DOI 10.1515/ama-2017-0049 acta mechanica et automatica, vol.11 no.4 (2017)

SIMULATION OF PROCESSES OCCURRING IN THE EXTRUSION HEAD USED IN ADDITIVE MANUFACTURING TECHNOLOGY

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received 6 June 2017, revised 5 December 2017, accepted 11 December 2017

Abstract: The purpose of this research is unsatisfactory state of knowledge of the abrasive wear of composites with thermoplastic polymer as matrix material and reinforcing material in the form of short and focused carbon fibers that can be used in additive manufacturing technologies. The paper presents a conceptual design of an extrusion head used in Fused Deposition Technology, which allows for the implementation of appropriately stacked fibers at the level of detail production. Finite element simulation was performed to simulate the thermal effect of the system to demonstrate the effect of head cooling on the system. The assumed extrusion temperature of the material was obtained at a uniform nozzle temperature and stable temperature of the entire system. Flow simulation of thermoplastic polymer was carried out in the designed extrusion nozzle. By supplying 0.5 mm wire of 1.75 mm diameter thermoplastic material to the nozzle, the extrusion rate was 0.192 m/s. The proper design of the extrusion head for the intended applications has been demonstrated and the purpose of further research in this field has been confirmed.

Key words: Additive Manufacturing, Fused Deposition Modelling, FEM Analysis, RFPC

1. INTRODUCTION

Additive manufacturing technologies are one of the main pillars of techniques related to Rapid Prototyping. Thanks to the constantly growing range of additive manufacturing methods and an ever-expanding number of available building materials it is possible to perform more and more specialized engineering details. Each manufacturing technology is characterized by some unique materials and components. One of the most widespread methods is Fused Deposition Modeling (FDM). It involves extrusion through a heated die of thermoplastic material and precisely laying it in the work space layer by layer until it reaches full detail.

Polymeric materials are widely used in many industries, among others in aviation and automotive because of the favorable weight to strength ratio of the components. It is possible to broaden the scope of possible application by using composite fiber reinforced composite polymers arranged in a non-accidental manner. Currently there is a shortage of composite plastics with uniformly oriented short fiber reinforcements that can be used in manufacturing devices using Additive Manufacturing. The development of this branch of materials will perform elements more resistant to wear than currently available. Carbon fiber reinforced polymer composites allow for high abrasion resistance while maintaining a low weight of the system.

The tensile strength of the detail made on FDM polymer composite with continuous carbon fiber has shown a significant increase in mechanical properties compared to polymeric material without fiber additions (Gardner et al., 2016). The study of wear of polymer composites with metal oxide additives (Boparai et al., 2016) showed a visible relationship between abrasion resistance and reinforcing additives of the composite. Lee and Huang (2013) fatigue analysis showed a significant effect of the layering of the material and its orientation relative to the main axis of the analysed parts on the strength values of the components. Abrasive wear of various polymers has been investigated - both for sliding friction and for rolling friction (Harrass et al., 2010), as well as the effect of temperature on abrasive wear on materials (Zhao et al., 2015).

Studies on the mechanisms of wear of polymer composites reinforced with carbon fibers (Kaczynski et al., 2014) indicate the important role of these materials in the production of elements working in different environments (Wilczewska and Kaczynski, 2009). Comparative studies on abrasive wear of vinyl matrix and carbon fiber reinforcements and polymeric copolymers with identical matrix material and fiberglass additives (Suresha et al., 2009) have been performed to show better properties of carbon fiber composites. The results of a study conducted by Kumar and Panneerselvam (2016) on abrasive wear in polymer composites based on Nylon 6 with different percent fiberglass showed a significant increase in abrasion resistance with increasing fiber content in the composite. Studies on polymer composites (Akinci et al., 2014) have shown a significant increase in abrasion resistance at various test speeds (Aigbodion et al., 2015). In addition, studies (Wenzheng et al., 2015) have shown the relationship between FDM filamentation and the strength properties of manufactured parts

At the same time, there is no in-depth research on the processes of wear of composite materials with oriented arrangement of fibers used in additive manufacturing technologies.

The authors devoted particular attention to the design of the FDM design with the possibility of application of short carbon fibers arranged in a targeted manner. Flow simulation of the ma-

DOI 10.1515/ama-2017-0049

trix material through the extrusion nozzle and thermal analysis of the system under various cooling conditions was performed. The presented results confirm the possibility of achieving the desired properties of the element by applying a suitable construction of the embossing head to the integrated feeders of the building materials. This will allow the targeted reinforcement fibers of a suitable length of the entire range of plastic having thermoplastic properties.

2. DESIGN OF EXTRUSION HEAD

2.1. Design assumptions

The main task facing the extrusion head in the incremental manufacturing apparatus is to obtain a strictly controlled flow of the building material, maintain the appropriate temperature and extrusion speed of the material, which determines the appropriate engagement of the subsequent layers and surface of the workpiece according to the requirements. The designed device should have a compact design and low weight due to the high acceleration generated in this type of manufacturing machine.

The authors have assumed that the designed head should be able to be installed on most FDM printing machines using a suitably complex control system for the entire device. This will allow the use of polymeric materials in the standard filament format used in FDM machines.

2.2. Matrix material

Correct selection of the matrix material in the composite polymer used in FDM technology allows to obtain a satisfactory mechanical property performed. Inappropriate selection of the used material can lead to premature degradation of the workpiece or lack of characteristic features.

Another factor influencing the choice of the appropriate material is its availability on the market in the form of a filament with fixed and well-defined diameter. This allows uncomplicated and precise dosing of the feed material. This also minimizes the cost of parts production due to the use of widely available materials.

Tab. 1. Materials used in FDM printing technology

Material	Melting temp. [°C]	Density g/cm^3	Abrasion resistance	Avaliable on the market
ABS	210 – 240	1.05	Good	Very Good
PLA	180 – 205	1.1	Poor	Very Good
Nylon PA66	240 – 260 (270)	1.14	Very Good	Good
HDPE	170 – 190	0.965	Good	Average

Tab. 1 shows one of the most commonly used FDM materials. It is evident that to achieve the proper model properties, the printhead must reach a temperature of 250 degrees Celsius. For further simulations, high density polyethylene (HDPE) and acrylonitrile-butadiene-styrene copolymer (ABS) were used as the matrix material.

2.3. Extrusion head model

Project extrusion head adapted to application-oriented reinforcement in the form of short carbon fiber was made in SolidWorks 2016. Fig. 1 shows the main elements included in the designed layout and its overall dimensions.

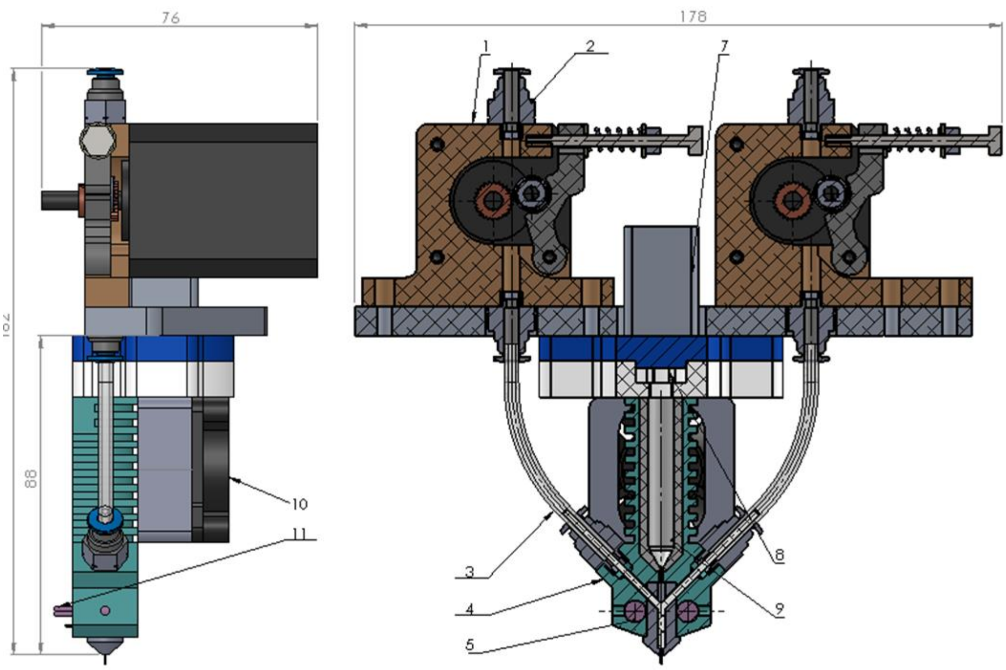

Fig. 1. Schematic Drawing of an Extrusion Head for use in FDM Technology

Building material in the form of a filament having a diameter of 1.75 mm passes through the plug-in connection – 2 – and then is drawn through the material feed roller – 1. The filament enters between a pinion gear mounted on the stepper motor shaft and

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a bearing with a profiled outer race acting as a pressing element. This allows for a precise control of the amount of material fed with no slippage between the active elements. Then the material is carried out by Teflon tube – 3 – and reaches the base of the head – 4 . This detail serves as a basis for embedding further components and serves as a heatsink for the entire system. This prevents heat transfer to the top of the head and overheating of the precision stepper motors. The material hitting the nozzle – 6 – has the optimum temperature by heating the heating resistors arranged symmetrically – 5.

The head base is cooled by blowing air at ambient temperature caused by the fan – 10 – from a specially shaped cooling channel. This eliminates the phenomenon of excessive heat convection to the upper part of the head where there are stepper motors. In addition, it prevents premature plasticization of the material which could lead to the folding of the filament and, consequently, clogging of the head. The temperature of the extrusion nozzle is monitored by a thermistor – 11 – placed in direct contact with the nozzle. Control of the operation of the heating resistors is done by a computer with special software and a PID controller that minimizes temperature fluctuations.

Short carbon fiber sections are placed in the intermediate container – 9 – through the rotary feeder – 8. On the output shaft of the stepper motor – 7 – is mounted rack and pinion fiber storage. This system is designed to accurately control the amount of reinforcement fed to the composite. It also allows the administering of fibers only in the places where this is necessary and results from the operating conditions of the part produced which results in reduced use of expensive reinforcing material.

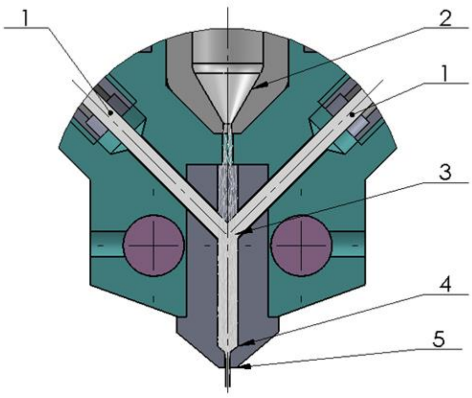

Fig. 2. Extrusion process of fiber reinforced composite from nozzle

Fig. 2 shows an extrusion nozzle fixed in the base of the head and heated with two heating elements. Extrusion head has two transport channels – 1 – arranged symetrically in relation to the composite extrusion axis feeding the thermoplastic material to the nozzle. Channel – 2 – is supplied with reinforcement fibers. In point – 3 – matrix material and fibers are mixed. At a short distance – 4 – from the nozzle exit, the fibers are set at the correct deviation. Properly selected geometric features of the nozzle output – 5 – opening ensure the alignment of the reinforcement fibers in the output material with a deviation from the extrusion axis by up to 20 degrees.

The head extrudes the circular cross section at the outlet due to the difficulty of producing nozzles with other output cross sections in the nozzle dimensions. The additional advantage of this cross sectional shape is the fact that Barus effect has been avoided by swirling the polymer stream leaving the head.

The authors used a symmetrical construction of the head and a doubling of the most important elements of the head because of the need to properly position the carbon fibers in the extruded material. Bringing both sides of the matrix material allowed for correcting the set of short fibers on one wall of the nozzle.

3. HEAD FEM ANALYSIS

Computer simulations made by the authors were aimed at demonstrating the rationality of the proposed head design and finding possible locations for improvement. Two types of simulation were performed: thermal simulation of the head during operation and flow of the matrix material through the extrussion nozzle. In both cases, the correct behavior of the system can be observed.

3.1. Thermal analysis

As part of the work, the authors performed a thermal simulation of the extrusion head. As the building material passing through the analyzed system, ABS was chosen because of the high plasticity temperature of up to 240 degrees Celsius, which is about 513.2 degrees Kelvin scale. It has been assumed that the components will be made of Aluminum PA6, Teflon, ABS and HSS tool steel.

SolidWorks 2016 software with Flow Simulation module was used to simulate the behavior of a heat treated element under normal conditions of use.

Two types of simulation were performed: without external cooling of the head base and with an external air flow directed at the head corresponding to the amount of air conveyed by a standard computer fan of these dimensions. This allowed us to check the suitability of the forced air flow in the head cooling.

Simulation time adopted in both cases is 300 seconds. Numerical analysis of simulated and experimental similar systems shows that after this time can be assumed that the system is in thermal equilibrium.

Two heat sources were installed at the locations of the heating elements. On both cylindrical surfaces, a constant temperature of 493.2 degrees Kelvin was applied which corresponds to the average actual temperature value needed to start the extrusion process for the material. The ambient temperature of the model during its operation was determined to be a constant value of 293.2 degrees Kelvin.

The model was simplified before simulations, which allowed for a significant reduction in numerical calculations. Due to the reduction of the stepper motors model, the authors have assumed that the safe value for the entire system measured at the top of the connecting plate is 380 K.

Fig. 3 shows the resulting temperature pattern in the embossing head after 300 seconds of simulation with two 493 K heat sources and without forcing the air circulation around the head radiator. It is evident uniform heating of the extrusion nozzle and its surroundings. With the distance from the heat source temperature is getting lower. The drop in temperature on the other ribs of the heat sink is noticeable.

A heat of 404.4 K. was provided to the upper connecting element of the designed head. This value is unacceptable because it results in higher temperature stepper motors which are particularly sensitive to improper temperature.

DOI 10.1515/ama-2017-0049

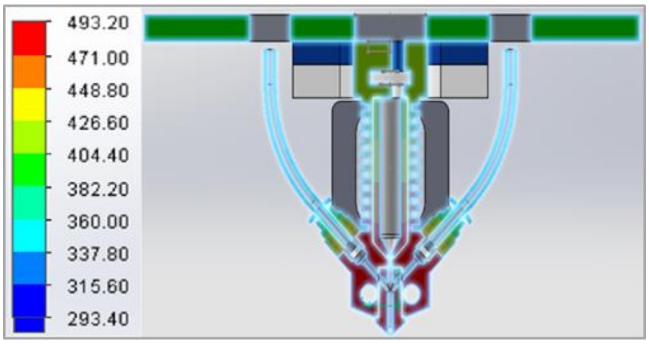

Fig. 3. Results of thermal analysis without external cooling

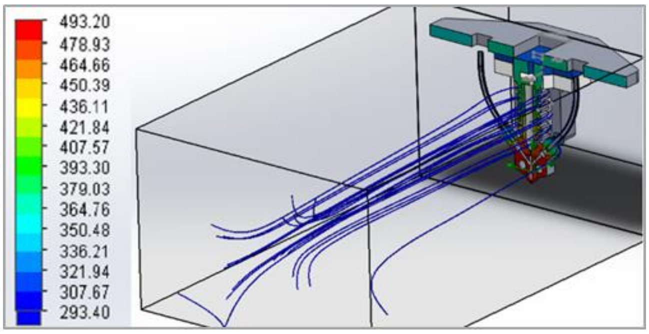

Fig. 4. Forced air flow stabilizing temperature of the extrusion head

In the second thermal simulation of the extrusion head, a cooling air flow was used to reduce the temperature in the upper part of the system. Other boundary conditions (e.g. heating surface temperature, material data) remained unchanged compared to the first simulation. Fig. 4 shows a simulated flow of air through the finned portion of the base of the head. The air flow rate was set at Q = 8.0x10^{-5} kg / s which corresponds to the value obtained from this type of fan. A temperature constant value of 293.4 K cooling air was adopted.

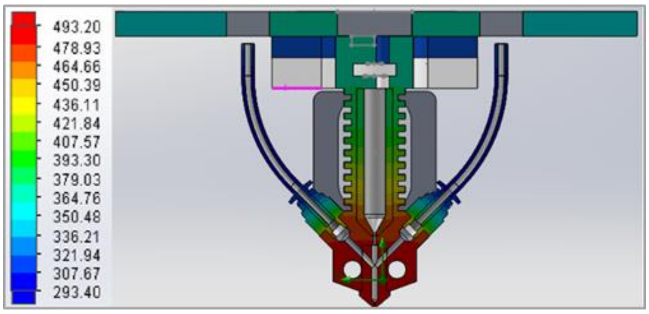

Fig. 5. Results of thermal analysis with additional cooling of the air stream

The temperature distribution of the system during simulation with additional cooling is shown in Fig. 5. As can be seen in the previous example, here also a homogeneous temperature field in the extrusion nozzle corresponding to the temperature emitted by the heat source is visible. It is easy to see that the system components are lower in temperature compared to the non-cooling system. The temperature of the upper connection plate is about 364 K which the authors have accepted for content that is satisfactory and safe for the operation of the whole system. In addition, the extruded material does not pass prematurely to the plastic state, which prevents clogging of the head and allows for proper properties.

3.2. Material flow analysis

As the second type of simulation performed, the authors adopted a simulated flow of building material through the designed extrusion nozzle. The material analyzed was high density polypropylene HDPE. Simulations were carried out using ANSYS R17.0 with Polyflow add-in dedicated for the extrusion and injection molding of materials.

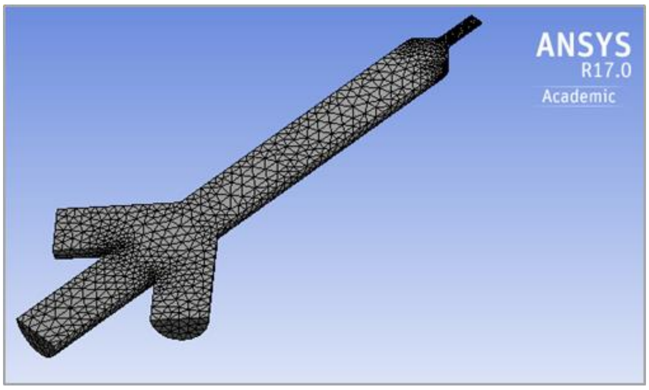

Fig. 6. Finite element mesh of extrusion nozzle flow channels

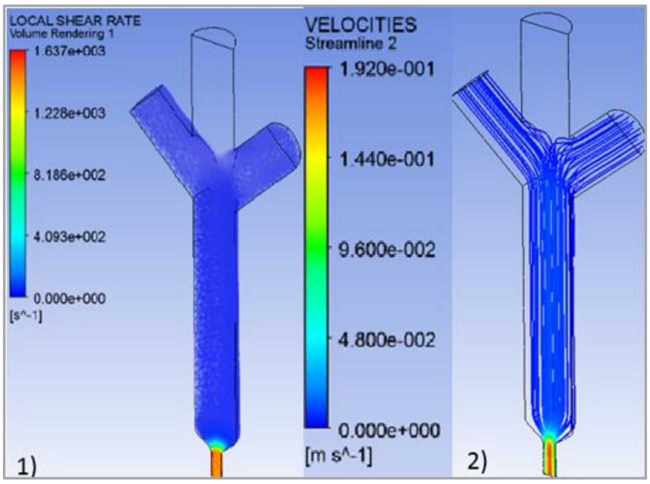

Fig. 7. Results obtained: 1) local shear rate and 2) velocity of extruded material

Fig. 6 shows the object on which the authors have studied the flow occurring in the head designed. This is the outline of the flow channels in the item. In order to shorten the computation time, a symmetry plane of the entire system is used.

On both sides of the nozzle is feeding a suitable temperature building material, while the central inlet channel is fed short carbon fibers. The outlet diameter of the system has a diameter of 0.4 mm. This value allows the behavior of the respective dimensional accuracy of the workpiece at an acceptable time of manufacturing an object.

As one of the assumptions for the simulation is that the volumetric flow rate for both inputs of the circuit is equal and is 4.8106x10^{-9} m^3/s. This value corresponds to the actual case of feeding on each side of a 0.5 mm filament segment of 1.75 mm

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diameter in 1 second. In the simulation flow rate at the contact of the building material wall $v = 0$ m³/s and the free flow of the material from the nozzle.

The results obtained by the authors are shown in Fig. 7. On the left side – subsection 1, the local shear rate of polymer material in the designed nozzle was determined. It is evident that at the upper part of the system no distinct velocity difference in material layers is evident. At the point of narrowing of the nozzle and passing into the final extrusion profile, it is clear that the local shear rate is significantly increased.

The velocity of extrusion of the building material from the nozzle is shown in Fig. 7, subsection 2. The flow of material is undisturbed. Extruded polymeric material shows no signs of stacking. The velocity of polymer material at the output of the head is 0.192 m / s which corresponds to the values obtained in such extruders used in Fused Deposition Modeling technology. This shows that the correct simulation conditions and the design of the head and nozzle are correct.

4. CONCLUSIONS

The authors have presented a design of a Fused Deposition Modeling extrusion head in which it is possible to add composite reinforcement in the form of targeted short carbon fibers at the manufacturing stage of the model. The described method allows for quick and trouble-free change of both matrix and reinforcement material without the need for material expenditure and time losses. It offers the possibility of obtaining a wide variety of components for the study of different pairs of composite plastic reinforcement in the form of fibers.

Simulations have shown the extrusion head components, the correctness of the structure and the validity of further work on this subject. The assumed extrusion temperature of the material was obtained at a uniform nozzle temperature and stable temperature of the entire system. Flow simulation of thermoplastic polymer was carried out in the designed extrusion nozzle.

It is planned to create a prototype of an extrusion head and to produce samples for research on wear mechanisms of composite polymer materials with targeted fiber reinforcement produced on Additive Manufacturing devices.

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