

Fused deposition modelling process: a literature review

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Abstract. It is well-known that the Additive Manufacturing is a one of the key technology of the fourth industrial revolution, and Fused Deposition Modelling process is one of the most used processes with a large applicability in many domains. Based on a literature review, the paper aims to approach the topic of the main process parameters definitions which ensure the management over the printing process. The paper is also focused on the current optimized manufacturing process, presenting the latest approach from the design phase to the post processing step. Another subject is referring to the used materials, with an accent over the composite carbon filaments in the context of Fused Deposition Modelling process limitations. In order to sum up, based on the main directions and purposes of the further research, this paper aims to be a binder between the current knowledge and what will be studied regarding Fused Deposition Modelling process.

1. Introduction

Currently, additive technologies used in the design and manufacturing of the industrial products are the subject of an extensive process of re-evaluation and restructuring of the traditional design and manufacturing processes. In contrast to the traditional manufacturing technologies, additive technologies aim to obtain a product by creating a model, a pattern for its cross sections, until to the physical realization and integration of all cross sections which are forming the desired object, based on geometry from a CAD model [1, 2]. The diagram of the realization of a product is presented in table 1.

Table 1. Diagram of the additive manufacturing process [3].

Additive Manufacturing Process				
Virtual Model		Machine with additive manufacturing technology		
3D CAD Model	Pre-processing software program for additive manufacturing	Front-End Software	Additive manufacturing process	Post processing

The main characteristics of the additive manufacturing are stated below:

- The models obtained by using the additive manufacturing processes are obtained after the unification of the same thickness layers. The layers are the cross-sections of the part in the XY plane of the printer and the height is provided by the thickness of the adjacent layers [3];
- Due to the each layer thickness, "the stair effect" appears - it can be reduced by decreasing the thickness of the layers [3];



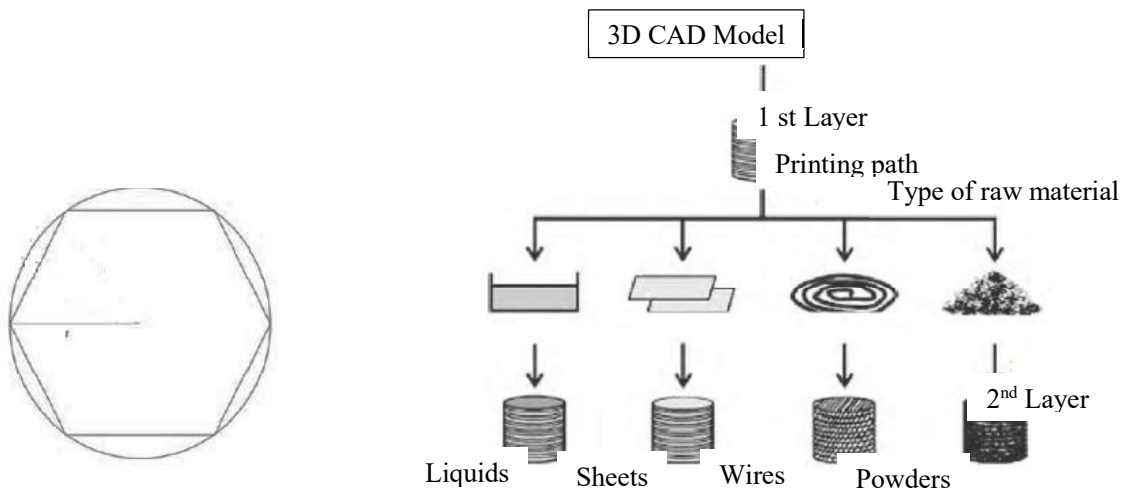


Figure 1. Approximation in *.stl format of a circle and its deviations from the original geometry [6].

Figure 2. Types of raw materials used in additive manufacturing [4].

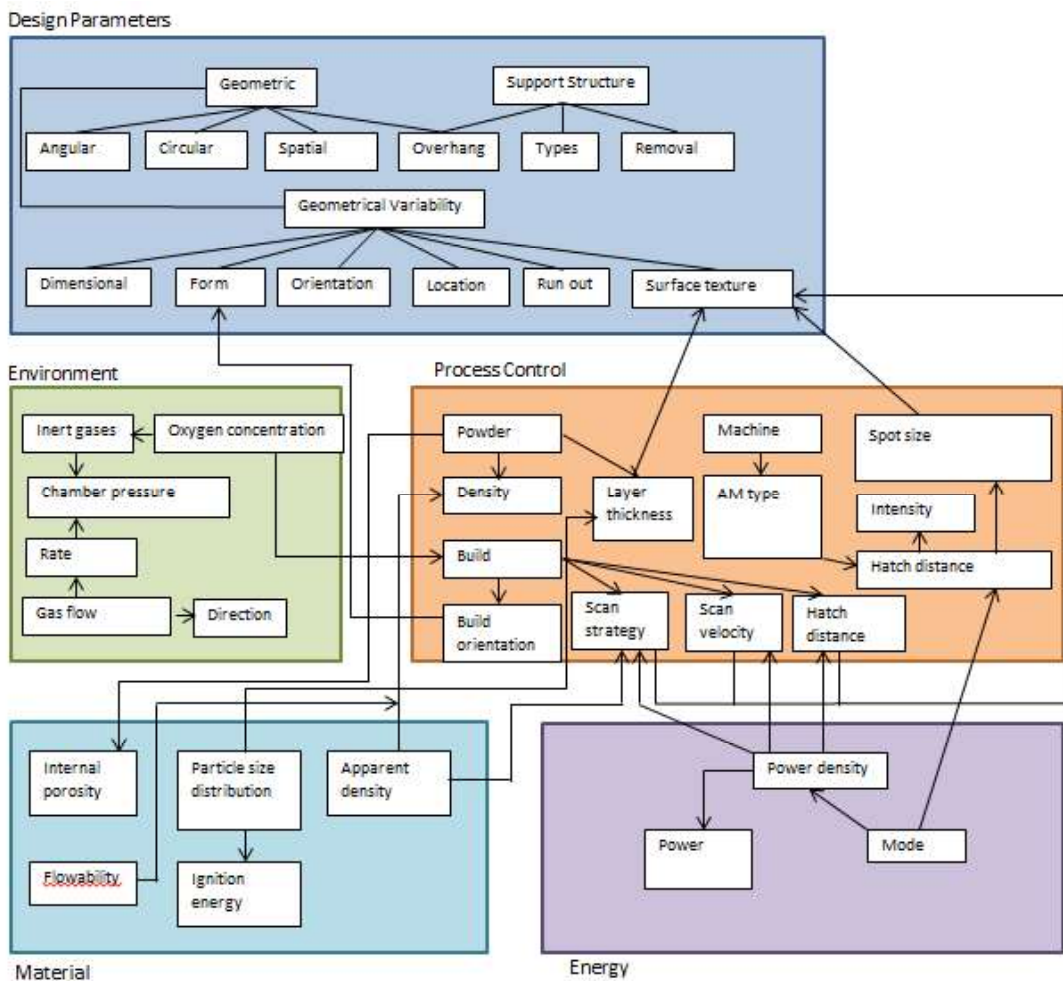


Figure 3. General parameters with an influence over the printing process [6].

- The output data from CAD software programs have a different accuracy in representing the geometry, with a certain level of errors in the process of meshing of each surface, for example the accuracy of approximating a curve (figure 1). Formats suitable for additive manufacturing are *.STL, *.3DMF or *.AMF [6];
- The layers of material that are deposited are generated from the virtual model of the part. Depending on the technology used, the base material can be found in various forms: liquid, sheets, wires or powder (figure 2);
- No excessive handling or constant change of work tools required, the parts being manufactured in a short time and with low stocks due to the flexibility of the process[4, 5];
- The material properties of the parts are influenced by the manufacturing process, having the possibility to control and optimize them [3, 4];
- In order to optimize the manufacturing process, the concept of "3D Nesting" can be applied - grouping parts on the printer table to maximize productivity and cost efficiency [8];
- Offers the possibility to create products with a lower level of carbon emissions, as well as the possibility to create parts with lower material consumption, at lower total costs compared by making the same part through conventional technologies [4];
- To maximize the quality of the finished part, a number of parameters are taken into account, having a certain impact on the manufacturing process (figure 3).

1.1. Advantages and disadvantages of additive manufacturing

Due to the advantages of additive technologies, there is a tendency to increase their use in various fields. The main advantages are presented hereafter.

- The possibility of using a wide range of materials compared to the conventional technologies. These materials can be metallic, polymers, composites or biological materials [4, 6];
- Manufacture of parts with complex, customized or modular geometry, with the possibility of avoiding creating junctions, without additional resources that could not be achieved by the available processes offered by the conventional technologies. Moreover, depending on the use, on a part the mechanical properties can be varied, having flexible and rigid areas [2, 4, 9, 10];
- In the most cases the tool is the head of the printer that generates cross sections of the part and it is not changed from one part to another [3];
- The parts are manufactured with increased quality of the geometry approximation to nominal dimensions of the CAD models, at a lower production and energy costs compared to the traditional technologies and also at a lower level of the waste of materials [2, 6, 10];
- The obtained mechanical properties can be controlled by the printing mode [12]. According to [13], the usage of additive manufacturing offers the possibility of increasing the strength of the parts by up to 4000%, elongation to failure by up to 2000% and stiffness by up to 200% [14];
- Without the intervention of distributors and manufacturers of parts, maintenance, repair and overhaul (MRO) operations can be performed faster [14];
- Regarding the level of pollution, carbon emissions are reduced compared to traditional technologies [2].

Disadvantages currently include the following:

- Additive manufacturing technologies are in a relatively early stage of development, requiring individual studies for each technology process and type of material to determine the manufacturing process of the part, as well as the resulting mechanical properties in order to understand each process [2];
- The dimensions of the parts that can be manufactured are limited by the table sizes of the available machines, but also by the increased production time for large parts [4];
- The surfaces of the parts obtained thru various additive manufacturing processes may require mechanical processing or heat treatments for strain relief [4];
- The accuracy in the XY plane is increased, but on Z direction the "step" effect appears, affecting the quality of the surfaces and mechanical properties in Z direction [3].

1.2. Fused deposition modelling process

Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF) is an additive manufacturing process which is based on the principle of extrusion of the material. Thus, the material from the filament roll is melted and evenly distributed by the print head along the established path. If the speed of the nozzle and the flow rate of the material are constant, theoretically the circular cross section of the deposited material is also constant. After deposition, the extruded material will unify with the rest of the material in order to form the printed layer and also the whole part – see figure 4 for working principle. The basic principles of the operation of any printing system by extruding the material are based on 7 key points (figure 5).

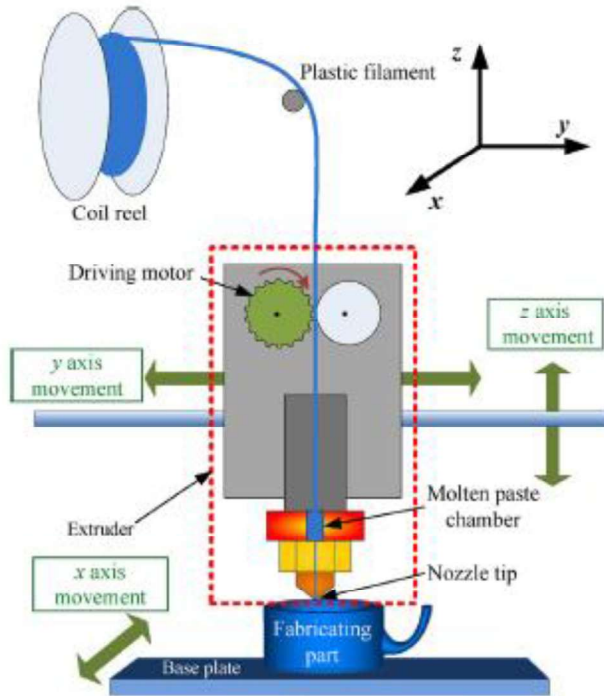


Figure 4. FDM working principle [16].

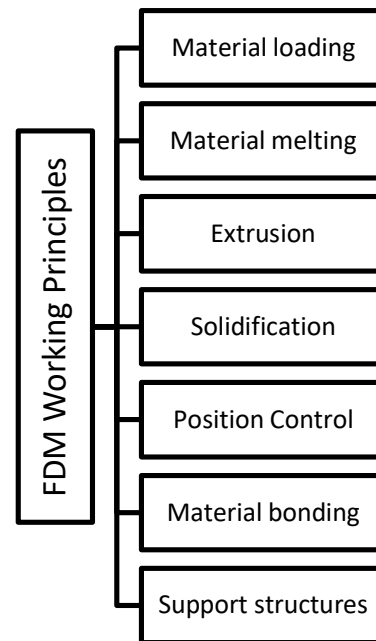


Figure 5. FDM – 7 working key points [15].

The FDM working principle combines the 7 key points presented above as following: if necessary, the nozzle is constantly supplied with material, where it is melted and maintained to a constant minimum temperature in this state until the extrusion in order to avoid the material burning. It flows through the tip of the nozzle over the layers of material already existing on the printer table, in the XY plane. The nozzle is moved in the XY plane and is directed to create the cross sections of the part.

After extrusion, the ideal material deposition is to remain in the same shape and dimensions, but gravity and surface stress will cause shape changes, the dimensions variations depending on cooling and drying effects, which are not linear. In order to minimize these effects, it is recommended that the temperature differences between the temperature at the building platform and the environment temperature to be minimal or manufactured in a controlled environment.

The bonding between the rows of material and also between the layers defines the quality of the part, so after the material has been extruded, it must solidify and form connections with the material in adjacent regions. The material regions can stick together, but not completely, the edges of each one being well defined. This will affect the mechanical properties of the part, as the two regions can be easily separated. It is also possible to have regions with too much deposited material, in this case the result being that the part will not be clearly defined.

Due to the complex parts which can be obtained on a printer with FDM technology, in certain situations it is necessary to make auxiliary supports that are made of either the same material as the part

or another material. They must be added to the part, taking into account the need for removal after manufacturing. The most effective method of making supports is to make them from special materials for this purpose [15, 16].

2. Main manufacturing parameters for FDM

Considering all the parameters presented in figure 3, for FDM it can be obtained a higher control over the manufacturing process, in order to obtain parts with mechanical properties and geometric accuracy as high as possible, in a shorter time and lower costs. In the printing process, certain factors have a higher influence on the final result, compared to others and the errors generated by each have an irreversible impact, the manufacturing process being unidirectional [17]. They are presented hereafter.

2.1. The quality of the filament

The quality of the filament influences the manufacturing process, but also the properties of the resulting manufactured parts, considering the variations of the filament nominal diameter value – see figure 6 for the impact over the deposited material.

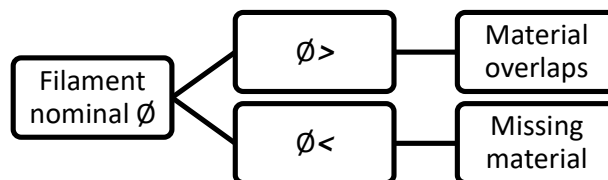


Figure 6. Variation of the filament diameter compared to the nominal value [18].

2.2. Part positioning on the building platform

The part positioning on the building platform is an important parameter that mainly influences the mechanical properties, appearance, part "slicing", printing time, material consumption and costs. The highest mechanical properties are obtained when the part is printed in the direction of tensile stress during use, thus avoiding the delamination effect, because in the end the materials have an orthotropic behaviour similar to the composite materials [20, 21].

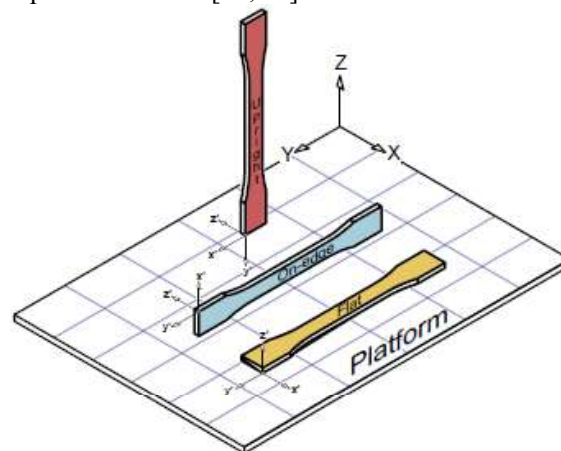


Figure 7. Part positioning on the building platform [20].

According to [22], from 55 design rules for additive manufacturing for FDM, 70% of them are directly or indirectly dependent on the orientation of the part on the building platform, implicitly on the direction of material deposition to form the part. Due to the importance of this parameter, work steps were established to define the orientation of the parts based on their usage, from the early stages of the projects, a work flow being presented in figure 8.

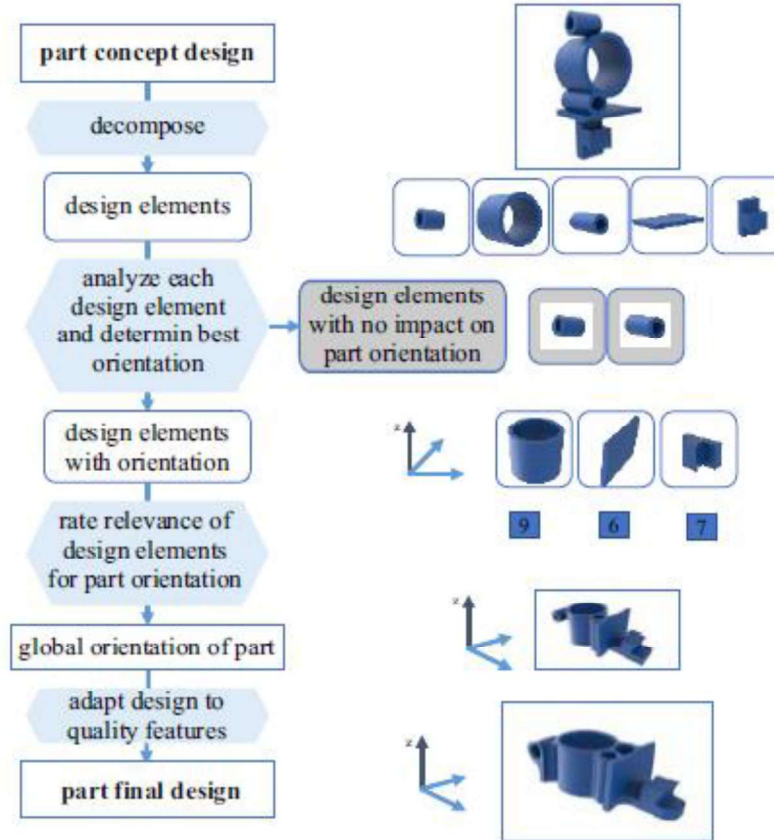


Figure 8. Defining the orientation of the part from early design stages [22].

2.3. Material direction – raster angle

The angle of deposition of the material with respect to the XY plane in the orthogonal system of the machine influences the mechanical properties of the resulting part, which can be higher or lower than the specifications of the basic filament offered by the manufacturer [23].

As a comparison to observe the importance of the material orientation, the results on stiffness presented in table 2 highlights the best result in the loading direction of tensile. The specimens are made of short carbon fibers composite filaments and TPU matrices, which also contain a different amount of fibers [24].

Table 2. Comparison based on the material orientation for tensile loading [24].

Carbon fiber quantity	E [MPa] at 45°	E [MPa] at 0°
0%	239.91	242.37
1%	300.23	313.85
2%	331.22	387.89
4%	479.04	642.26

The optimization regarding the orientation on the building platform can be performed considering the geometric parameters of the part: consider the dimensions (width, depth), the slenderness, the degree of filling with material, areas with discontinuities, but also the appearance of each layer. The aim is to obtain as large, continuous surfaces as possible and to minimize the irregularities of the material layers by analysing each layer of the part [19].

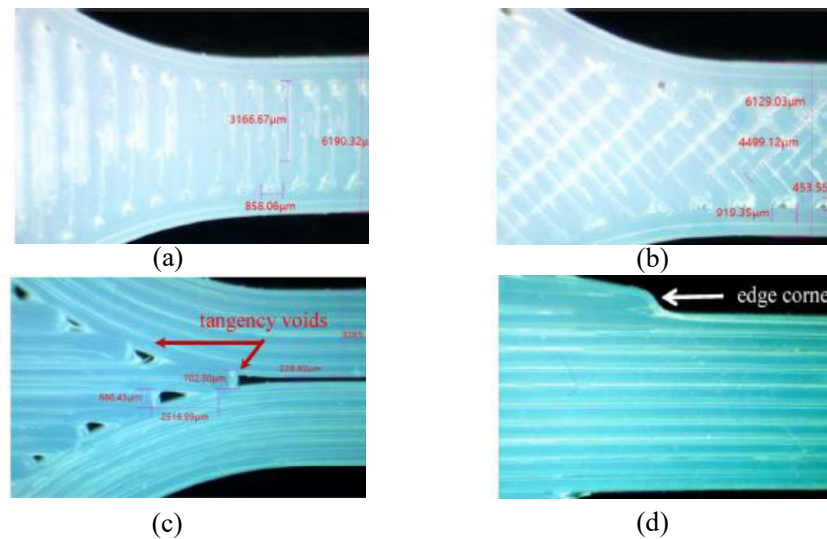


Figure 9. Top view of 4 specimens (a) orientation at 90° ; (b) orientation at $\pm 45^\circ$; (c) and (d) orientation at 0° [25].

Figure 9 shows four specimens made with a different material deposition angle, the manufacturing defects that appear being visible: edge corners or material gaps.

In order to increase the precision of the part, it is recommended to initially make its contour, the limits between which the material will be deposited being defined by the defined edges [19, 25].

The infill can be 100% with material or to have a different structure, as is presented in section.

The rows of material deposited and the layers between them must achieve a continuity of the material to ensure the load transfer which implicitly increases the strength of the part. If material gaps are provided, then stress peaks can appear in those areas which will cause the local failure of the material. In the printing process, initially the deposited rows of material come into contact as in area (a) of the figure 10. A heat transfer and diffusion of the material is initiated which generates a neck as in point (b), but which is influenced by the viscosity of the material. Once the temperature in that area decreases, the neck and diffusion effect decreases. In (c) and (d) after cooling, the contact and joint area stabilizes [23, 26].

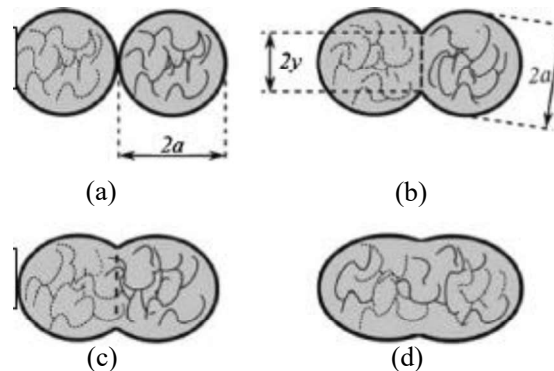


Figure 10. Sintering steps of polymers by FDM process [23].

Also, the approach of the raster angle is an important factor for the mechanical properties of the part. If the material rows overlap exactly, then the mechanical properties of the final part will be lower than if the layers are interspersed and the stress states are evenly distributed in all regions of the part. However, each interspersed model determines a discontinuity which materializes in weak points for the

created part [15]. In figure 11 are presented two variants of material orientation in order to obtain areas without material as reduced as possible [23].

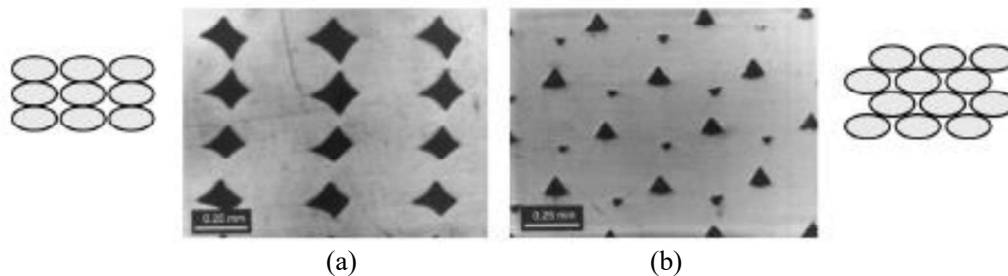


Figure 11. Layer layout models (a) rectangular model; (b) triangular model [23].

2.4. Temperature

Another important parameter is temperature. An ideal situation is to maintain a constant temperature in the nozzle, reducing variations that influence the speed and flow rate of the material. As a compensatory action, the inlet pressure can be increased to maintain the same flow rate. This parameter is the decisive factor in forming the bonds between the layers [27]. Depending on the size, the cooling time of the parts varies, having an effect on the control of the FDM machine, but also on the environment [15].

Temperature measurements cannot be performed conventionally (at several points) because this stage will interfere with the manufacturing process and the measured values are only from the surface of the part or near the surface area. Areas of interest - areas from contact between the deposited layers - are not captured by classical measurements. However, to validate the simulation, surface measurements are performed to compare the obtained values with the simulation results, where the temperatures for the whole part are obtained [27].

The cooling process is important for creating the bindings between the rows and the layers in order to create the final part. As long as the cooling process is taking longer, the obtained mechanical properties are higher due to a better linkage of the material. The cooling process is influenced by the size of the part, the material, the FDM machine, but also by the cooling method. If the temperature is not evenly distributed between the layers, residual stresses can occur, causing delamination of the layers, because these stresses cannot be transmitted between the layers [28].

2.5. Thickness of the printed layer

An important feature is the thickness of a manufactured layer – the influence of this parameter over the quality of the final part is presented in figure 12.

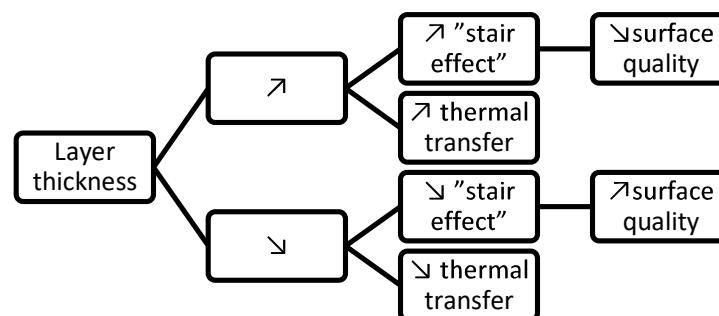


Figure 12. Influence of the layer thickness over the quality of the final part [16, 29].

Statistically, the dimensional accuracy is mainly influenced by the density of the inner structure (infill) and the dimensions of the layers of the material, the software program having also an influence on the quality and planning of the manufacturing with the settings of the manufacturing parameters [30].

2.6. Work environment

Although the working environment for the FDM manufacturing process is usually the normal environment, there are studies that aim the influence of a specific working environment on the characteristics of the parts after the manufacturing process. Thus, for a Nylon polymer the manufacturing in a nitrogen environment had an increase of the strength up to 30% and the oxidation process was diminished due to the lack of oxygen, causing an improvement during the adhesion process of the layers.

For manufacturing ABS, PLA and PA6 samples in a low pressure environment; compared to specimens of the same materials printed in normal environmental conditions, there are more qualitative parts surfaces, the traces of the manufacturing route being less visible (figure 13) and a lower roughness value. Also, there is an increase on the weight, density and volume of the part due to the longer cooling process and more deposited material due to a better bonding. There is also a decrease in the porosity of the part due to the high adhesion of the material layers [32].

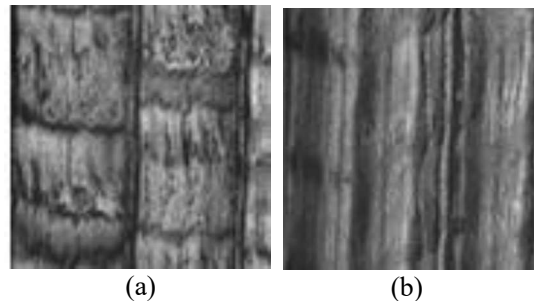


Figure 13. Manufacturing ABS specimens (a) in normal environment; (b) in controlled environment [32].

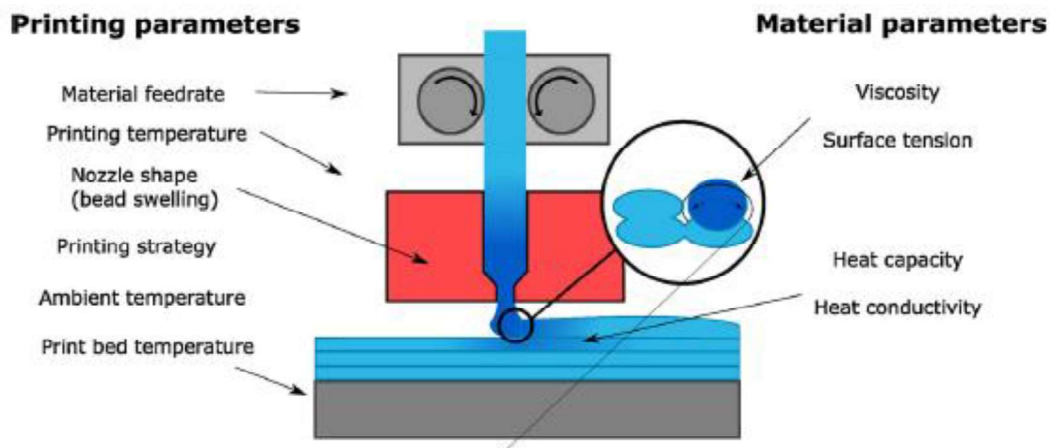


Figure 14. The main parameters that influence the FDM printing process [23].

2.7. Other parameters

In the FDM manufacturing process other manufacturing parameters are involved, which through their interdependencies, determine the user to create and use an optimal variant of them.

- Nozzle diameter - this value is a constant, but there are manufacturing systems which allow the user to change it to the desired accuracy;
- Material properties - the behaviour of the material is difficult to predict, but in most cases it is anisotropic;
- Gravity - due to gravity the molten material may flow, even if no inlet pressure is applied;

- Deposition speed – as the manufacturing speed is higher, the slower the printing time is and the time for material cooling during the manufacturing process is reduced [20, 27].
- Type of infill – presented in the next section.

In conclusion, the main parameters that influence the manufacturing process are described in figure 14 and the physical phenomena that occur during the deposition of the material are described in figure 15.

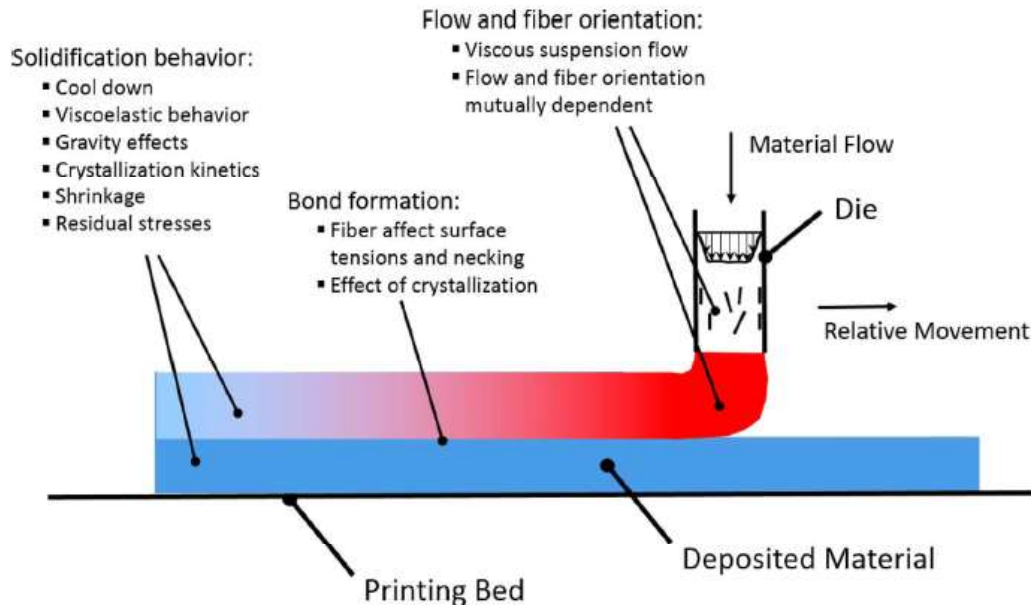


Figure 15. Physical phenomena in the FDM manufacturing process [31].

3. FDM – optimization

The optimization process for parts obtained thru FDM process occurs on each step of a product development – from design phase to its post processing after manufacturing and testing – the steps are presented below.

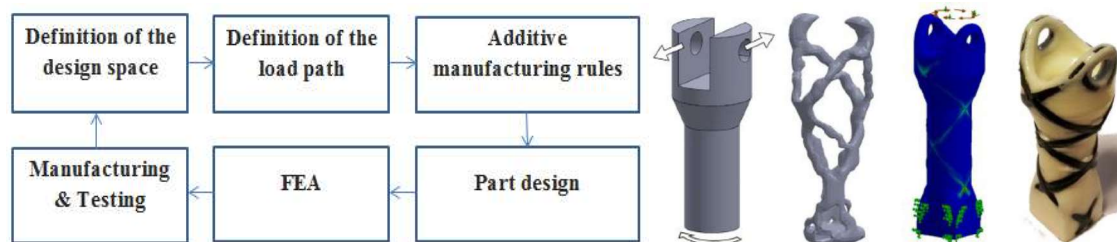


Figure 16. Part design & optimization process [13].

In the design phase, based on the experience obtained in Additive Manufacturing for simple polymer filaments or with reinforcement, there are several adapted rules (figure 16) which can be followed in order to obtain an improved part, taking in consideration the anisotropy of the material and lower strength values in Z direction compared to other directions [13].

- The reinforcement path must cover all areas where there are von Mises stresses, but must be aligned according to the stresses generated by tension-compression (definition of normal);
- The reinforcement route/ the deposited material row is recommended to be continuous;

- In areas of high stresses, the areas of curvature must be oriented towards the inside of the part in order to avoid the possibility of having material fibers out from the matrix;
- Internal channels are an alternative to open channels - increases the connection between reinforcement and part, having the effect of delaying buckling in areas prone to compression;
- The start and end areas of reinforcements / the deposited row material must be in low-demand areas;
- Access areas to the internal channels to allow their reinforcement;
- Inflection points must be accessible [33].

Also, for the design optimization process can be taken in consideration the infill type, the internal structure being adapted based on the application, obtaining increased properties. However, certain properties, such as rigidity, strength and energy absorption capacity, are still limited in development by the random microstructure, which translates into structural defects with local peaks [36].

Now, considering the manufacturing machine, the optimization can occur on the manufacturing parameters (see section 2 for details) or the type of the printer. Due to the large spectrum of available printers on the market, printers can be created by reconverting CNC machines or industrial robots, in this way the FDM process can be developed to be used in several planes, with several nozzles, having thus the ability to use more materials (figure 17) [21].

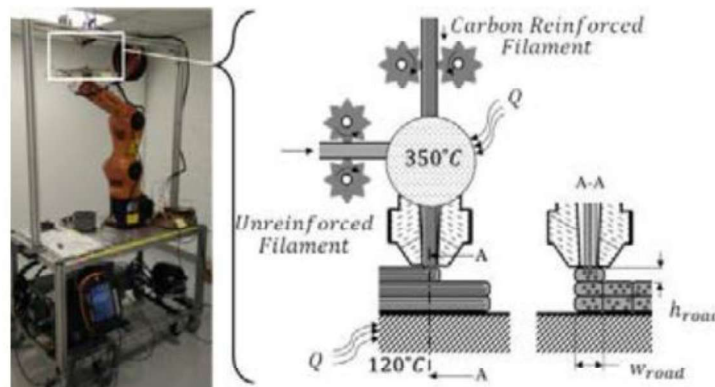


Figure 17. Reconversion of an industrial robot into a FDM machine [21].

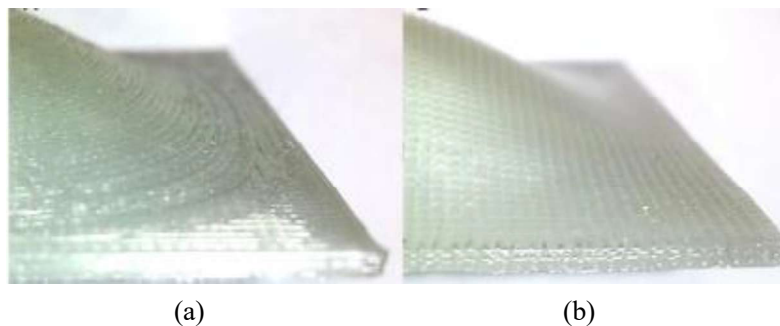


Figure 18. Part obtained (a) FDM; (b) CLFFF [21].

Due to the weakness of the material in the Z direction for the classic FDM technology and the overlapping of the walls of the layers which may have defects in their joining, a solution is to use the improved process of FDM printing, namely curved layer printing CLFFF (Curved Layer Fused Filament Fabrication), where the print head is not static as in the case of the traditional FDM process, thus avoiding the step effect – see figure 18 for comparison between processes [34].

Another optimization process can be possibility of reducing the loss of heat. This deficiency can be reduced by infrared heating of the material already deposited to ensure a higher heat transfer on the next pass as is presented in figure 19 [35].

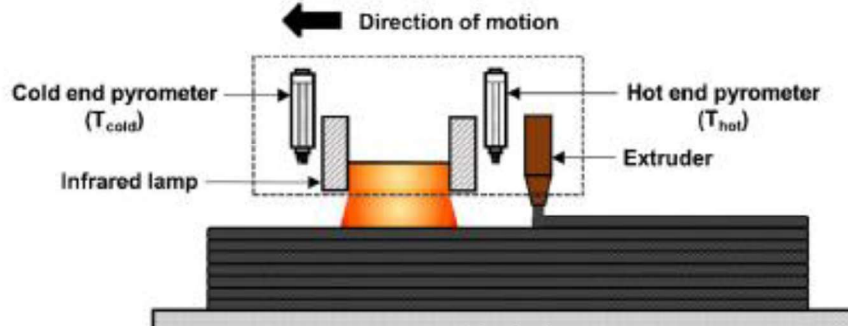


Figure 19. Part design & optimization process [35].

4. FDM – materials – carbon fiber filaments (CFF)

Due to the evolution and accessibility of the FDM manufacturing process, the field of materials used followed its trend, experiencing a rapid development of new thermoplastic materials, with properties from various categories: magnetic, conductive, flexible, soluble [36]. Research has shown that parts manufactured by the FDM process have behaviour similar to the laminated materials than that of a cast isotropic resin. [37].

If initially only polymer filaments were used, now these filaments can contain several types of materials, thus developing the concept of composite filament. By definition, a composite filament is a mixture of at least two materials which have different physical and chemical properties. After the combination of the materials, new material results with superior properties compared to the properties of each component [39].

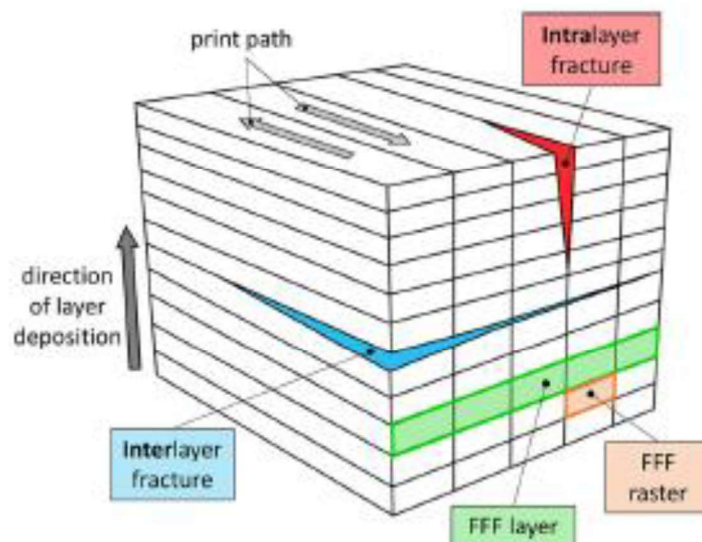


Figure 20. Inter-laminar area definitions and its deficiencies for CFF [40].

The topic of this section is the carbon fiber filaments – the filaments are made of carbon fibers that are embedded in a matrix of thermoplastic material in order to increase the rigidity and strength of the part in the direction of carbon fibers. In the other directions, the mechanical properties register much lower values, due to the fact that in these directions the material is dependent on the strength of the matrix and the area between the layers, called inter-laminar area (figure 20) [27].

Parts made by the FDM process with carbon fiber composite filaments have a behavior similar to conventional composite materials due to the similarity between the layers that form the manufactured part and the sheets of the composite material.

As common failure criteria observed for filament composite parts, delamination or inter-laminar failure, matrix cracks, fiber matrix detachment, fiber failure or their exit from the composite were recorded. Delamination may occur from manufacturing reasons, such as defective material deposition, cracks between layers or matrices with poor mechanical properties, or from mechanical reasons such as tensions in inter-laminar areas, compression load or a too high load or fatigue [27].

Table 3. Comparison between matrix polymer specimens and carbon fiber composite filament specimens [42].

Matrix polymer vs carbon fiber composite filament ($l \cong 100 \mu\text{m}$)	Printing direction[°]	σ matrix polymer [MPa]	σ CFF [MPa]	σ [%]	E matrix polymer [GPa]	E CFF [GPa]	E [%]
PLA vs CFF PLA	0	60.0	68.4	14	3.5	9.28	162.9
	45	49.6	50.7	2.2	3.4	5.08	50.7
	± 45	52.2	54.6	4.6	3.3	5.20	59.5
	90	45.5	43.7	-4	3.2	4.61	44.5
PETG vs CFF PETG	0	46.1	68.3	48.2	2.05	8.47	313.2
	45	41.9	45.2	7.9	1.96	3.60	83.7
	± 45	41.3	50.9	23.2	1.91	4.23	121.5
	90	41.4	42.6	2.9	1.89	3.19	68.8
ABS vs CFF ABS	0	38.2	50.9	33.2	2.3	7.15	212.2
	45	34.8	30.1	13.5	2.2	3.14	44.0
	± 45	34.7	29.2	15.9	2.1	3.09	45.8
	90	32.4	27.34	-15.7	2.1	3.03	47.1
Amphora vs CFF Amphora	0	46.9	49.3	5.1	2.01	3.93	95.5
	45	43.6	40.9	6.2	1.91	2.48	29.8
	± 45	44.4	42.0	5.4	1.96	2.63	34.2
	90	44.2	40.5	-8.4	1.90	2.45	28.9

Composite filaments with carbon constituents may have short or long fibers or carbon fiber particles.

Short fiber filaments increase the rigidity of the part, but the increase in strength is limited by the possibility of the fibers to get off the matrix before failure. In addition to advanced mechanical characteristics, the advantages of using carbon fibers are described by their electrical conductivity, high heat transfer capacity and biocompatibility.

Studies show that short carbon fibers of about 0.1 mm that are mixed with a thermoplastic polymer have a strength and stiffness increased by 65% compared to simple polymers [41]. In table 3 is presented a comparison between matrix polymer specimens and carbon fiber composite filament specimens, considering also the printing direction.

It is emphasizing that for an orientation to 0° the strength and the stiffness have the most increased values and an orientation to 90°, the weakest values. Also, the matrix type has an increased influence over the mechanical properties, the highest strength value being recorded by PETG and the highest stiffness to PLA. Considering also the material direction, it can be observed that to a 90° orientation,

the CFF can register lower strength values compared to the specimens manufactured only by the matrix polymer.

Another important topic of these filaments is the porosity of the material. It is determined as a percentage of the material gaps in the cross-section of a specimen by scanning and measuring the pixels showing the holes. The porosity is influenced by the amount of the fibers (figure 21) [39].

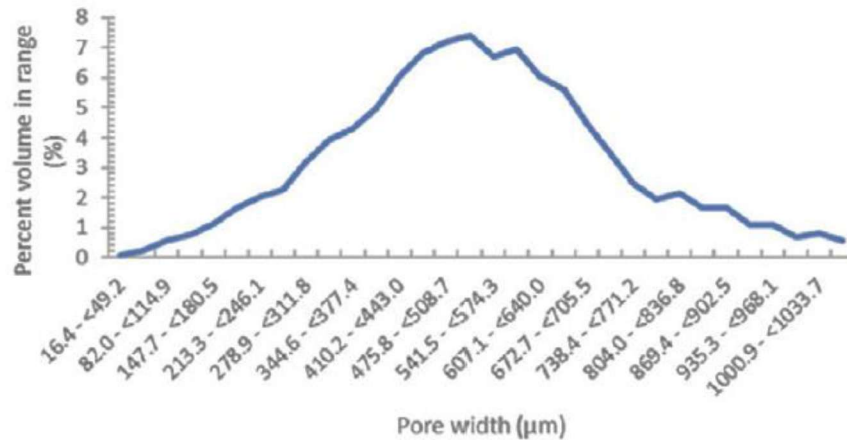


Figure 21. The size of the porosities depending on the amount of fibers [39].

However, material gaps can be attributed to a poor adhesion between the fibers and the matrix. A high number of fibers degenerates the heat transfer energy between the printed layers and the flow of material from the nozzle [23].

As a result of the manufacturing process, the carbon fibers undergo changes in size, which are reduced [42]. The manufacturing with continuous fibers is limited due to the possibility of arranging the rows of material. For a Nylon matrix, Mark Forged registered a maximum strength of 700 MPa and $E=50\text{GPa}$. As a manufacturing process, the FDM machine (figure 22) has 2 nozzles: one with not reinforced Nylon fiber and the other contains continuous Nylon filament reinforced with carbon fiber. In the outer areas of the piece, for complex and thin areas only not reinforced Nylon filament is used because the reinforced fiber does not have the capacity to manufacture these areas. Otherwise, the part is made of reinforced filament. The variation of the manufacturing parameters is limited, the material being deposited in a circular pattern (figure 23), from outside to inside - the direction of the fiber is known [23].

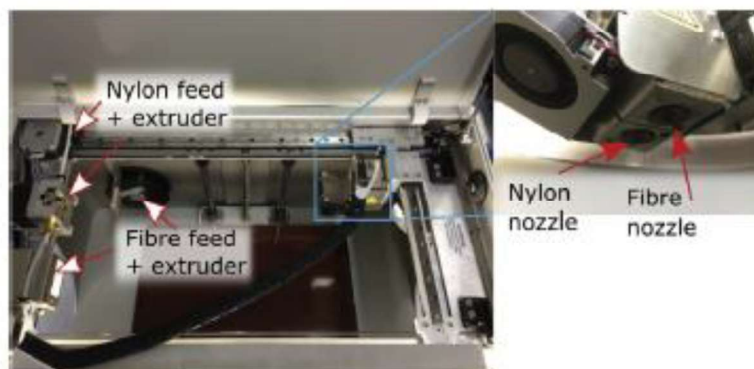


Figure 22. Continuous fiber printer [23].

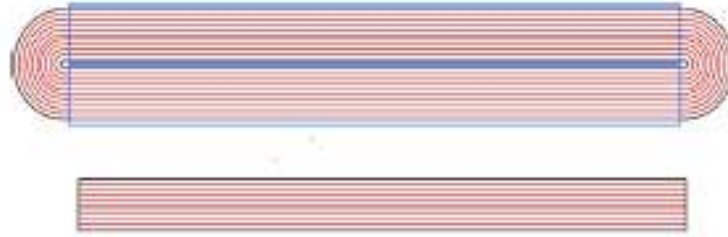


Figure 23. Deposition of a continuous fiber printer [23].

Due to the carbon fiber contained by the filament, its thickness determines the thickness of the printed layer. Because continuous fiber is used, the orientation of the material is limited [23].

Studies on carbon fiber composite filaments with various matrices are presented in the literature, the results being presented in the following table.

Hereafter, in figure 24 and 25 are presented a comparison of the mechanical properties between different types of matrix, with different lengths of the fibers.

As presented in figure 24, the matrix type, the type and quantity of the fiber are the main factors which affect the stiffness of the material. It is emphasizing that the highest influence is offered by the matrix type, continuing with the type of fiber and the amount of carbon fibers. With the same type of fiber and almost the same amount of fibers, comparing the stiffness between ABS and Nylon, the ABS matrix is offering higher values of the rigidity.

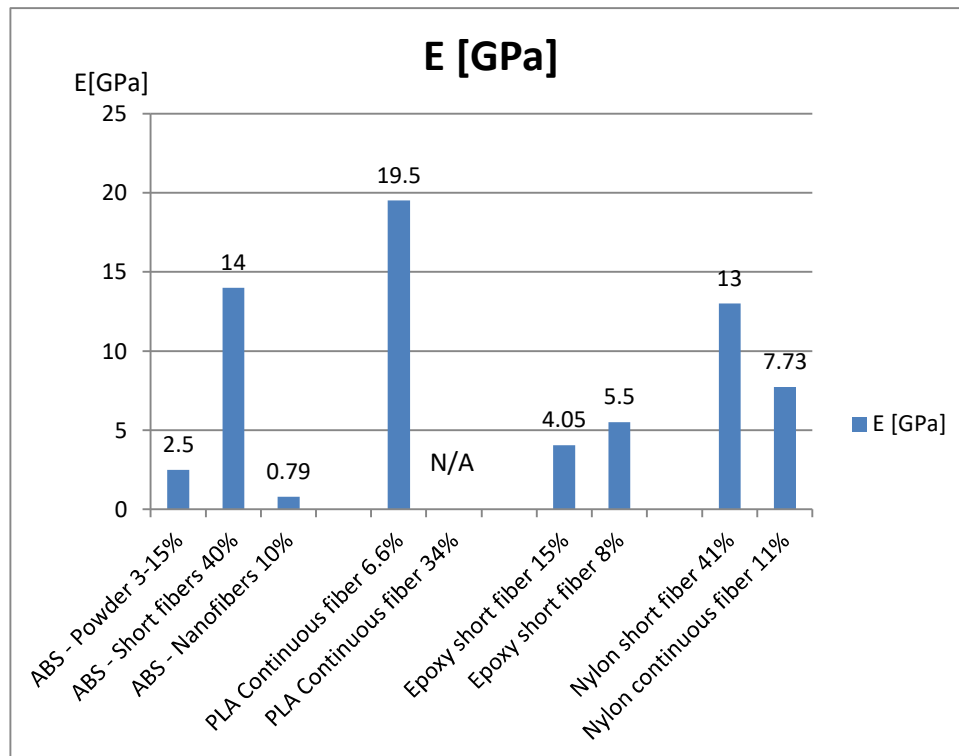


Figure 24. Comparison of the Young Modulus between different composite filaments with carbon fibers [23, 39, 44, 45].

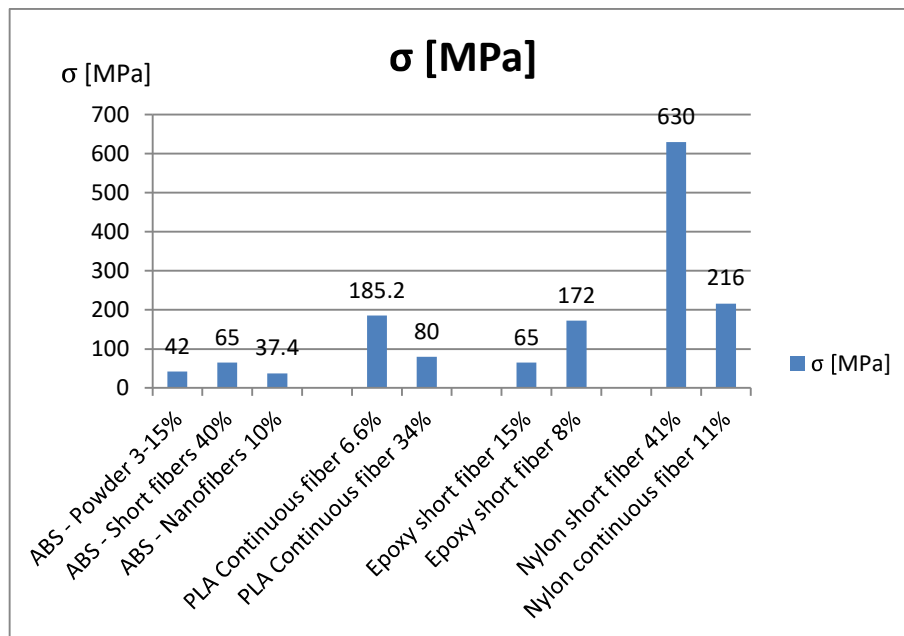


Figure 25. Comparison of the strength between different composite filaments with carbon fiber [23, 39, 44, 45].

As presented in figure 25, the matrix type has the highest influence over the strength of the material, the Nylon matrix having the highest strength value in comparison with ABS with the same type and amount of fibers. The second factor, after comparing the PLA and Nylon with continuous fiber is the type of the fiber and the third factor as importance is the amount of fibers.

It is emphasizing that for both types of parameters of the mechanical properties, the highest influence is offered by the type of matrix, followed by the type of fiber and by the amount of them.

For all types of carbon fiber composite filaments, different failure modes may occur as a result of stress, for example: fractures of the carbon fibers, cracks in the matrix, must be taken into account for the process of optimizing the manufacturing parameters polymer or delamination phenomenon may occur.

5. Limitations of the FDM process

As every manufacturing process, also the FDM process has several limitations. The main of them are listed below.

- FDM technology has a limitation in terms of the maximum temperature that can be used, this feature being directly related to the types of materials that are suitable for use;
- Parts with complex geometry can be made only by creating supports that support geometric accuracy;
- For some types of material, such as continuous carbon fiber composite filaments, the manufacturing technique does not currently allow all manufacturing parameters to be changed [23];
- The fatigue resistance of the parts is most influenced by the density of the material deposited inside the contour, followed by the size of the nozzle and the height of the layer;
- The diameter of the nozzle is recommended to be at least 1.5 times the value of the material layer height to ensure the integrity of the part;
- Printing parameters and part sizes are limited to the technical capabilities of the printer.

6. Conclusion

The research directions identified and detailed in the previous sections of the paper are outlined in figure 21.

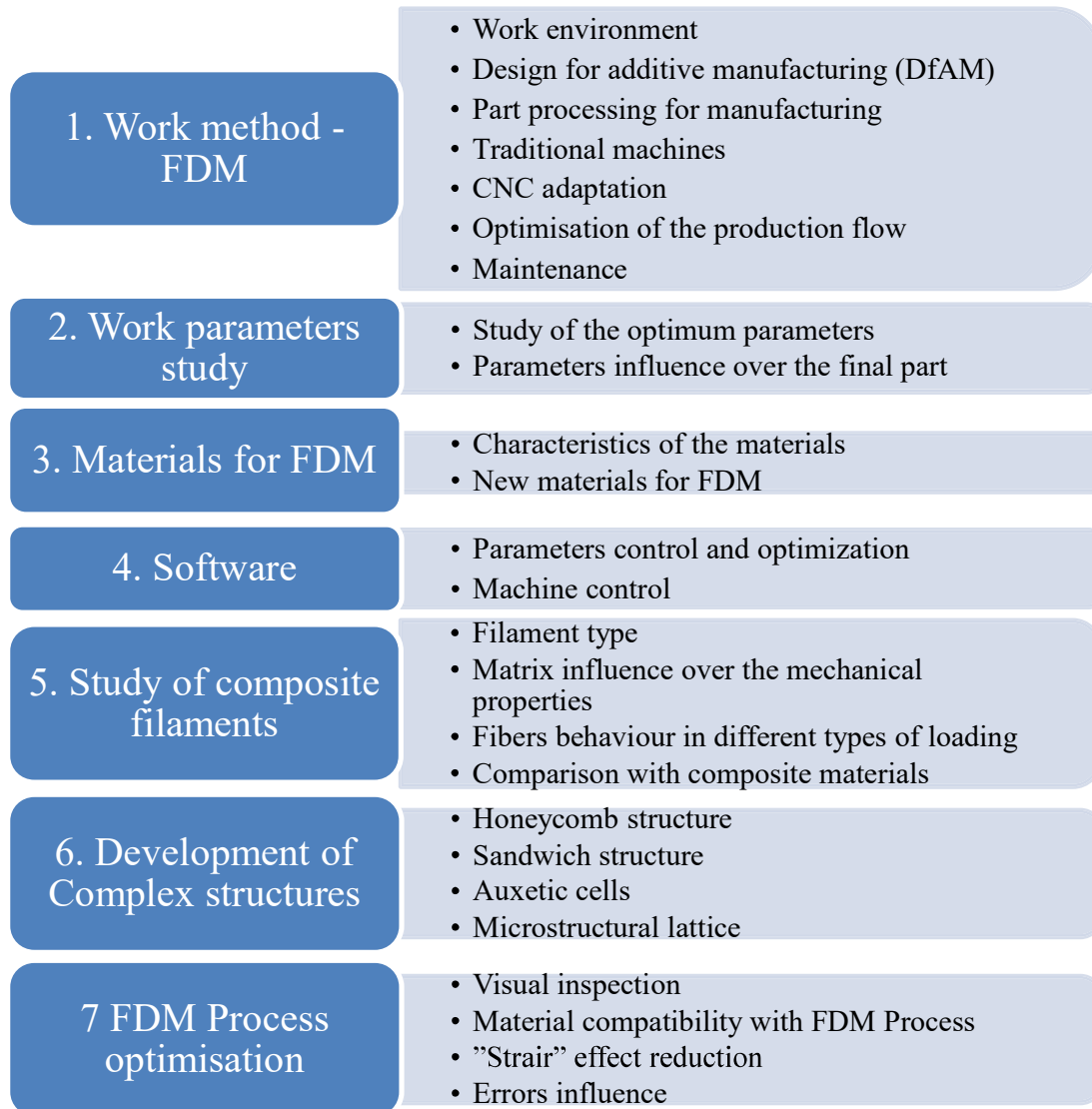


Figure 26. Research directions of FDM process.

As a conclusion, it is found that the manufacturing speed, the temperature of the working environment, but also the method of the deposition of the material, the infill, the thickness of the layer, the orientation of the part on the building platform are the most important parameters that lead to the improvement of the mechanical properties.

In addition to the manufacturing parameters, the material used has an important influence in improving the mechanical properties. As manufacturing with continuous carbon fiber filaments, additive manufacturing is not possible on conventional FDM machines, the use of short fiber composite filaments is being studied, in addition to the mechanical properties and failure criteria of such materials, such as the failure of the fibers, crushing and breaking them and delamination of the material.

Another possibility of obtaining increased mechanical properties is to create different complex structures, as lattice, honeycomb or auxetic cells based on the loading type.

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