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*Article*

# Calculating Feed of Filament in Extrusion-Based Additive Manufacturing to Correctly Print Continuous Fibers Composites in Curved Paths

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**Abstract:** The extrusion-based additive manufacturing is a popular fabrication method, which has attracted the attention of various industries due to its simplicity, cheapness, ability to produce complex geometric shapes, and high production speed. One of the effective parameters in this process is the feed of filament that is presented in the production G-code. The feed of filament is calculated according to the layer height, the extrusion width and the length of printing path. All the required motion paths and filling patterns created by commercial software are a set of straight lines or circular arcs that are placed next to each other at a fixed distance. In special curved paths, the distance of adjacent ones is not equal at different points, and due to the weakness of common commercial software, it is not possible to create curved paths for proper printing. Therefore, making a special computer code that can be used to create various functions of curved paths is investigated in this research, and also the feed of filament parameter is studied in detail. Next, by introducing a correction technique, the feed of filament is changed during the curved path to distribute the polymer material uniformly. Finally, composite samples (which have variable stiffness) consisting of curved fibers are produced with the proposed method, and the high quality of printed samples confirm the suggested code and technique.

**Keywords:** Extrusion-Based Additive Manufacturing; 3D Printing; Feed of Filament; Curvilinear Path; Variable Stiffness Composites.

## 1. Introduction

In recent years, additive manufacturing (AM) techniques have made it possible to produce complex parts with the desired geometric shape without the need to provide special tools [1]. Unlike subtractive manufacturing and machining methods, AM forms parts layer by layer [2]. Extrusion-based AM (as a special kind of AM techniques) has been popular among ordinary and industrial users because of the simplicity of the process, high reliability and the ability to produce complex parts from thermoplastic materials [3-5]. Despite significant advantages, the process has some limitations, and extensive studies have been done to overcome these [1, 6-8]. The main limitations of this method are directional mechanical properties, material restrictions, low

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dimensional accuracy and surface finish, lower strength compared to other production methods, and weakness in commercial software [9-11]. The majority of researches in the literature have been designed to improve the mechanical properties and optimize the parameters of this process [12, 13]. Some studied different materials [1, 11, 14] and feeding mechanisms by the consideration of melting and extrusion system [15], surface finish and dimensional accuracy [16], material swelling [17], in-process cooling [18, 19], thermal analysis of layers [2], and melt stability [20]. Also, some other examined the effect of printing parameters such as nozzle temperature, bed temperature, nozzle diameter, nozzle geometry, layer height, extrusion width, sample's orientation, raster angle, filling percentage, filling pattern, air gap, and printing speed [3, 21]. With great improvement in extrusion-based AM, recent and novel studies have been emerged; like producing composites with continuous fibers [10, 22, 23] (that have significant effects on mechanical properties) or optimizing nozzle path and filling pattern (which have influential impacts on mechanical properties, dimensional accuracy and surface smoothness) [24, 25].

Baich et al. [26] investigated the effect of low, high, double dense, and solid filling patterns on tensile, flexural, and compressive strength and modulus. Chakraborty et al. [27] created three-dimensional curved paths for the extrusion-based AM to reduce the stair-step effect, increase the strength and decrease the number of layers, and also proposed an adaptive method to increase the surface smoothness and dimensional accuracy in the process. Jin et al. [28] employed the parallel-based generation method to create optimal paths in the process. Akhoundi and Behravesh [2] conducted the thermal analysis on the filling patterns (concentric, rectilinear, honeycomb and Hilbert curve) and examined their effects on the tensile and flexural properties of printed samples. Koch et al. [29] investigated the mechanical anisotropy of printed products by customized tool path generation. Guan et al. [30] studied the effect of fill gap on the flexural strength of parts fabricated by curved layer fused deposition modeling. Kumar et al. [31] examined the mechanical properties of printed samples by creating paths based on fractal curves.

The instructions for printing a sample and determining the motion path of nozzle in extrusion-based AM are provided as a single code given to the 3D printer. All necessary settings such as nozzle and bed temperature, all movement paths, the filling pattern and percentage, fan speed, printing speed, feed of filament and etc. are provided by commercial software in the form of standard codes. One of the critical parameters in G-Code is the feed of filament, which is calculated according to the extrusion width, the layer height and the length of printing path. The feed of filament (based on the three parameters) is always constant and it is not possible to change it in different sections of the program. Available commercial software implements various filling patterns such as linear, rectilinear, grid, triangular, star, cube, concentric, honeycomb, 3D honeycomb, Hilbert curve, Archimedes curve, spiral, and etc. The important point in all these patterns provided by commercial software is that all paths are a set of straight lines or circular arcs which are placed next to each other at a constant distance. In some cases, such as the production of composites with curved fibers, which are variable stiffness composites, it is necessary to produce curved paths for nozzle motion. Due to the weakness of current commercial software, it is not possible to create curved paths for proper printing. Since the distance between adjacent paths is not equal at different points in printing the curved ones, it is vital to change the amount of feed of filament along the nozzle motion, so the polymeric materials are uniformly distributed throughout the curved path as a proper printing. Also, if there are continuous fibers in the nozzle outlet, the feed of filament must be reduced by a certain amount according to the diameter of fibers [10].

Regarding the mentioned limitations, the main goal of this study is achieving a special computer code by which various functions of curved paths can be created. Indeed, since the feed of filament is variable along the curved paths (depending on the path type), gaining a uniform distribution of polymeric materials is another purpose of the study.

## 2. Materials and Methods

In this research, polylactic acid with a diameter of 1.75 mm made by DigitMakers, and E-glass fibers are used to produce the composites. The text of the main yarn is 800 and the diameter of each

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glass fiber is 8 micrometers, so the diameter of the glass yarn is about 225 micrometers [9]. A 3D printer with a bed size of 195×195×200 mm is used to print the products. The nozzle and bed temperatures are considered to be 210 °C and 50 °C, respectively, and MATLAB software is employed to create the necessary program for printing composites.

## 3. Generating G-code

At the first step to generate the G-code required for the 3D printer (extrusion-based technique), path points must be identified. Since the goal is to create curved paths, the path function and its points must be identified and then the feed of filament must be calculated by the specified points and the length of the paths. It is possible that the distance between adjacent paths is variable at different points, so the feed of filament must be determined according to each specific path, and then final G-code can be generated. Also, considerations should be given to the flow percentage in the program for the proper printing of composites with continuous fibers.

### *3.1. Creating curved paths*

If the curved path of **Error! Reference source not found.** is considered, this reference curve is u sed to produce composites consisting of curved fibers in the transfer method by an automated fiber placement machine [32]. The path equation of the curve can be presented in terms of angles at the side edges and at the center. The angle of the curve at the side edges is $T_1$ and at the center is $T_0$. If the path is moved in the y direction, the path angle changes in the x direction and remains constant in the y direction. Therefore, by defining the relation of changing the angle of the reference curve in terms of x, the angle of the fibers at any point on the plane (in terms of x) can be easily calculated.

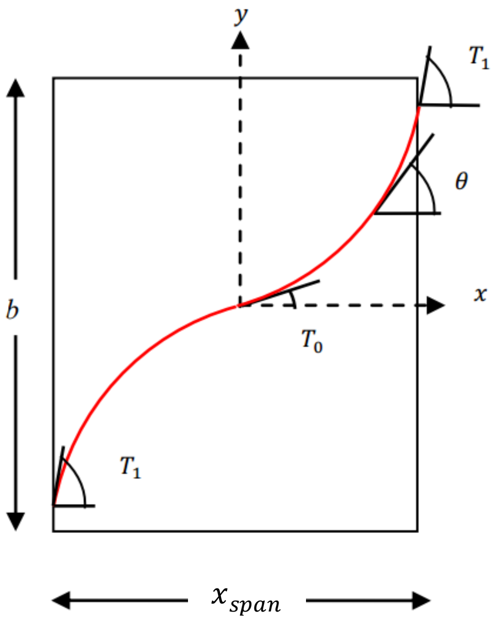


**Figure 1.** Reference curve with its determining parameters [32].

Equation 1 can be used to linearly change the angle of the fibers in the transfer mode in the y direction [32].

$$\theta(x) = T_0 + 2(T_1 - T_0)(|x|/x_{span}) \quad (1)$$

Where $T_0$ is the center angle of the reference curve, $T_1$ is the angle of the side edges, x is the coordinate of each point along the horizontal axis, and $x_{span}$ is the range of $x$. Points from the curved path are needed to generate G-code, so if the curved path is a Curvilinear function, this only determines the slope of the line in certain coordinates. So, the differential equation of Equation 2 must be solved to extract the coordinates of the path.

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$$dy/dx = \tan^{-1}(T_0 + 2(T_1 - T_0)(|x|/x_{span})) \quad (2)$$

This equation is solved using the Runge-Kutta method in each iteration and the coordinates of the path points are obtained. By determining the points from the curved path, the feed of filament must be calculated.

*3.2. Calculating feed of filament*

According to **Error! Reference source not found.**, by assuming the density changes with t emperature are negligible, the volume of material entering the inlet ($V_{in}$) can be equal to the volume of material leaving the outlet ($V_{out}$). The value of feed of filament is obtained from Equation 3 by determining the parameters of layer height (h), extrusion width ($w$), the length of deposited raster ($L$), and filament diameter ($D$).

$$E = (4w.h.L)/\pi D^2 \quad (3)$$

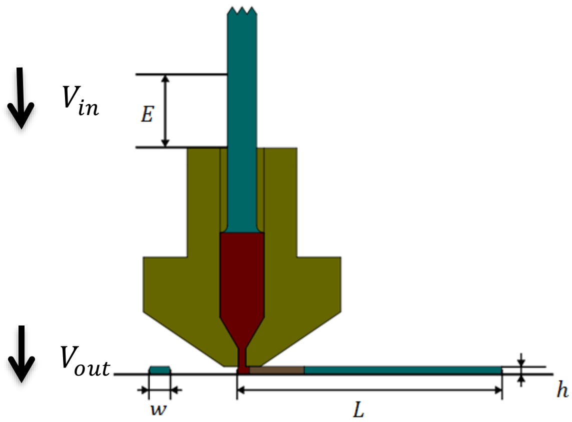


**Figure 2.** The deposited a raster to the specified extrusion width and layer height in the specified length.

The path in **Error! Reference source not found.** is supposed for printing where the nozzle m oved from point A to B; then from point B to C and finally from point C to A. By assuming the extrusion width of 0.5 mm and the layer height of 0.2 mm, **Error! Reference source not found.** is a chieved.

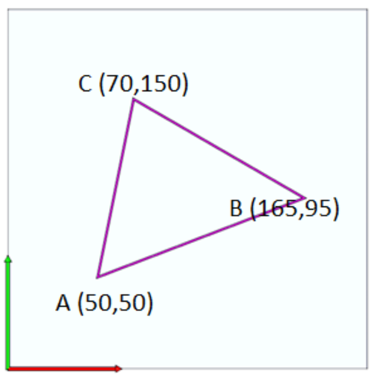


**Figure 3.** Triangular path created to calculate the feed of the filament.

**Table 1.** Coordinates of points, path length and calculation of feed of filament for each path.

| Point | X | Y | ΔX | ΔY | Path Length (L) | E (For Each Path) | E (continuous program) |
|---|---|---|---|---|---|---|---|
| A | 50 | 50 | 0 | 0 | 0 | 0 | 0 |
| B | 165 | 95 | 115 | 45 | 123.4909 | 5.1342 | 5.1342 |
| C | 70 | 150 | -95 | 55 | 109.7725 | 4.5638 | 9.6980 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| D | 50 | 50 | -20 | -100 | 101.9804 | 4.2399 | 13.9379 |

The program of this path is written based on the feed of filament in both continuous and discrete forms. In the continuous program, the value of E is cumulative and in each line of the program is added to the previous value. The continuous program is computed by Relations 4.

```
G0   X50  Y50
G1   X165      Y95  E5.1342
G1   X70  Y150      E9.6980
G1   X50  Y50  E13.9379
```
(4)

The discrete program is based on Relations 5 where G0 shows the nozzle movement without depositing, G1 indicates the nozzle movement by depositing, X and Y are coordinates of each point, E is the feed of filament, and G92 resets the feed of filament for the next line in the program.

```
G0   X50  Y50
G1   X165      Y95  E5.1342
G92  E0
G1   X70  Y150      E4.5638
G92  E0
G1   X50  Y50  E4.2399
```
(5)

*3.3. Calculating feed of filament for curved paths*

If a curved function is transferred in a direction, the vertical distances between two adjacent curved paths will no longer be the same. In the special Curvilinear function, as the fibers angle close to 90 degrees, the vertical distance between the two paths decreases. Indeed, at 0 degree the vertical distance is equal to the transfer value. **Error! Reference source not found.** presents a curved path w ith a start and end angle of 70 degrees, a center angle of 0 degree, and a transfer value that is twice the extrusion width.

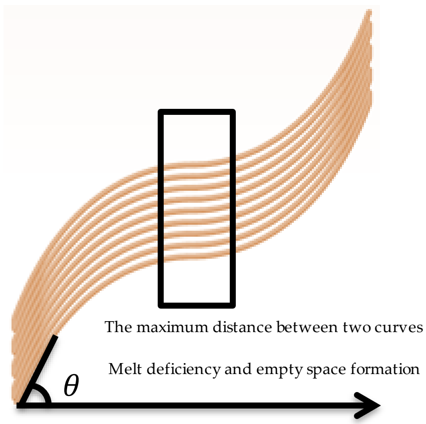


**Figure 4.** Curved paths with a start and end angle of 70 degrees and a center angle of 0.

According to **Error! Reference source not found.**, the volume of polymer becomes uneven at d ifferent points because of the constant feed of filament and the variable vertical distance between the two curves. It is even possible to observe some empty space in parts where the distance between two adjacent paths reaches its maximum and this indicates the lack of sufficient polymeric material. If the feed of filament rises to a constant value, the polymer accumulates in areas with smaller distances and the dimensional accuracy and surface finish of the printed part decrease. To remove these defects, the feed of filament is changed in proportion to the distance of two adjacent curves. Equation 6 is used to calculate the correct feed of filament.

$$E = \int_0^L [wh/((\pi/4)D^2)]\, dL \tag{6}$$

Where $w$ is the extrusion width, $h$ is the layer height, $D$ is the diameter of the filament, and $dL$ is the differential length between two consecutive points in a curved path. The extrusion width

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can be replaced by the vertical distance between two adjacent curves. The geometric interpretation of the method for calculating the vertical distance between two curves at 0 degree is shown in **Error! Reference source not found.**.

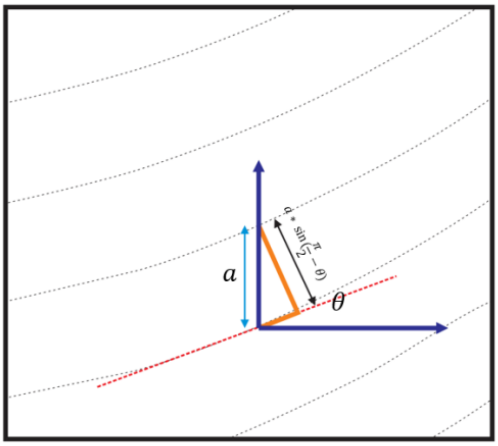


**Figure 5.** Schematic of the geometric calculation of the vertical distance between two curvilinear paths.

Finally, according to the geometric relations shown in Figure 5, the formula for calculating the feed of filament is presented as Equation 7.

$$E = \int_0^L [(h) a \cos(\theta) / ((\pi/4) D^2)]\, dL \qquad (7)$$

where $\theta$ is the angle tangent to the curve and a is the transfer value of the curve. The value of a can be considered equal to the extrusion width.

### *3.4. Computer program for generating G-code*

A computer program is designed to create different curved paths. The main purpose of the program is being able to use different mathematical functions to move nozzle with different parameters and also is generating the G-code. The main features of the program are the possibility of entering an optional function for the path and changing its parameters at any point. Another benefit of the program is the ability to change any of the motion parameters for the curve, such as angles and distances in each iteration of the program retrieval, by which it is possible to create complex curves. For printing composite samples, the nozzle returns to its origin outside the perimeter of the part at the end of each nozzle layer due to the continuity of the fibers and the impossibility of cutting them. This situation is shown in Figure 1. The program's start and end commands are automatically added to the main body of it.

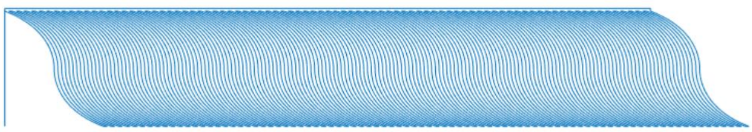

Figure 1. The created curve path in a layer with a start and end angle of 70 degrees and a middle angle of 0 degrees using computer code

## 4. Results and discussion

In this section, the results of the created curve paths, the correction of feed of filament, and producing composite samples are presented.

### *4.1. The result of modified G-code for curved paths*

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The polymeric sample made by the curved paths with a start and end angle of 70 degrees and a center angle of 0 without modifying the feed of filament is shown in **Error! Reference source not found.**.

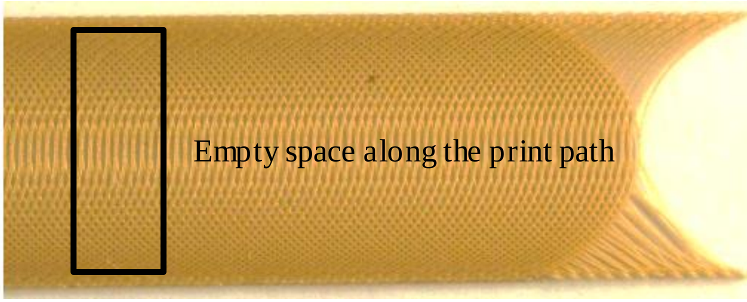


**Figure 7.** Polymeric printed sample in curved paths with start and end angle of 70 degrees and center angle of 0.

The amount of polymer is constant here due to the constant feed of filament. When the distance between the two paths increases, there is a lack of polymer throughout the path (except for the corners of the part) and empty space with different sizes are observable. As a remedy, if the feed of filament rises to a constant value, there is no polymer deficiency at the maximum distance between the two curves, but polymer accumulation occurs at the edges of the part. As shown in **Error! Reference source not found.**, this defect is observable at the edges of the sample due to the increase in angle and the decrease in the vertical distance of the curve.

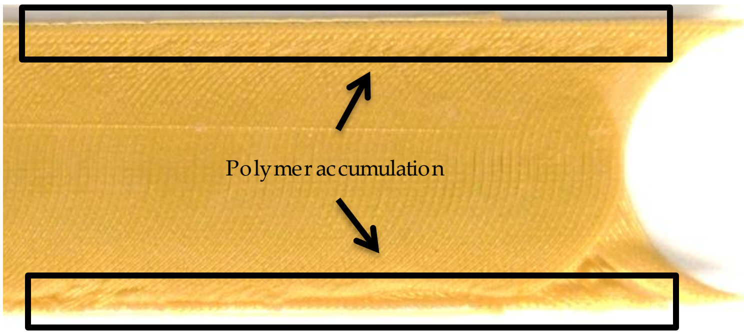


**Figure 8.** Polymer accumulation and reduced surface finish if the feed of filament increases as a constant value.

The sample produced by modifying the feed of filament is shown in **Error! Reference source not found.**. As shown in **Error! Reference source not found.**a and **Error! Reference source not found.**, the polymer deficiency is observed along the path when the amount of feed of filament is constant. **Error! Reference source not found.**b is obtained if the feed of filament is modified according to Equation 7. As indicated in the code simulation, the thickness of the curved path varies along it, and polymer deficiency and accumulation are not observed anywhere. The correct printed sample is shown in **Error! Reference source not found.**c. Properly printing of the sample, the absence of cavities, and removing polymer accumulation indicate the correctness of the feed of filament.

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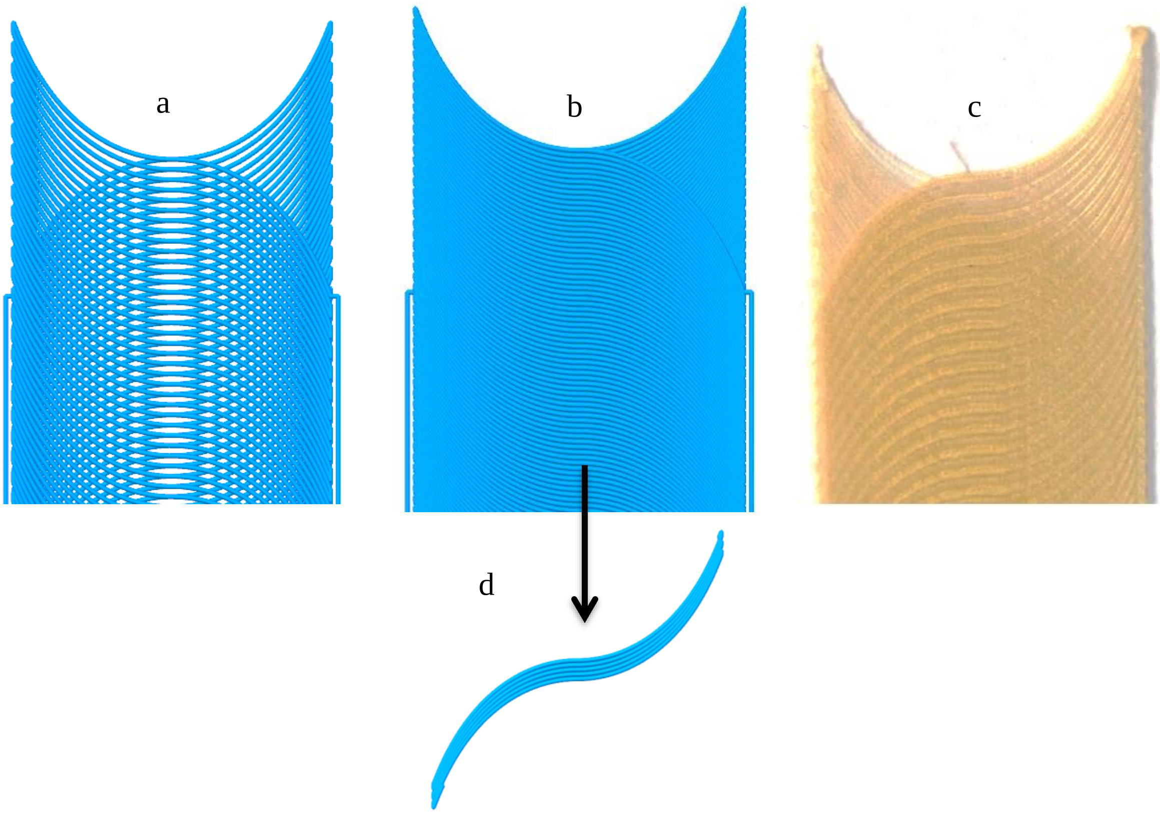
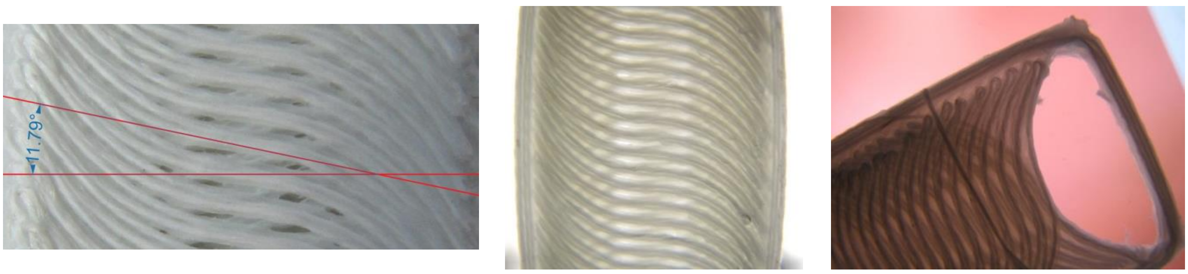



**Figure 9.** The effect of modified feed of filament on the absence of empty space and accumulation of polymeric materials as well as the quality and surface finish of the final surface of the part.

*4.2. The result of printing composites with curved fibers*

Variable-stiffness composites are designed to have variable stiffness in different points, and this property improved the performance of composites compared to fixed-stiffness ones [32]. One of the methods of producing variable-stiffness composites is changing the angle of fibers by considering specific curves (instead of straight lines). The automatic layering technique is a way to produce parts with curved paths, but its cost is high and there are likely various defects in production [32]. In this study, variable-stiffness composites are examined using the mentioned technique. It is important to note that when the goal is producing composites with continuous fibers, the feed of filament must be reduced for proper printing according to process parameters and fibers' diameter. The calculations to reduce the feed of filament based on the volume percentage of fibers have been studied in previous papers in detail [9, 10]. The printed composite sample is shown in Figure 2, with a fiber angle of 0 degree in the middle and 70 degrees at the corners.




a b c

Figure 2. Printing composite samples with curved fibers. a) angle of curve center is about 11°, b,c) angle of curve center is 0°

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As shown in Figure 2, by precisely controlling the feed of filament, it is possible to produce composites with curved fibers using the extrusion-based AM technique. The prominent point here is the deviation of fibers' angle from the specified value. In the current impregnation method, the glass fibers are pulled by the molten filament, which passes through the nozzle and feeds the outlet. As a result, a tensile force is created in the direction of fibers and this can change the radius of curvature and even make complete crumpling of fibers. To eliminate the crumpling of the fibers, a margin is considered around the sample to make the fibers stickier with the polymer. From the observation of prototypes, it is determined that the angle of curve center, which should be zero degree, is about 11 degrees. To fix this defect, it is considered to replace the value of zero degree in the curve with a negative angle. The best curve with an angle of zero degree in its center is selected after trial and errors. As a result, after moving the nozzle at the specified speed, the -5 degrees becomes zero

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

## 5. Conclusions

The goal of this study is proper printing of composites with continuous fibers in curved paths by the extrusion-based AM technique. For achieving the purpose, a novel method is designed that is able to create curved paths and generate necessary G-codes with modifying the feed of filament. Finally, using the proposed technique, composite samples with curved fibers are properly produced. The important conclusions of this research can be presented as follows.

- 3D printers based extrusion-based AM can be used to produce variable-stiffness composites with thermoplastic materials, which has many advantages such as low cost and higher quality compared to other methods.
- By modifying the feed of filament according to the distance between two adjacent paths, the empty space made by the transfer of a curve is filled and the surface smoothness of composites is improved. Also, in areas where the distance between the two curves decreases, the feed of filament is reduced to prevent projections on the surface.
- Due to the tension of the fibers in the current method of 3D printing, the angle of fibers changes according to the nozzle speed. This defect can be reduced by modifying the program and changing the angle of fibers in the middle of curve.

**Author Contributions:** Conceptualization, Behnam Akhoundi; Behnam Akhoundi; software, Faramarz Hajami; validation, Behnam Akhoundi, Mojtaba Nabipour; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, Mojtaba Nabipour; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.;

**Conflicts of Interest:** The authors declare no conflicts of interest.

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