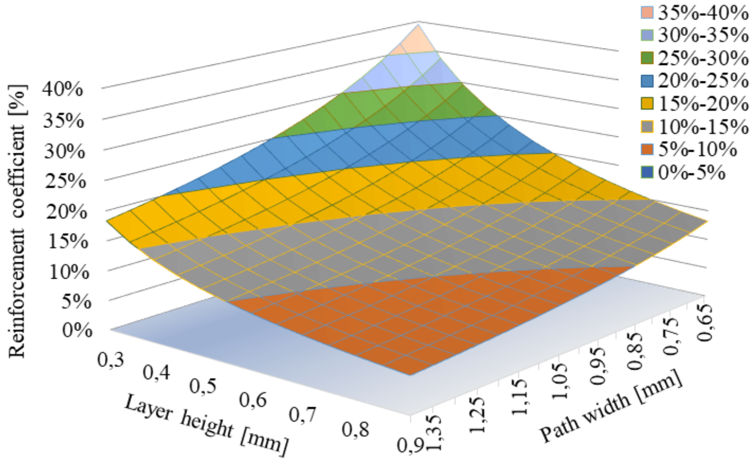


Fig. 9.4. The effect of track height and width on the gain content factor

The graph shows that as the height of the material layer and the width of a single track decreases, the ratio of effective reinforcement content increases. It is possible to control the amount of gain obtained composite materials without changing the amount of reinforcing fiber fed - it is only necessary to correct the process variables at the level of control software.

The presented formula allows taking into account the different number of reinforced paths in individual layers and the deviation of the cross-section of the path from the adopted reference plane. Anisotropic properties of the obtained composites were taken into account.

The calculated effective fiber reinforcement value is potentially more accurate method in comparison to a method based on the matrix / reinforcement volume ratio without specifying the orientation. The formula can be easily implemented in some CAD software.

## 9.4. MECHANICAL PROPERTIES OF FORMED FIBER COMPOSITES

The industrial application of fibrous polymer composites that can be used in 3D printing requires testing of their strength properties. Tensile strength tests of obtained materials were carried out. This is one of the most common methods of assessing the properties of materials, mainly because of its simplicity and the speed of obtaining results. The object of the study were polymer composites of the ABS matrix and reinforcement in the form of continuous carbon fibers of varying the percentage of the resulting material. The matrix was an acrylonitrile-butadiene-styrene polymer - ABS, while the reinforcement was a continuous carbon fiber Torayca® T300-1000 66 TEX. The tests were performed on the MTS 858 Mini Bionix testing machine. The influence of the number of reinforcing fillers in the volume of the test sample on the tensile strength of the material was examined.

Fig. 9.5 presents a comparative graph of static tensile tests of materials with an ABS matrix and various fiber content as well as material without additional reinforcing elements. A test sample made only of polymer showed elastic - plastic character during stretching, obtaining over 5% elongation at break - not shown in the graph.

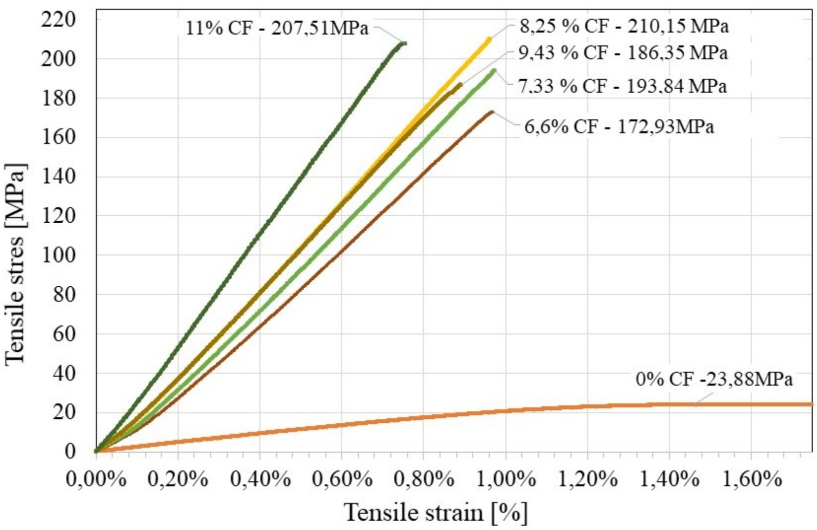


Fig. 9.5. Tensile strength of ABS / CF composites
with reinforcement content {0%; 6,6%; 7,33%; 8,25%; 9,43%; 11%}

The maximum stress in the ABS sample was 23.88 MPa with a relative strain of 1.40%. Materials reinforced with carbon fibers showed elastic nature of stretching. The sample with 8.25% carbon fibers achieved a breaking stress of 210.15 MPa. The tensile strength of the tested composites increases in direct proportion to the percentage of fiber content in the composite.

## 9.5. CONCLUSIONS

The paper presents the method for estimating the effective content of reinforcements and forming fiber composites using the FDM technique. It has been demonstrated that it is possible to control the amount of reinforcing material in such a composite only by interfering with the height and width of the applied material path, with a constant amount of reinforcing fiber applied. Anisotropicity of obtained composites was taken into account. The calculated effective fiber reinforcement value is potentially a more accurate method compared to that based on the matrix / reinforcement volume ratio throughout the composite without specifying the orientation.

Materials reinforced with carbon fibers - regardless of their percentage content, showed elasticity in a static tensile test. The tensile strength of the tested composites increase in direct proportion to the percentage of fiber content in the composite.

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