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Experimental Investigation of Injection Pattern Effect on Tensile Strength of PLA Material in FDM Processes

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Fused deposition modeling (FDM) is the most popular, simplest, and least expensive method of additive manufacturing and 3D printing. This technique, based on extruding molten thermoplastic filament, is favored across industries for rapid prototyping and creating complex geometries without molds or extra equipment. A key challenge in FDM is the significant impact of printing parameters on the mechanical and physical properties of the final product. This research aims to examine how basic printing parameters, specifically using a 0.4 mm nozzle diameter in two injection mold patterns (linear and concentric), affect tensile strength. Results showed that altering the injection pattern changes tensile strength, ranging from 28.1 MPa to 27.8 MPa at 190℃. The linear pattern achieved the highest tensile strength, while the concentric pattern had the lowest. Additionally, scanning electron microscope images of the fracture surfaces revealed that all samples had micro holes at the layer interfaces, a characteristic inherent to the FDM process.

Keywords: Additive manufacturing, 3D printing, Injection pattern, Tensile strength

1 Introduction

Additive manufacturing (AM) refers to one of the manufacturing methods in which the final product is fabricated by adding a source of material based on the desired geometry.

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The AM approach differs from the reducing methods, such as machining in which the material is removed from the original size. Production of more complicated components could be achieved by using AM method [1, 2].
The layer-by-layer structure of a 3D design in this print is basically what distinguishes 3D printing not only from other 2D printing, but also from all traditional methods of producing objects such as shaping, machining, casting and molding. To make an object by a 3D printer, hundreds or even thousands of layers are printed on top of each other to create the final, three-dimensional form and complete it on the topmost layer in its vertical direction. That is why this process is called additive manufacturing [4].
One of the most popular and widely used additive manufacturing methods is material extrusion (FDM). The FDM process is the most widely used among all additive manufacturing methods due to its simple mechanism, low production cost, and the ability to print relatively complex parts. The schematic of the FDM process is shown in Figure (1), according to which the consumables are thermoplastic filaments of the same diameter, which are heated in the chamber and extruded in a semi-liquid form through the nozzle onto the printer screen. The final shape is selected from the extruded layer by layer of melted filament based on the designed file [3].
The widespread adoption of FDM is largely attributed to its ability to produce prototypes quickly and affordably, which is crucial for iterative design processes and reducing time to market. Moreover, the range of materials compatible with FDM, including PLA, ABS, PETG, and more advanced composites, extends its utility across different applications [5].
However, despite its advantages, the FDM process faces significant challenges related to the mechanical and physical properties of the produced parts. These properties are highly dependent on a multitude of printing parameters such as nozzle diameter, layer height, printing speed, and infill pattern, among others [6, 7].
Poly Lactic Acid (PLA) is one of the materials produced by AM process. This material is also called plant-based thermoplastic. One more important thing is that PLA is a biodegradable and recyclable material prepared from renewable raw materials [1, 2].

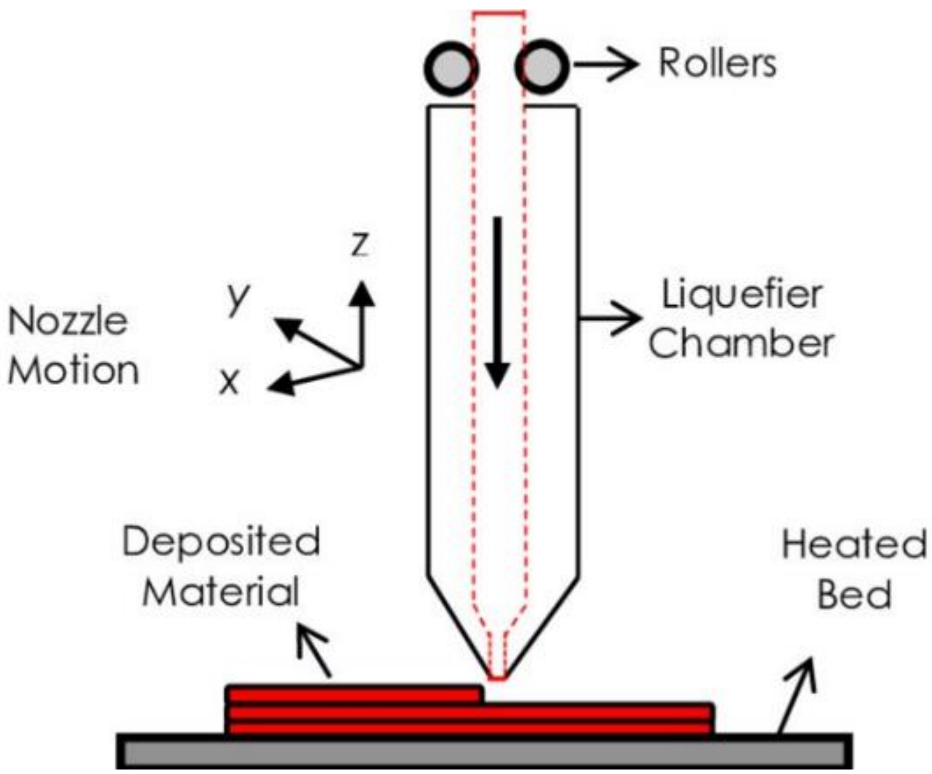

Figure 1 Print schema by FDM method [3]

As you can see in Figure (2) the conventional thermoplastic materials used in this method, which are generally divided into two types of semi-crystalline and amorphous thermoplastics, each of which has its own printing challenge from the point of view of different microstructural and rheological behaviors with temperature. Semi-crystalline polymers, the most famous of which in 3D printing in this way, is poly lactic acid, for printing, they must melt the crystals of the raw material, which exists at a special temperature and at different cutting rates and printing speeds [8].
One of the critical aspects influencing the mechanical properties of FDM-printed parts is the infill pattern. The infill pattern not only affects the internal structure and density of the printed object but also has a substantial impact on its mechanical properties, including tensile strength, impact resistance, and overall durability. Commonly used infill patterns in FDM include linear, concentric, honeycomb, and gyroid, each offering different trade-offs between strength, weight, and material usage [9, 10].
In Kiendl's research, it was shown that by changing the direction of printing for PLA material, it is possible to control the mechanical properties and determine the failure mechanism. They showed that the anisotropy (difference of mechanical properties in different directions) is much less for the crossed state, and by increasing the angle of the print filaments compared to the angle of application of force, more favorable mechanical properties can be achieved. In addition, due to the tendency of the filaments to stretch in the direction of force application, samples with a higher print angle exhibit a softer behavior when are breaking [11].
Afros investigated the effect of manufacturing orientation on tensile strength and fatigue properties of PLA filament. All the standard samples were printed in three manufacturing directions of 0, 45 and 90 degrees, and after applying the tensile test, the fatigue was evaluated at four levels. As expected, the tensile strength was maximized in the 0° fabrication direction, but the fatigue life was maximized in the 45° fabrication direction at all cyclic loading levels. They also calculated the strain energy absorbed during the cyclic test and concluded that the strain energy trend was similar to the life cycle number and the highest value was obtained in the 45° orientation [12].

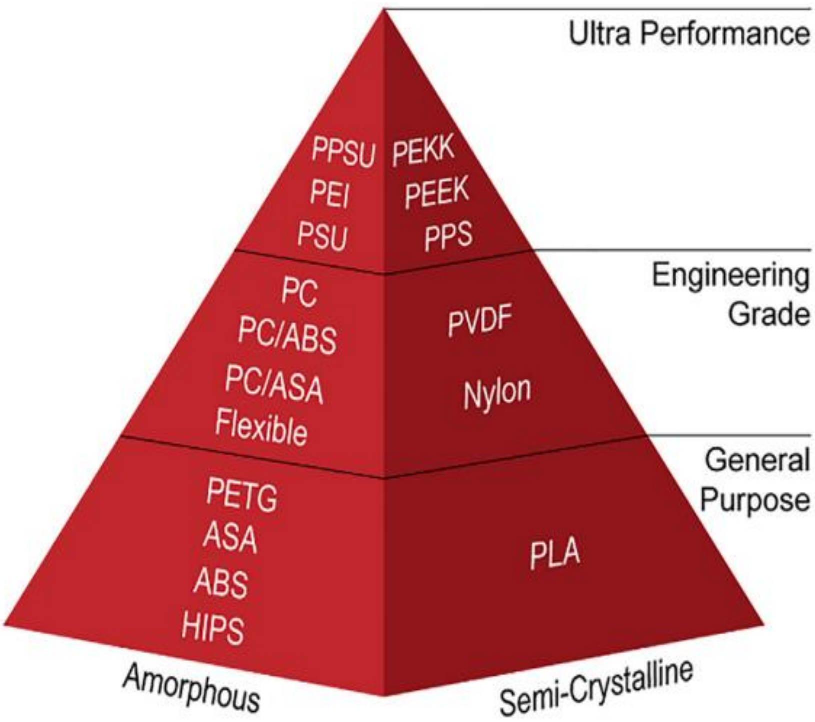

Figure 2 Thermoplastic materials used in the FDM process by application [8]

Another print parameter that strongly affects the print quality, feeding rate and adhesion between threads and layers of the printed part is the nozzle temperature. Akhundi showed that increasing the temperature of the nozzle improves the quality of the printed layers, and the results of their mechanical tests showed that polylactic acid printed at the highest temperature has the highest mechanical properties. They used five nozzle temperatures of 210, 220, 230, 240, and 250℃ [13].

2 Method

In this research, polylactic acid filament with standard diameter of 1.75 mm, glass to rubber transition temperature of 70°C and melting temperature of 175°C was used. PLA is known for its commendable mechanical specifications, which make it a versatile material in numerous applications. It exhibits high tensile strength, typically ranging from 50 to 70 MPa, and a Young's modulus between 2.7 and 16 GPa, indicating its significant stiffness and rigidity. In this article, the injection pattern parameter as a variable parameter and its effect on mechanical properties and tensile strength have been investigated. In Table (1), the investigated parameters are presented as input to the process. The selection ranges have been selected based on the PLA filament manufacturer's proposal so that the minimum melting temperature is 180°C and the maximum is 230°C. In addition, in Table (2), the fixed parameters of printing, such as the temperature of the printing plate, printing speed, melt flow, and layer thickness and in Table (3) specifications of print samples are presented.

Table 1 Variable print parameters

Number	Print parameters	Variable	Unit
1	Nozzle temperature	190, 200, 210	℃
2	Injection pattern	Linear, Concentric	-

Table 2 Fixed print parameters

Numbers	Print Parameters	Values	Unit
1	Plate temperature	60	℃
2	Layer thickness	0.2	mm
3	Print speed	30	mm/s
4	Filling density	100	%
5	Current density	100	%
6	Nozzle diameter	0.4	mm

Table 3 Specification of print samples

Numbers	Temperature ℃	Unit
1	190	linear
2	200	linear
3	210	linear
4	190	concentric
5	200	concentric
6	210	concentric

Figure 3 Stretch samples after printing in line pattern

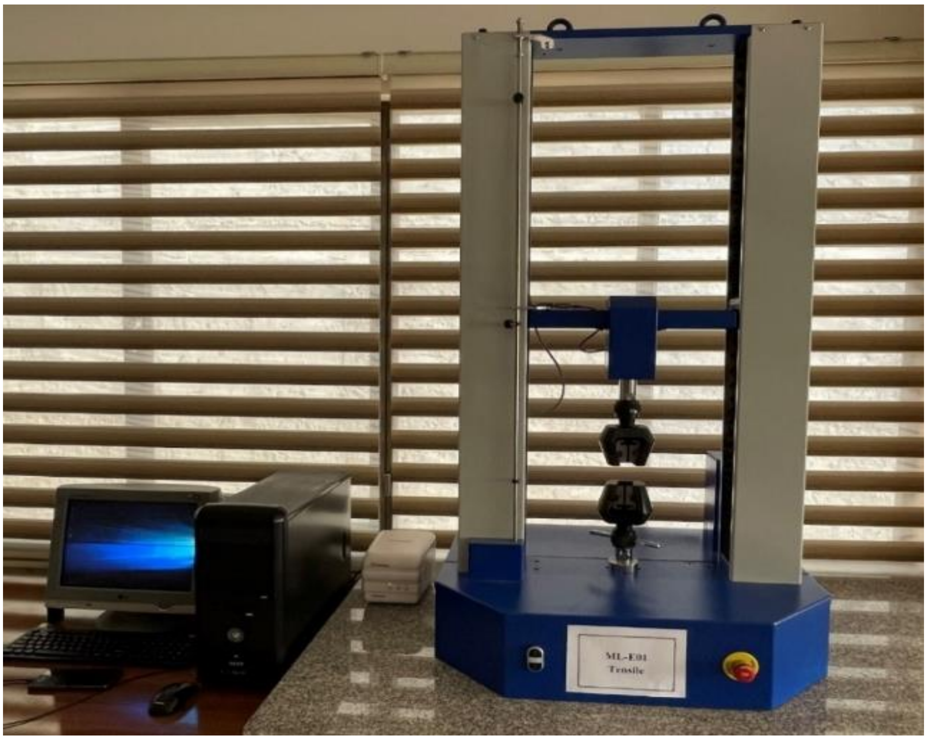

Figure 4 Tensile testing machine

The sample design is drawn according to ASTM-D638 tensile test standard in CATIA software for printing in 3D printing machine and the printer used is Creality Ender 3V3 model (made in China). In Figure (3), the printed samples are shown according to the input parameters.

Tensile strength, measured with the Universal Tensile Tester, is the ability of polymers to withstand the maximum amount of tensile stress they can withstand without failing. This point is when the material changes from elastic deformation to plastic deformation. It is one of the most important and widely used tests of polymers and plays an important role in selecting materials for the production of various polymer products. Figure (4) shows the tensile test device used in this research and Table (4) shows the specifications of the tensile test device used in this experiment.

Table 4 Specifications of tensile testing machine

Specification	Data
Model	TM-2000-S
Standard number	ASTM D638-E8
Max force	20 KN
Speed Rang	0.5-1000 mm/min
Cross head travel	1200 mm
Columns	2 rod ball-screw
Monitoring	Software on pc
Processor	Delta PLC
Column spacing	450 mm
Power supply	220 V 5A

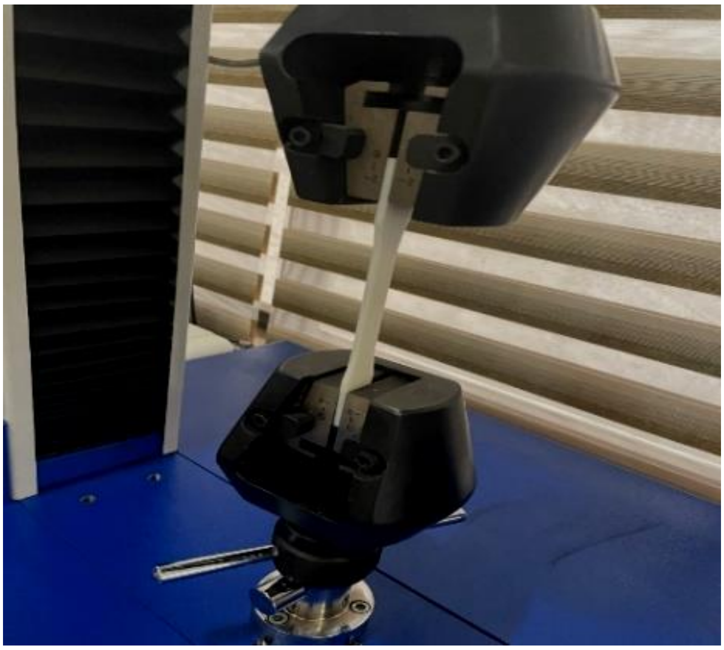

Figure 5 Sample during stretching

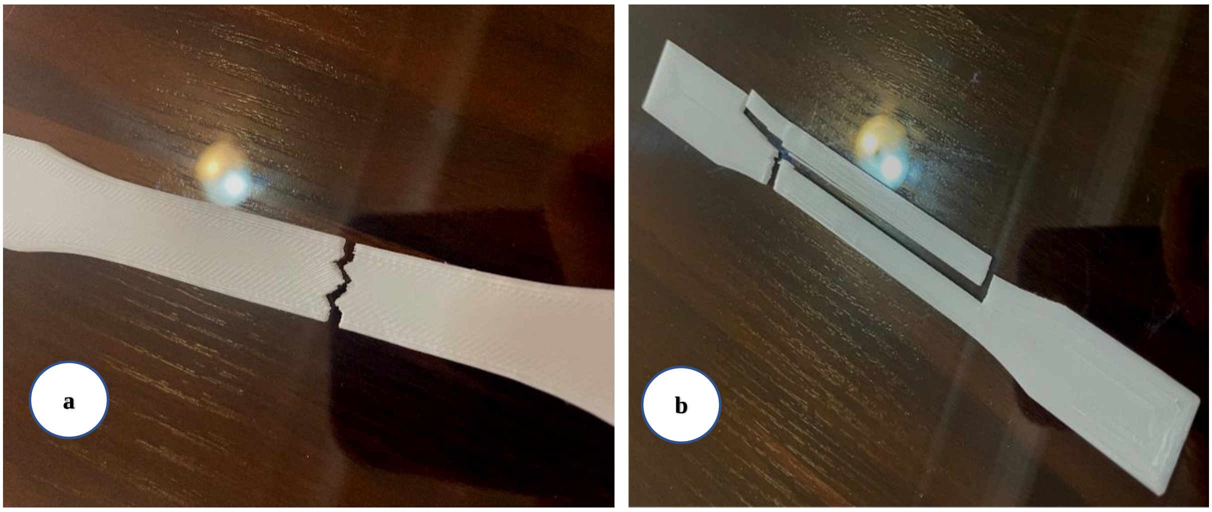

Figure 6 Tensile sample after uniaxial tensile test with (**a**) linear pattern (**b**) concentric pattern

In order to check the reproducibility of the results, the uniaxial tensile test for each group of parameters has been repeated at least three times for some samples. The tensile test was carried out at ambient temperature with a displacement rate of 1 mm/min and the test continued until the complete rupture of the samples. After the tensile test, the results were extracted as displacement force curves and finally the results were converted into strain stress. In addition, in order to qualitatively and numerically examine the results, the elastic area (slope of the linear area), ultimate tensile strength and elongation have been compared. Due to the high sensitivity of the samples, the alignment of the tensile samples with the direction of force application is one of the basic parameters that can be seen in Figure (5), Figure (6) shows the failure of the sample after the tensile test.

Furthermore, scanning electron microscope (SEM) images of the fracture surfaces were analyzed to understand the microstructural differences between the patterns. The SEM analysis indicated the presence of micro holes at the layer interfaces in all printed samples, a characteristic feature inherent to the FDM process. These micro holes, resulting from incomplete layer adhesion and air entrapment, pose a challenge to achieving optimal mechanical properties.

The SEM device used in this experiment is MIRA3 FEG-SEM, manufactured by Tescan, Czech Republic. This device has field emission films and works in two modes: high vacuum and low vacuum (suitable for non-conductive samples). The resolution of this device is up to 1 nanometer and its magnification power is up to 1 million times when applying 30kv voltage.

In order to ensure the brittle failure of the printed samples, each sample was placed in liquid nitrogen and after a few minutes, the samples failed. In the next step, in order to improve the quality of the images, the surface of the fracture samples was coated with gold.

3 Results and discussion

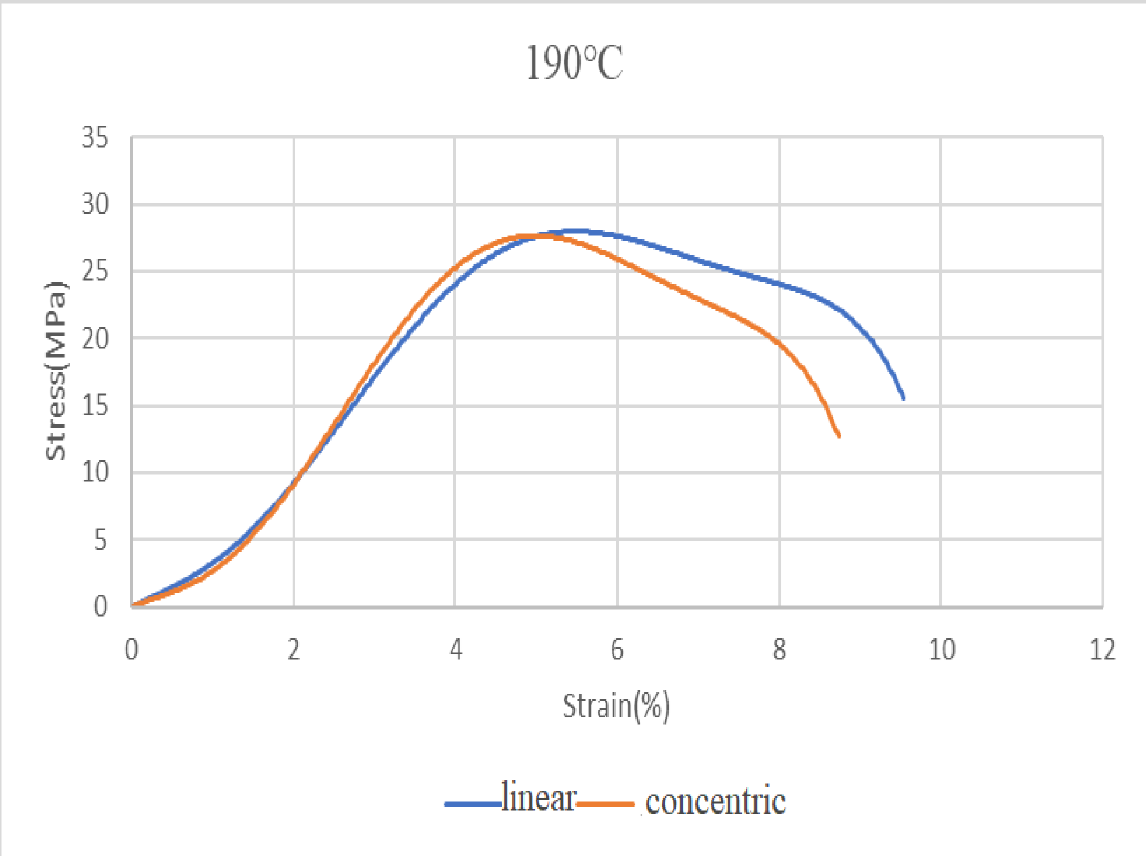

Figure 7 Strain stress diagram to check the effect of printing pattern for samples printed with linear and concentric injection pattern at 190°C

In Figure (7) up to Figure (9), strain stress diagrams are presented for samples printed with two linear and concentric printing patterns for nozzle diameter 0.4 and at three different printing temperrture. As can be seen, in all of them, the slop of linear region , which is a measure of the yield stress and elastic modulus, is higher for the samples printed with a linear pattern.

In order to investigate the mechanical properties more precisely, tensile strength and elongation were extracted from the engineering strain stress diagrams for all the printed samples and presented in the form of bar graphs. In Figure (10), As can be seen, the sample printed with a linear pattern at a temperature of 210℃ and a nozzle diameter of 0.4 mm has a final tensile strength of 32.1MPa and an increase in length of 9.6%, but the sample printed with concentric pattern at this temperature has a final tensile strength of 31.4MPa and 9.3%. In Figure (11), As can be seen, the sample printed with a linear pattern at a temperature of 200℃ and a nozzle diameter of 0.4 mm has a final tensile strength of 30.3MPa and an increase in length of 9.1%, but the sample printed with concentric pattern at this temperature has a final tensile strength of 29.8MPa and 7.2%. In Figure (12) by reducing the printing temperature to 190℃ both parameters of final tensile strength and elongation are higher for the sample printed with a linear pattern. At this temperature, PLA printed with a linear pattern has tensile strength and elongation of 28.1MPa and 7.1%, respectively but for the sample printed with a concentric pattern At this temperature pattern has tensile strength and elongation of 27.8MPa and 6.9%. According to the figure, the sample printed with the concentric pattern shows less performance and mechanical behavior than the linear pattern.

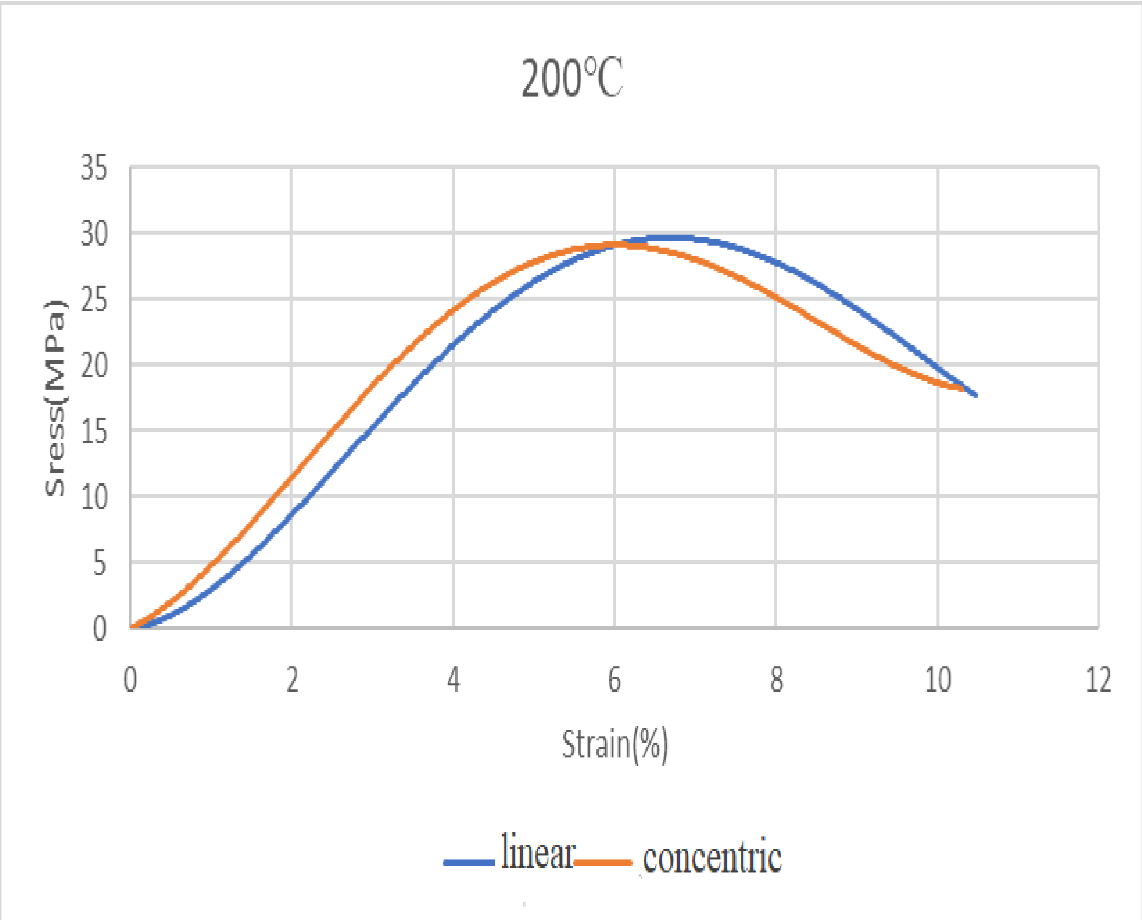

Figure 8 Strain stress diagram to check the effect of printing pattern for samples printed with linear and concentric injection pattern at 200℃

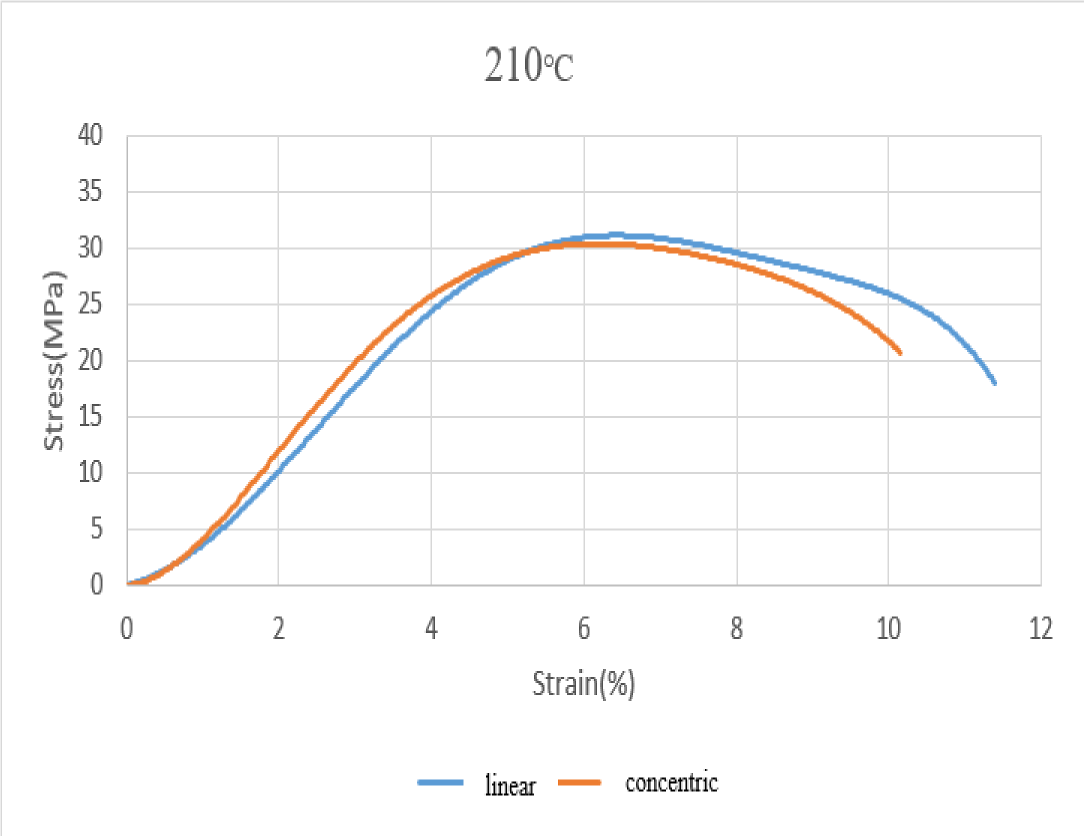

Figure 9 Strain stress diagram to check the effect of printing pattern for samples printed with linear and concentric injection pattern at 210℃

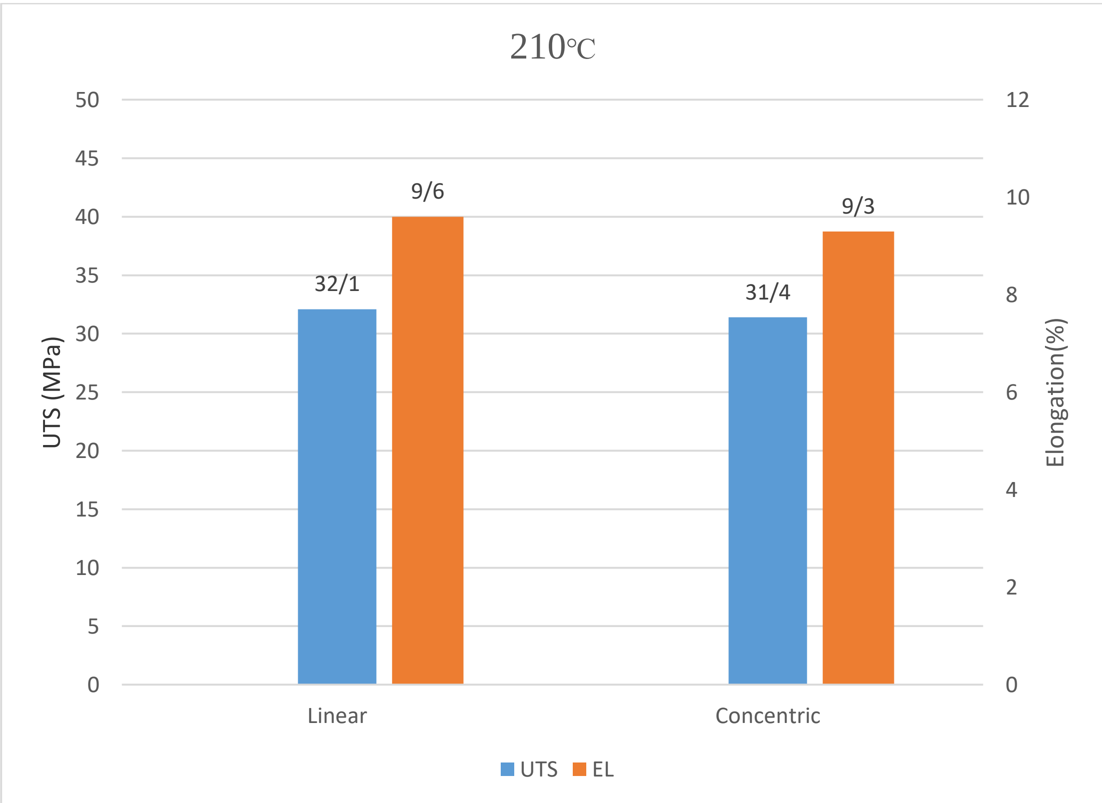

Figure 10 Tensile strength values and elongation of strain stress graphs to investigate the effect of printing pattern for printed samples at 210℃

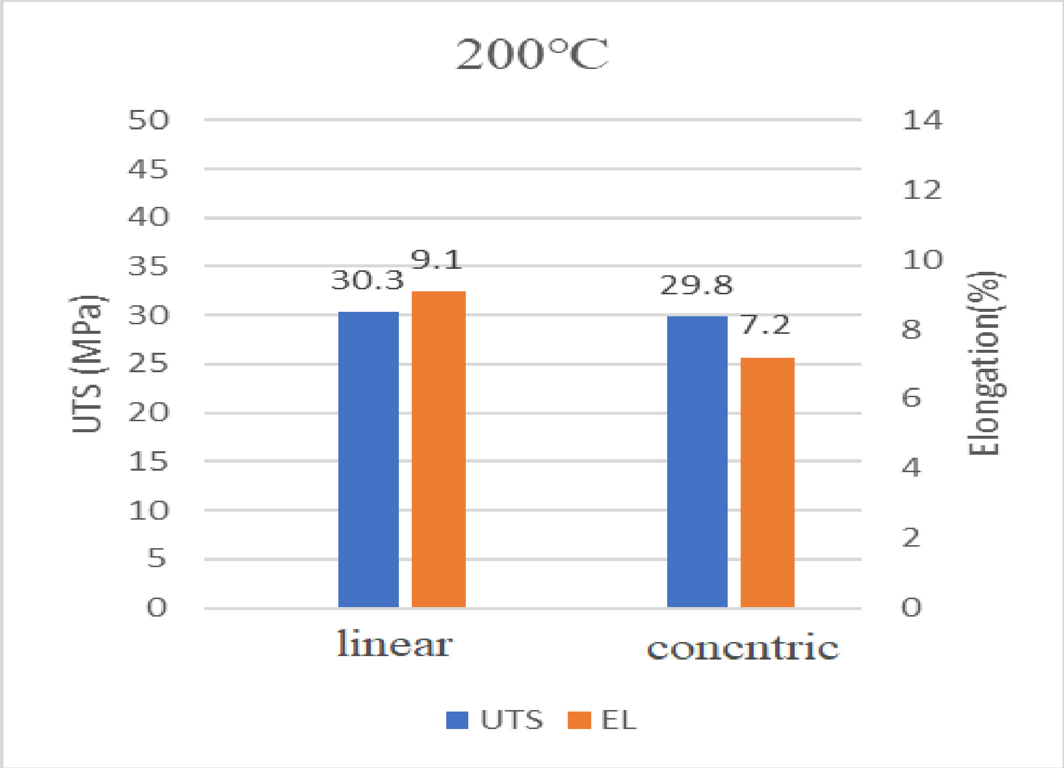

Figure 11 Tensile strength values and elongation of strain stress graphs to investigate the effect of printing pattern for printed samples at 200°C

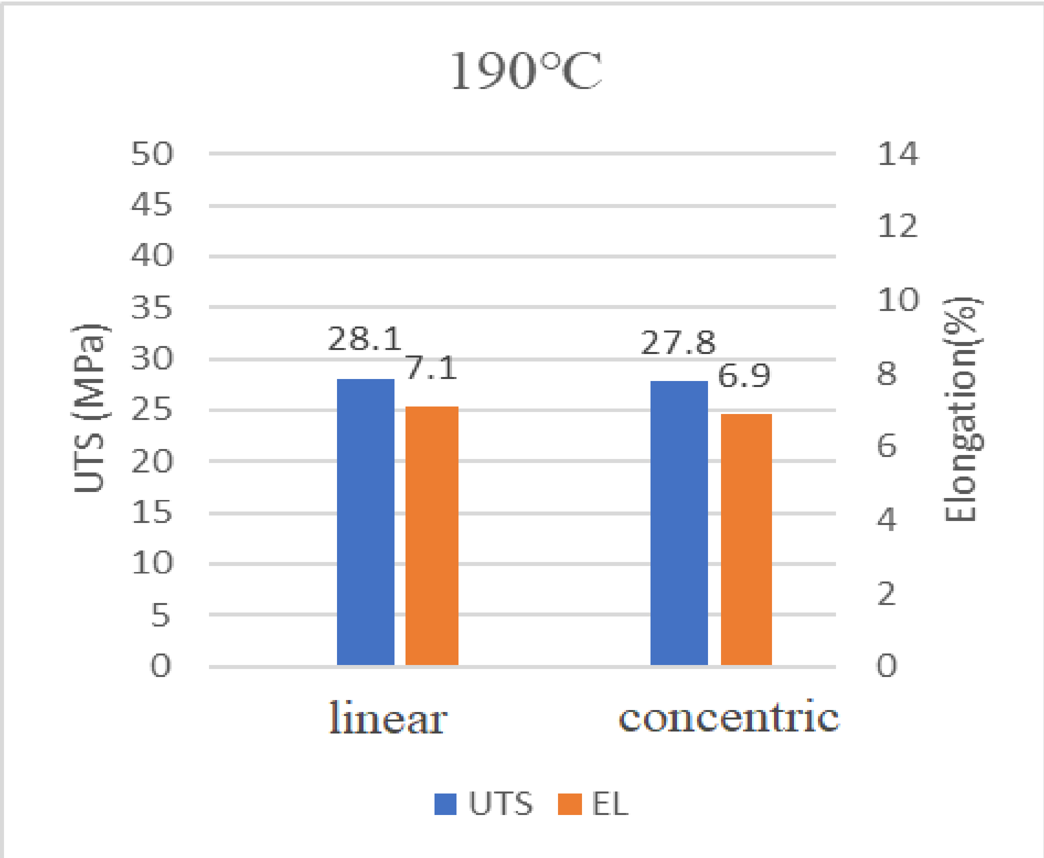

Figure 12 Tensile strength values and elongation of strain stress graphs to investigate the effect of printing pattern for printed samples at 190°C

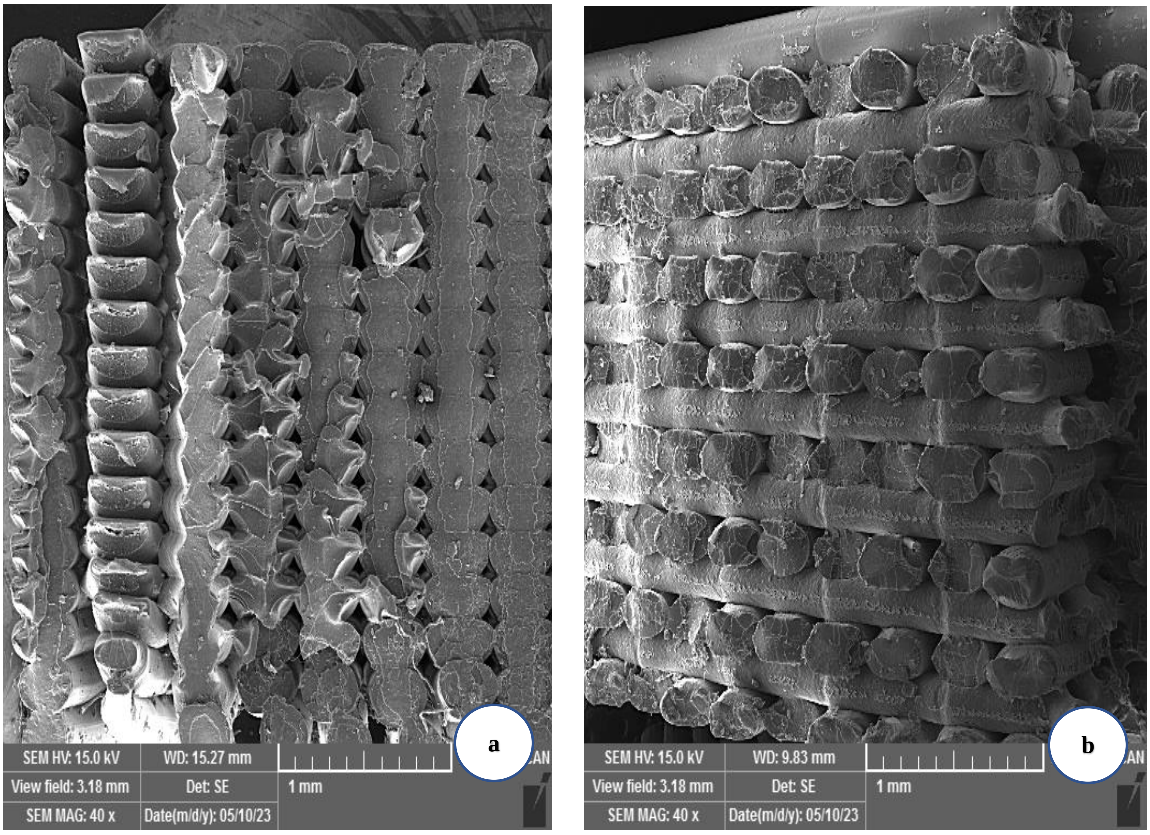

Figure 13 SEM images taken for a temperature of 190 °C in two (**a**) concentric and (**b**) linear injection patterns with 40x magnification

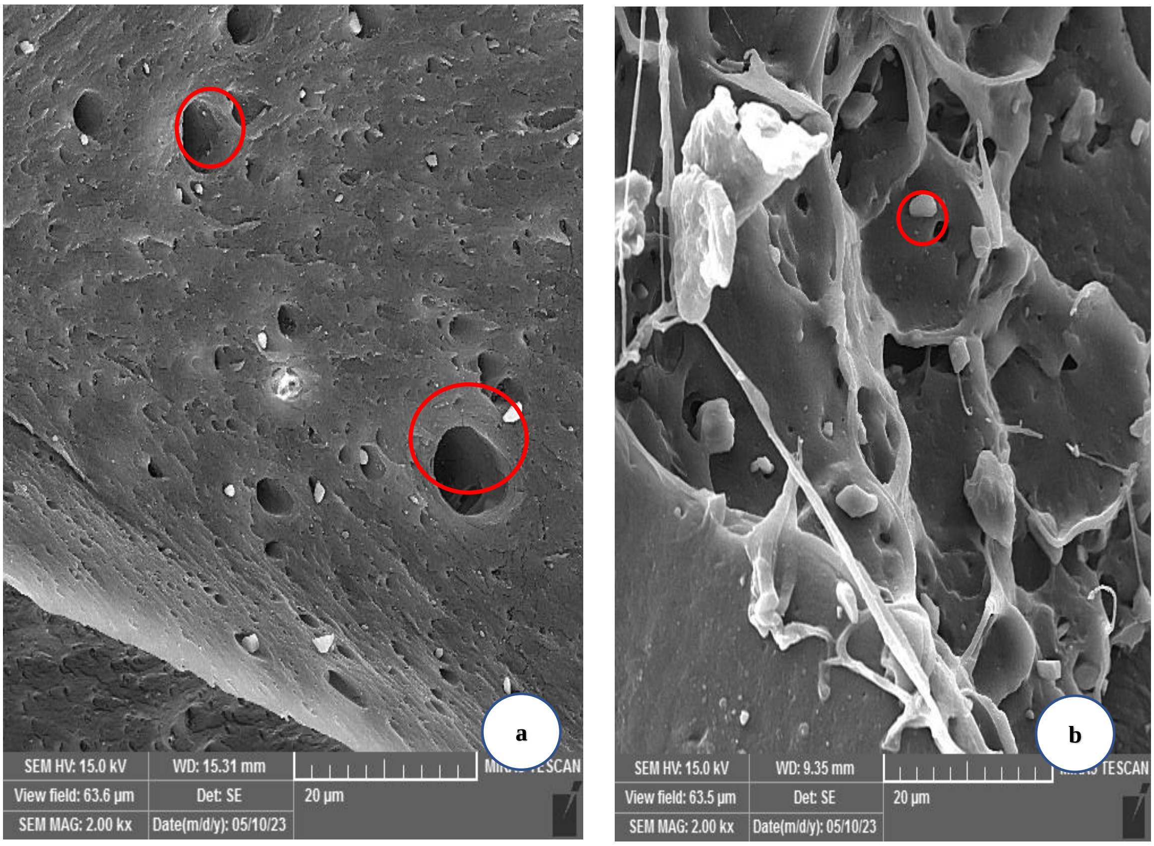

Figure 14 SEM images taken for a temperature of 190 °C in two (**a**) concentric and (**b**) linear injection patterns with 2.00kx magnification

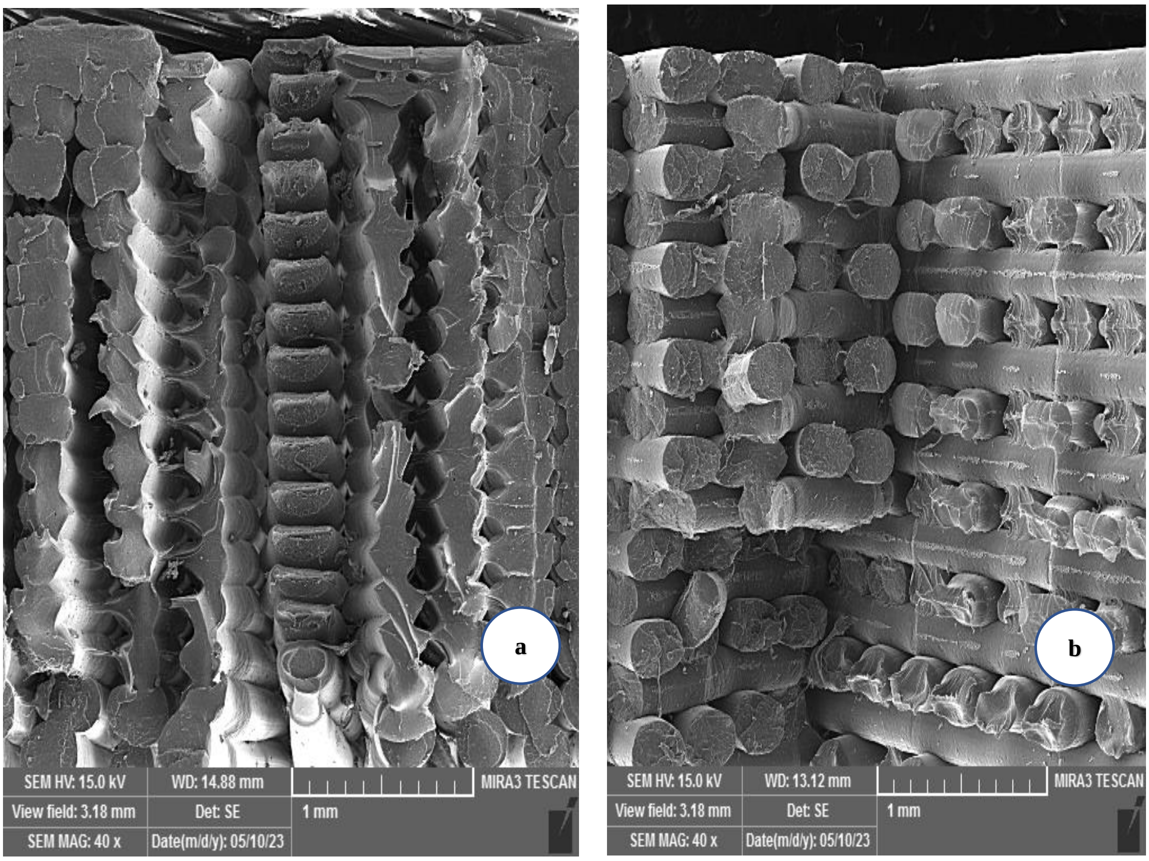

Figure 15 SEM images taken for a temperature of 200 °C in two (**a**) concentric and (**b**) linear injection patterns with 40x magnification

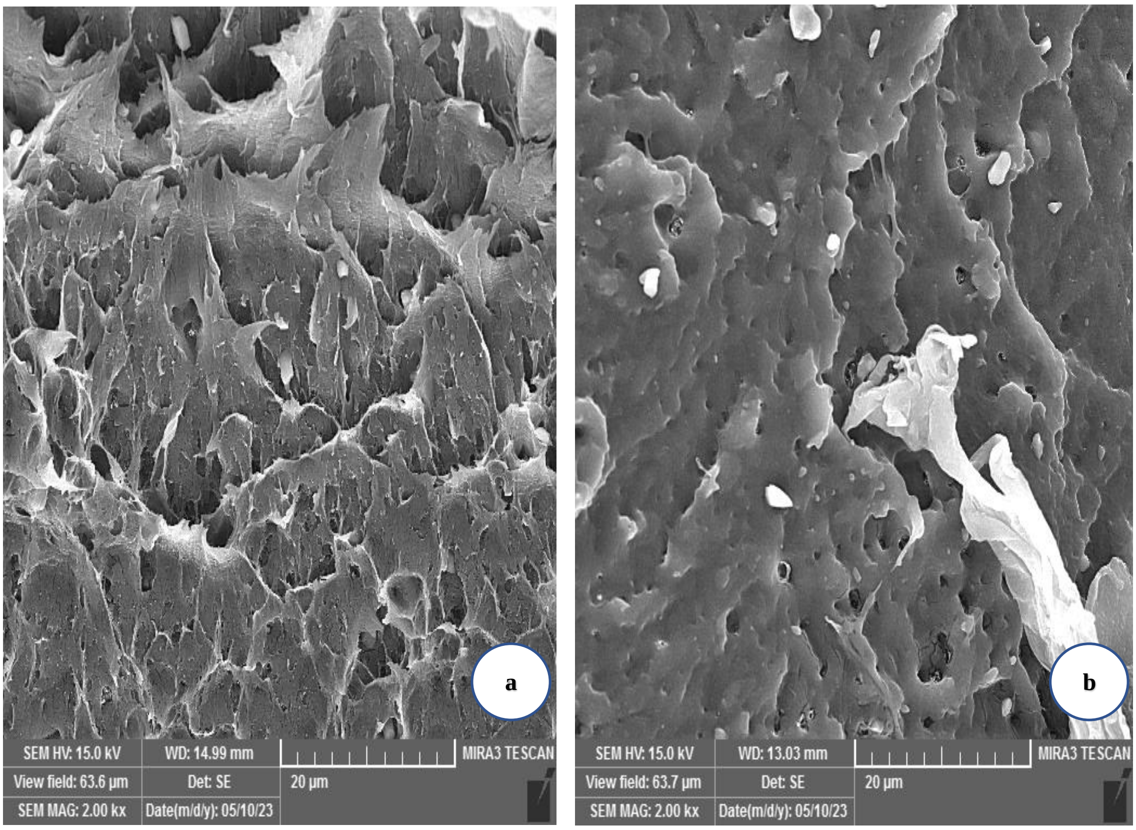

Figure 16 SEM images taken for a temperature of 200 °C in two (**a**) concentric and (**b**) linear injection patterns with 2.00kx magnification

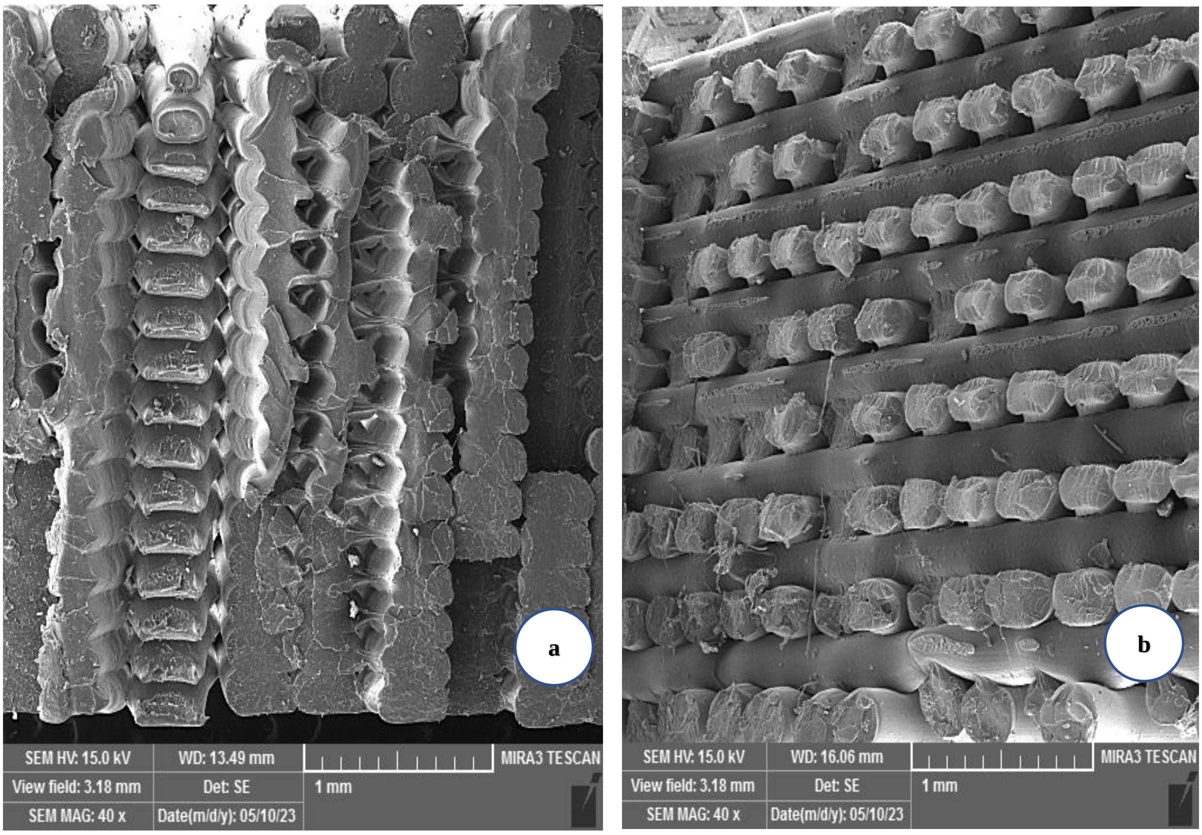

Figure 17 SEM images taken for a temperature of 210 °C in two (**a**) concentric and (**b**) linear injection patterns with 40x magnification

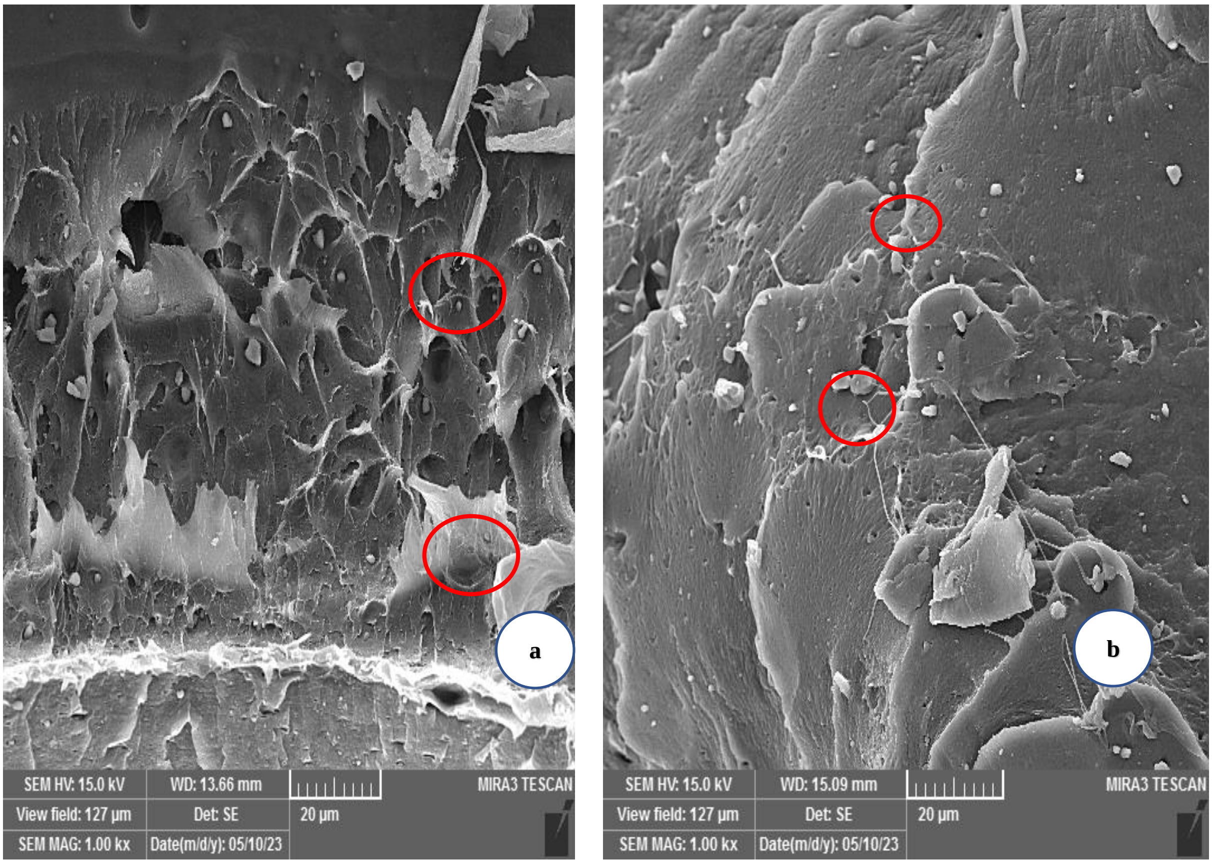

Figure 18 SEM images taken for a temperature of 210 °C in two (**a**) concentric and (**b**) linear injection patterns with 2.00kx magnification

Considering the nature of the printing process using filament melting and extruding and the layered structure of the printed parts, adhesion between layers is the most important parameter to achieve better mechanical properties. In addition, the rapid cooling of the molten layers with a small diameter causes them to shrink and create holes in the interface, which act as points prone to failure and stress concentration, and weakens the performance against external forces. They become static and dynamic. It is also worth mentioning that the arrangement and placement of the layers strongly affects the mechanical and microstructural anisotropy as one of the main and fundamental challenges in the parts printed with the FDM process.

As can be seen in the pictures of SEM in Figure (13), up to Figure (18) the linear injection pattern at different temperatures has a more regular pattern and the density of micro holes at the interface of the layer decreases, which increases the tensile strength.

4 Conclusion

In this research, the mechanical properties, microstructure and printability of PLA samples were considered by considering the basic parameter of FDM printing, the injection pattern at three temperatures of 190, 200 and 210℃ on two levels for printing PLA samples which were concentric and linear pattern. After the successful printing of the samples, the mechanical properties and printability were checked using uniaxial tensile test and scanning electron microscope, and the following results were obtained as the most prominent achievements:

1. The scanning electron microscope images of the fracture surface of the printed PLA samples showed that all the printed samples have micro holes at the interface between the layers and removing these micro holes is inevitable due to the nature of FDM 3D printing.
2. The linear injection pattern at different temperatures has a more regular pattern and the density of micro holes at the interface of the layer decreases, which increases the tensile strength.
3. The linear pattern compared to concentric pattern creates better bonding and adhesion in the background and better fluidity in the arrangement of layers and increases the relative density by reducing the air pores.
4. In addition to the injection pattern, at the same time, other mechanical factors such as the nozzle temperature also affect the tensile strength of the printed parts in such a way that at higher temperatures, the number and thickness of the holes on the surface of the layers decreases and the tensile strength improves.

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