Designing of an original extruding system for 3D printing of parts made of plastic material in powder-state form

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Designing of an original extruding system for 3D printing of parts made of plastic material in powder-state form

R Păcurar[1*], S Pascu[1], A Păcurar[1], D S Stan[2], E Teuţan[2], D I Băilă[3] and A Sadeh[4]

[1] Department of Manufacturing Engineering, Technical University of Cluj-Napoca, B-dul Muncii 103-105, 400641, Romania
[2] Department of Mechatronics and Machine Dynamics, Technical University of Cluj-Napoca, B-dul Muncii 103-105, 400641, Romania
[3] Department of Manufacturing Engineering, Polytechnic University of Bucharest, Splaiul Independentei 313, 060032, Romania
[4] Department of Management of Technology, Holon Institute of Technology, GolombStreet, 5810201, Israel

*E-mail:razvan.pacurar@tcm.utcluj.ro

Abstract. Since their advent, various 3D printing technologies have been developed, out of which the Fused Filament Fabrication, FFF has completely revolutionized the industry in the last years. Classical FFF printers are using a thermoplastic filament, which is heated to its melting point and then extruded layer by layer to materialize a three dimensional part. One of the most important subassemblies of the 3D printer which is the most representative is the extrusion sub-assembly system and the thermal demands to which is subjected. In this article, one original constructive variant of the extruding sub-assembly system has been conceived and thermal analyses of the variant was performed by using the finite element method so as to be used not only for printing parts made of plastic materials in filament form, but also plastic materials in the powder state form at the Technical University of Cluj-Napoca, Romania.

1.Introduction

The manufacturing processes by using 3D printing methods are more and more widespread in many areas. These areas can be in the automotive, medical and aeronautical fields, etc [1-3]. These processes can be used for prototyping in order to avoid the high costs that are involved in these cases. Various 3D printing technologies have been developed, out of which the Fused Filament Fabrication (FFF) has completely revolutionized the industry in the last years [4]. FFF printers are using a thermoplastic filament, which is heated to its melting point and then extruded layer by layer to materialize a three dimensional part [5]. FFF printers are highly accurate machines, which due to their affordability have been included into various small and medium enterprises to be used for the production of functional prototyping and low volume production. One of the most important subassemblies of the 3D printer is the extrusion subassembly system and the thermal demands to which is subjected [6]. The extruder is usually adapted from the designing and manufacturing point of view according to the type of material that is used in 3D printing process, the accuracy, surface roughness and mechanical characteristics that are required for the realization of plastic parts [7-11]. The FFF technology uses the material in the filament form, which is melted within a specially designed head, the plastic filament being deposited afterwards in a form of a layer according to generated section data from a prepared 3D CAD model.

The accuracy and mechanical properties of plastic parts that are 3D printed are closed to the ones of plastic parts produced by injection moulding process [12, 13]. The main aim of research that has been presented in the current paper was to develop one new type of extruder that is suitable to print out parts made from plastic material in powder state form. Duraform Polyamide has been considered as raw material for the experiments. For the proposed research designing of a new extrusion mechanism for 3D printer Reprap Prusa i3 type has been considered, the validation of the constructive solution being made on the finite element analyses bases and experiments that were done for printing several samples that were subjected to tensile strength tests and surface roughness measurements that were made at the end.

2. Constructive design of the extrusion subassembly system

One of the most important subassemblies of the 3D printer which is the most representative is the extrusion subassembly system and the thermal demands to which is subjected. For the made research the 3D printer Reprap Prusa i3 type shown in figure1 has been considered.

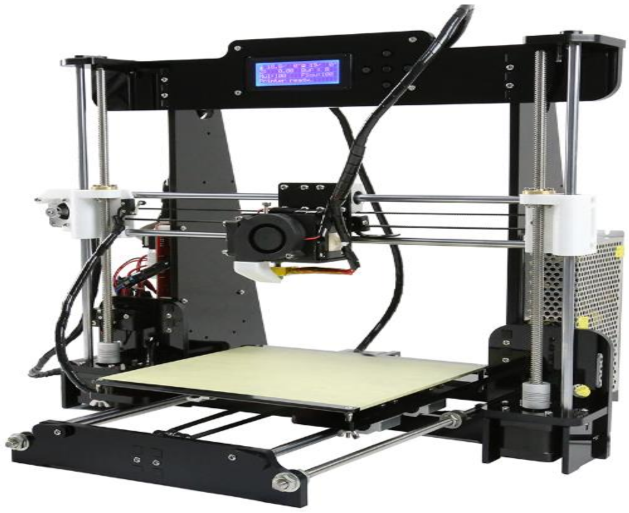

Figure 1. Reprap Prusa i3 [14].

Table 1. Technical characteristics of the 3D printing equipment [14].

Brand Name	Anet;
Model Number	Anet A8
Layer thickness	0.1-0.3mm
Hotbed	3mm Aluminium Heatbed
Structure	Metallic
Print speed	100mm/s
Print materials	PLA,ABS,PVA,NYLON
File formats	STL/G-code
Max paper	220x220x240mm

In table 1 there are presented some specifications of the original 3D printer. In figure 2 is schematically presented the variant which was conceived and in figure 3 is presented the 3D model of this variant. The construction of this type of extruder is a simple one, based entirely on the classical extrusion concept. The rotation movement of the feeding screw combined with the gravitational force pushes the material towards the nozzle for extrusion. This aspect reduces the minimum required drilling length to achieve and providing optimum extrusion pressure. The melting of the material is realised by the resistance which is mounted in the crucible in the lower end of the extrusion subassembly. For good operating stability and high reliability the subassembly has been considered to be kept at a lower weight to avoid the high load of column, guiding systems, belt and motors. In order to reduce the amount of heat transferred to the upper part of the subassembly a weakly conductive thermal element such as ebonite has been taken into consideration. Ebonite can be machined by normal methods, but becomes flexible and shows rubber like elasticity when it is above its yield temperature which ranges between 80 ℃ to 280 ℃. Taking into consideration the functionality aspects, two-hole crucible were designed and considered by mounting two 40W thermal resistors in order to reach the desired temperature faster, but also to provide a better thermal stability at the end.

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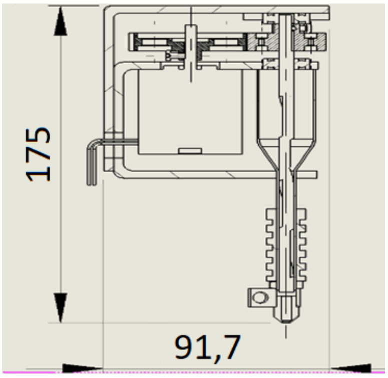


Figure 2. The 3D schematic of the extruder.

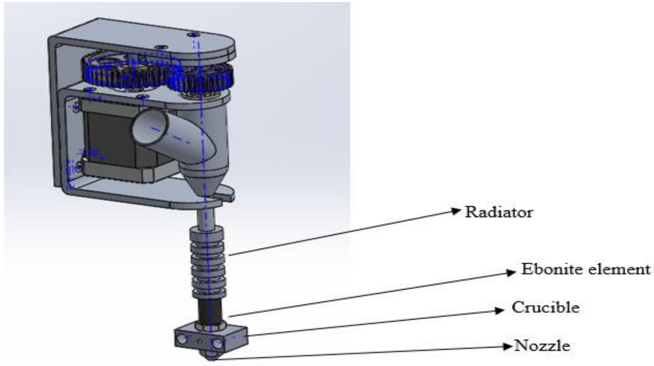
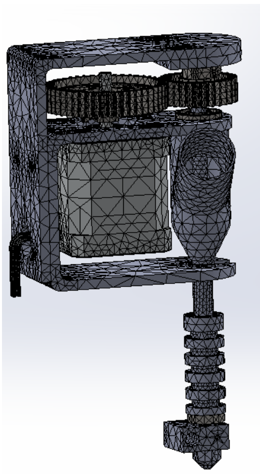


Figure 3. The 3D model of the extruder.

3. Finite element analysis of the new extrusion mechanism

Because the extrusion mechanism is subject to thermal loads, the simulating working conditions of the designed variants require the use of a program with the ability to perform the finite elements analysis of the extrusion mechanism. SolidWorks Simulation module that is compatible with the SolidWorks 2019 CAD program has been considered to simulate the thermal behaviour of extrusion mechanism. The SolidWorks Simulation module was preconfigured for stationary analyses. A total time for the nozzle was set to warm up the system (in this case 3600 seconds) and the time increment in which the temperature measurement was made was set from 15 to 15 seconds. At the initial data input stage it was considered the use of a 40 W resistance, the ambient thermal transfer coefficient being set at 15 $W/m^2 * K$, the initial temperature of the components and the environment being pre-set at 20 °C (293,15 K). In figure 4 is shown how the 3D model was discretized within the program simulation. Solid mesh and curvature based mesh were used as main settings in the process of mesh generating. The total number of elements was 75082, and the number of nodes was 129301.The thermal and convection constraints to which the analysed model was subjected were introduced in this stage of the analysis as shown in figure 5. Taking into account the functioning principle of the extrusion subassembly a high attention must be focused on the thermal loads at which the sub-assembly mechanism is subjected, due to the thermal conduction phenomenon.



Mesh information

Mesh type	Solid Mesh
Mesher Used:	Curvature-based mesh
Jacobian points	4 Points
Maximum element size	11.9497 mm
Minimum element size	2.38994 mm
Mesh Quality	High
Remesh failed parts with incompatible mesh	On

Mesh information - Details

Total Nodes	129301
Total Elements	75082
Maximum Aspect Ratio	40.035
% of elements with Aspect Ratio < 3	63.7
% of elements with Aspect Ratio > 10	5.3
% of distorted elements(Jacobian)	0
Time to complete mesh(hh;mm;ss):	00:00:16

Figure 4. Discretization of the 3D CAD model.

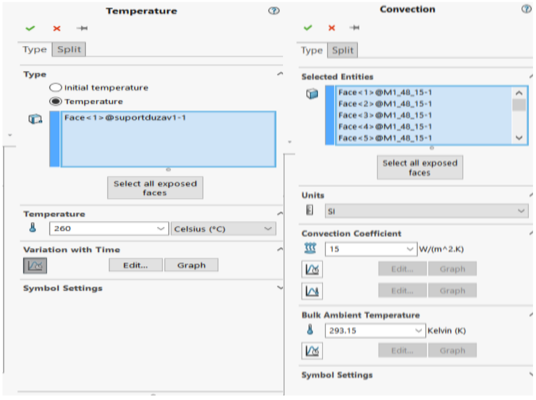


Figure 5. Boundary conditions.

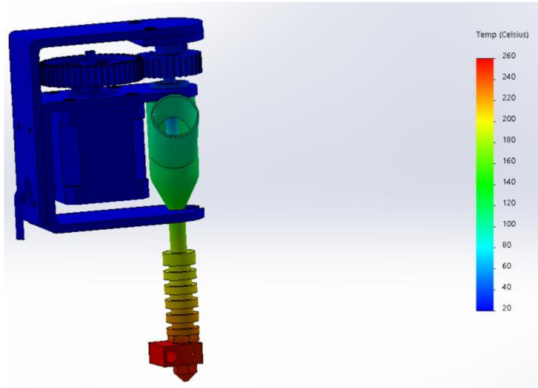


Figure 6. Temperature associated with the last time increment of transitory thermal process.

Taking into account the functioning principle of the extrusion mechanism, a high attention must be focused on the thermal loads at which it is subjected the sub-assembly mechanism, due to the thermal conduction phenomenon. In figure 6 is presented the temperature distribution associated with the last time increment of a transitory thermal process analysis. It can be observed that the heat distribution with temperatures is ranging from 20 °C to 260 °C. The maximum temperature was considered as being 260 °C and was reached by the crucible and the minimum temperature of 20°C was registered in the stepper motor area. This can be considered a positive result due to the fact that the main interest region is in the crucible area and not in the whole subassembly. Figure 8 shows the temperature over time, the temperature that was recorded at a certain time gradient during the transient-type analysis. This graph is valid only for the elements of the subassembly that are thermally loaded with a temperature higher than 20 °C according to figure 3 namely: nozzle, crucible and radiator. As one may notice in figure 8, the minimum temperature stabilizes at 100 °C after 500 seconds. The problem encountered in this variant after finite element analysis that was made is that, even after the 3600-second heating period, the nozzle tip shows variations of the temperature between 249 °C and 257 °C (figure 7), a difference of 11°C respectively 3 °C from the temperature at the resistance was set. This problem is due to the convection of temperature from the crucible to the rest of the subassembly. One of the most important conclusions of the analysis was that it is necessary to pre-heat the nozzle for 90 seconds, so the use of a thermostat for the rigorous control of the temperature in that area is an essential aspect to be taken into account for good operation of the extrusion mechanism. This variant of the nozzle has been considered for experiments that were made using the extruder adapted for printing plastic material like Duraform Polyamide in powder state form (the melting point of this material is 180 °C, which is below the temperature of heated nozzle) [15]. Temperature of 260 °C has been considered for the nozzle, since 3D printing extruder was tested for realization of parts using plastic materials in powder state form.

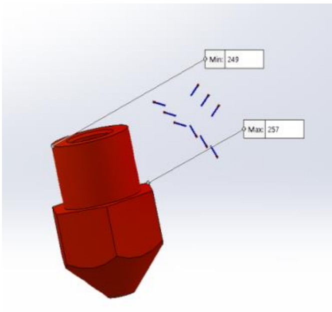


Figure 7. The temperature distribution of the nozzle.

Timp [s]	Tmin [°c]	Tmax [°c]
0	20	20
15	20	260
30	20	260
90	23	260
120	36,9	260
150	58,8	260
210	81,5	260
300	93	260
405	96,8	260
615	98,4	260
1005	99,2	260
1500	99,4	260
3000	99,5	260

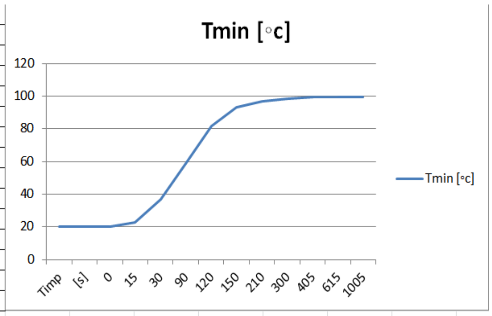


Figure 8. Temperature variation for the nozzle versus time.

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4. The manufacturing and testing of the extrusion sub-assembly system

The 3D printing extruder was realized using several types of processes such as: welding, turning, bending, etc. Figure 9 shows the manufactured extruder subassembly of the 3D printer. Samples that were tested to determine the tensile strength were printed using this type of extruder that was mounted on Reprap Prusa i3 equipment. The samples were made of Duraform PA12 powder material, having a granulation of 50 microns, this type of material being normally used in the process of producing plastic parts by Selective Laser Sintering (SLS) process. The technological parameters that were used in the process of printing were the following ones: temperature of the nozzle 180 °C; bed temperature 100 °C; layer height 0.2mm; solid layers on the top 3, solid layer on the bottom 3, fill density 40%, fill pattern –line, fill angle 45°. Dimensions of samples that were printed are shown in figure 10, while an image with the printing process of one sample is emphasized in figure 11.

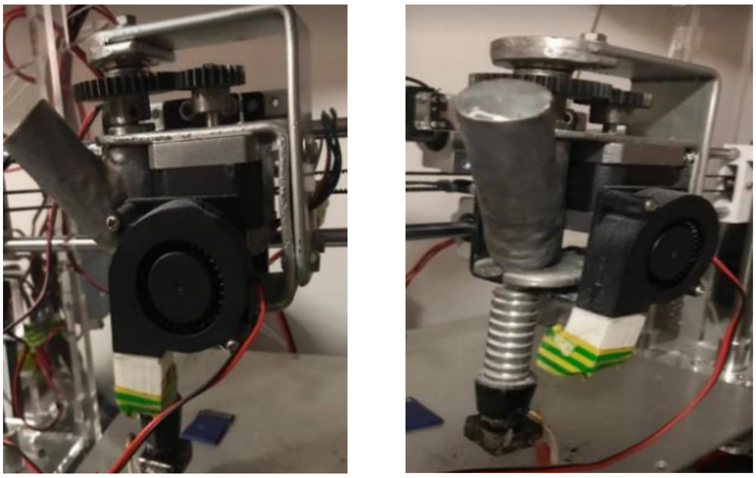

Figure 9. The manufactured extrusion subassembly.

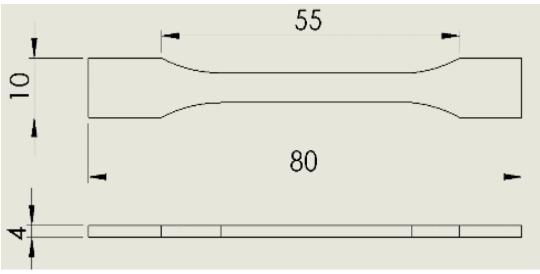

Figure 10. The dimensions of the designed sample.

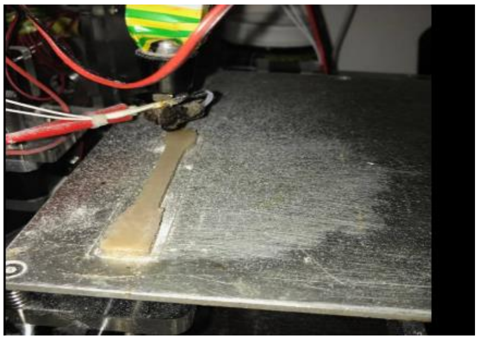

Figure 11. 3D printed part made from Duraform PA 12 material by using the manufactured extrusion subassembly system.

Tests for determining the mechanical characteristics were carried out by using the Instron tensile-compression load cell Type 2511-308 at the Technical University from Cluj-Napoca (see figure 12). A comparison was made between the tensile strength of the samples which were printed using the designed extrusion mechanism and the tensile strength of samples that were made by Selective Laser Sintering (SLS) from Duraform PA 12 material. As shown in figure13, it was observed that the tensile strength in the case of the printed part using the designed extrusion mechanism had a value of 26.39 MPa, as compared to the one made by SLS, in which case the reached value was 39.6 MPa.

Figure 12. Instron tensile-compression testing equipment.

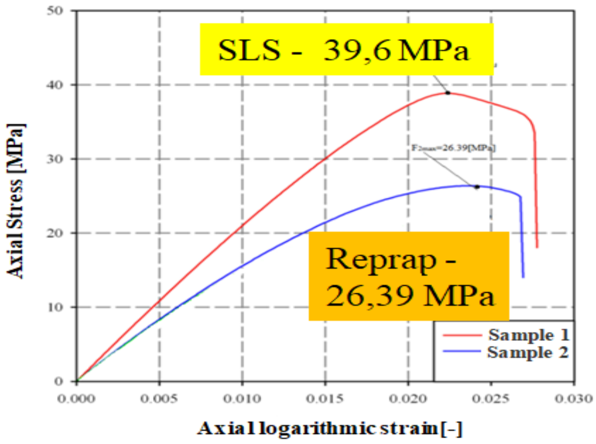

Figure 13. Stress-strain curves

Roughness measurements were made in the case of these samples using roughness tester Mitutoyo SJ-201 type. The reached results emphasized that the Ra values was significantly variable in the case of samples that were made using the extrusion mechanism mounted on Reprap Prusa i3 equipment. Values of Ra were between 7.39 µm and 20.17 µm due to the instability of the printing process. The best value of roughness was obtained in the case of the first deposited layers during the printing process, which were in contact with the heated bed, thus improving the roughness, while the highest value of roughness was obtained on the top surface, this phenomenon being caused mainly by to the high compaction of the plastic material while going through the heated nozzle. A solution for improving the roughness of the printed parts is to design and manufacture a sharpened head nozzle, reducing in this way the contact surface between the nozzle and the plastic material while going through the heated nozzle. Difficulties were encountered during the printing tests that were noticed also in terms of nozzle diameter, which are dependent by the layer height of the printed part. The solution that was found for improving the bounding of the successive deposited layers was to use a nozzle of Φ0.7 mm and a layer height of 0.25 mm. This correlation was important to avoid layer delamination. Before finding such a solution it was used a nozzle of Φ6 mm and a height of 0.5 mm for printing.

5. Conclusions

One original extrusion mechanism has been designed and tested in 3D printing process of parts made of Duraform PA12 material in powder state form as raw materials. Finite element analyses were made in order to analyse the transfer conduction and to reduce the amount of heat transferred from the nozzle to the upper part of the extrusion mechanism. Following the same analyses it was found that for a proper functioning of the printer it is necessary to pre-heat the nozzle for 90 seconds, so the use of a thermostat for the rigorous control of the temperature in that area is an essential aspect to be taken into account for good operation of the extrusion mechanism. Samples were produced using this type of extruding mechanism and tests were made in order to determine the tensile strength of parts made of Duraform PA material. The tensile strength had a value of 26.39 MPa, value that is comparable to the one reached in the case of samples made of Duraform PA material by SLS process (in this case the reached value was 39.6 MPa). Best value of roughness (7.39µm) was obtained in the case of the first deposited layers during the printing process. A solution for improving the roughness of the printed parts is to design and manufacture a sharpened head nozzle, reducing in this way the contact surface between the nozzle and the plastic material while going through the heated nozzle.

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