Incremental Forming of Polymeric Sheet Printed by Fused Deposition Modeling

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Abstract: Single point incremental forming (SPIF) and fused deposition modeling 3D printing (FDM) are two methods of rapid prototyping. Each method has its own pros and cons. using SPIF method can provide an accurate forming process to shape sheets fabricated by 3D printing with their special characteristics. In this study, single-point incremental forming of Poly Lactic Acid (PLA) sheets fabricated by FDM 3D printer was investigated by experiments. The formability process was evaluated by two different experiments. In the first experiment, a lubricant was used at ambient temperature and SPIF was investigated and for the second experiment hot air and lubrication were employed to achieve better formability. In addition, the effects of sheet thickness and strategy of layering of printed sheets by FDM were also studied on SPIF formability. The results showed that the incremental forming of printed PLA sheets in hot air is a more successful state to produce dome shapes parts and ruptures are less and this forming method can be used for some applications such as making partial curve of skull as a medicine solution in surgeries. Also, it was shown that the best layering strategy to print the PLA sheets used for better forming of SPIF is triangular pattern strategy against with rectangular strategy. It was found that thickness of 2mm printed sheet has better formability and less rupture versus 3mm of thickness.

Keywords: 3D Printer, Formability, Incremental Forming, Orthopedic Appliance

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1 INTRODUCTION

1.1. Definition and Importance

The incremental forming method is a relatively new method of rapid-forming due to the process speed and less cost. The incremental forming process involves many advantages compared to the traditional production methods by molds. Incremental forming is applicable in different types such as single-point incremental forming (SPIF), two-point incremental forming with partial die (TPIFPD), two-point incremental forming with full die (TPIFFD), and two-point incremental forming (TPIF) [1]. Figure 1 shows a schematic representation of the types of incremental forming methods.

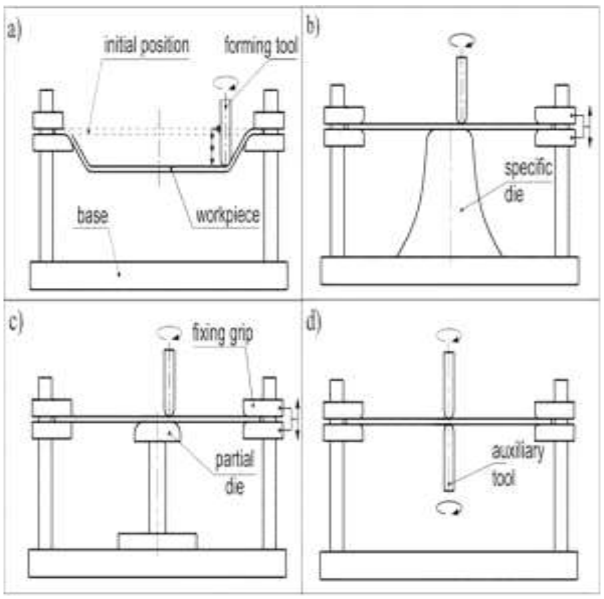

Fig. 1 Types of incremental forming: (a): Single-point incremental forming, (b): Two-point incremental forming with full die, (c): Two-point incremental forming with partial die and (d): Two-point incremental forming [1].

This is an advantage of single point technique, which expensive equipment is not required for the forming process. In this process, by utilizing a simple holder, a small tool, and a numerical control machine the desired shape in the sheet could be formed. Therefore, this process can be used to produce of the small samples, rapidly. On the other hand, utilizing this operation is also appropriate even in some complex curves. The application of this method is increasing in different industries. In addition, different types of auxiliary parts of the human body which are used in medical applications are formed by this aforementioned method. Figure 2 represents a part of a fractured human skull. By using this method, the curvature of the fractured part can be produced from titanium and implanted by skull surgery [2].

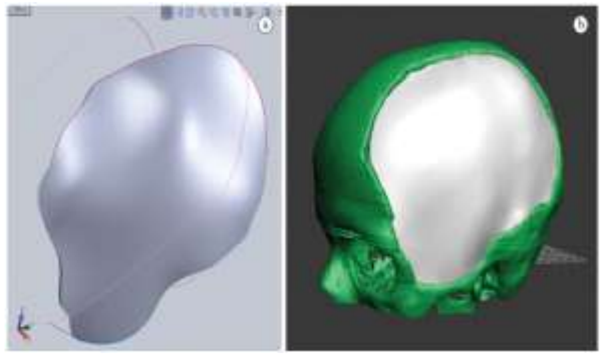

Fig. 2 Application of the incremental forming in medical products [2].

Incremental forming does not only include metallic materials. The researchers have devised this process for different types of materials including polymers.

1.2. Literature Review

Martins et al. [3] analyzed polymeric components using single-point incremental forming on five thermoplastic materials of Polyoxymethylene, Polyethylene, Polyamide, Polyvinyl chloride, and Polycarbonate with two cone wall angles of 40 and 60 degrees by a CNC milling machine at ambient temperature. Franzen et al. [4] studied the incremental forming of the polyvinyl chloride sheet at ambient temperature by the experimental method. They concluded that the production of complex components with a very high depth on the polymer sheets could be possible. Silva et al. [5] described the yield deformation process and the structural equations of the PVC sheets. They finally determined the values of the principal and the secondary strains occurred by the incremental forming process.

Le et al. [6] published the experimental results of the SPIF Polypropylene sheet. These researchers studied the analytical analysis of the forming model based on the design of experiments data. They also investigated the effect of the step size, tool size, feeding rate, and the spindle speed of a Polypropylene sheet with thickness of three millimeters. They concluded that the current knowledge of the technical process of SPIF for metal sheets could be used in thermoplastic sheets with potentially prominent advantages.

Davar Panah et al. [7] studied on forming of PVC sheets and then compared the SPIF method and the multi-point method. They examined various parameters such as shapeability, bending, and etc. Theses researchers found that the mentioned parameters influence on the multi-point incremental process at ambient temperature. By these researches, effective parameters were find out. Parameters such as temperature during forming and thickness of sheets are two important factors for incremental forming showed in previous researches. But formability of 3D printed polymer sheets are still unknown.

Because of strategy of making these sheets, there are some differences inside those sheets and also changing interlayer pattern during making sheets provide less weight sheets.

1.3. Importance of 3D Printing

The three-dimensional printing techniques such as FDM, LOM and SLA include a various range of processes and technologies for the production of the components and products with different materials. Basically, the common aspect of all these technologies is the way in which layer-by-layer production is formed in an additive process. 3D printing is a different technique based on advanced technology that adds components in layers less than one millimetre thickness. This technique is fundamentally different from any other conventional production technique. Some 3D printers use nylon powder, plastic, ceramic and metal. The most widely used and inexpensive 3D printing technology is the FDM method. The FDM machine uses polymer wires with two standard diameters of 1.75 and 3 mm that is used as filaments. The filaments are often made of a thermoplastic polymer. When these filaments heated, they become melted and could get out of the nozzle.

One of the most useful thermoplastic materials using in the 3D printer is PLA due to its mechanical, biological and biodegradable properties. PLA is one of the most appropriate biodegradable polymers. The PLA, which is a produced linear polystyrene can be completely derived from renewable sources. The PLA has been considered in the various industries such as textile and lab tools. This polymer is also used in medical science as a retainer of broken bones. After bone healing, the polymer also decomposes in water and carbon dioxide from the body and does not require surgery again. At first glance, the 3D printer has the capability to build complex components, but the FDM method has a weakness in interlayer adhesion and the strength of the layers because the adhesion between the layers is less than its strength over the length. Therefore, the importance of incremental forming is considered.

The sheet formed by the incremental forming method has a higher strength and longer lifetime, and the probability of degradation at different pressures is less than the sheet produced directly by the printer. This feature occurred because the strength depends on the layering itself, and it is not dependent on the amount of adhesion between the layers. In addition, three-dimensional printing of dome-shaped components cannot be produced without support structures. By incremental forming, the dome-shape and curved sheet can be easily made after the sheet is made by the printer. The advantage of the present method is to eliminate the need for the support structure for formed shapes.

1.4. Study Targets

In this study, the possibility of forming sheets produced by 3D printers is investigated by the incremental forming with different densities and thicknesses of 2 and 3 mm, it is the novelty that has not happened in previous studies. In addition, an innovative method to improve the formability of the process is suggested. Several interlayer patterns were examined to achieve the desired shape without any defect. The main goal of this study is finding a solution to do a successful incremental forming of a FDM printed sheet.

2 MATERIALS AND METHODS

In this research, an FDM technique was in preparation of raw materials and samples to produce dome shape parts by the incremental forming. In the FDM process, the temperature of the table was adjusted to 70° C for the stability and adhesion of PLA material dipped to the table plate. The diameter of the extruder nozzle was 0.3 mm, which is common in these types of printers. The nozzle temperature was determined to 190° C for all printed sheets.

The polymer from PLA is biodegradable and biocompatible polymer as mentioned before. The temperature of the filament, which takes the form of a paste, is 190°C. The pattern of movement inside the body of sheets produced by a 3D printer whose inner layers are poured into it that is called the "layering pattern". These patterns are divided into several general categories, among which are two methods of square path and triangular path. Figure 3 illustrates the schematic movement of these two printing paths.

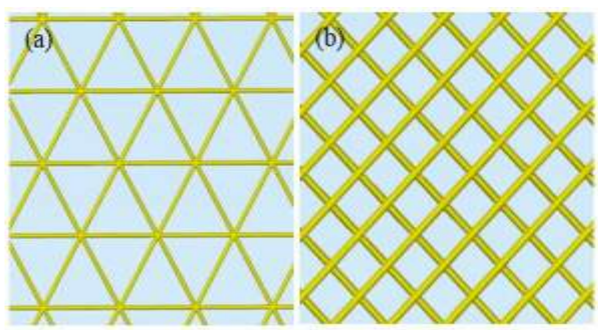

Fig. 3 Different methods of printer movement: (a): Triangular method and (b): Rectangular method.

The approximate time of making each sheet lasted 2 hours. Figure 4 shows two samples of a 2 mm sheet and a density of 80%, which is made by triangular pattern and "Fig. 5" shows tool path strategy of forming.

Fig. 4 Two specimen sheets made with a thickness of 2 mm.

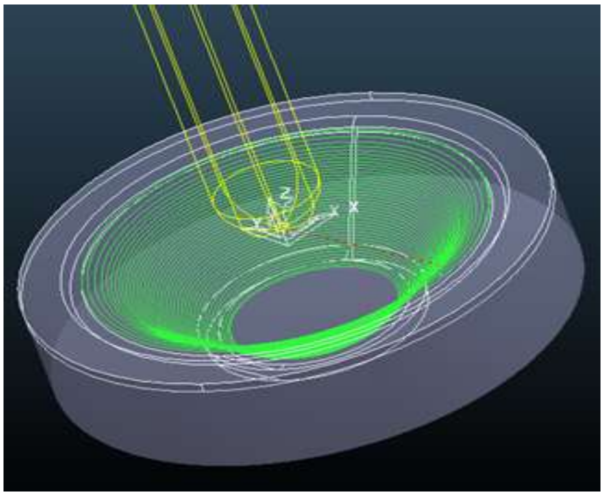

Fig. 5 Tool path strategy used for the incremental forming.

A ball-nose tool with diameter of 20 mm and 100 mm in height was used to perform the incremental forming process. Step-down was set at 0.5mm for each forming step (showed on “Fig. 5”). The speed of the spindle was set at zero to avoid local heating at deformation zones. The feed rate was set at 300 mm / min and thus the approximate time of each test was about 20 minutes. The experiments were carried in three states. In the first sample, the experiment was carried out at the ambient temperature and simple oil was used for lubrication. In the second experiment, the effect of hot air blowing by an industrial blower was investigated and the oil was used as a lubricant between the tool and sheet. In the third experiment, the effect of interlayering pattern in FDM printed sheets on the formability in SPIF was studied. The details of each experiment is introduced in the following sections.

2.1. Incremental Forming of Printed Sheets at Ambient Temperature

The sheet was printed with thickness of 3 mm and density of 80%, and a rectangular pattern. The workpiece was held in a holder and lubricated with simple oil. The operating temperature was ambient temperature and no heating element was used.

2.2. Incremental Forming of Heated Printed Sheets by Air Blowing

In this experiment, a hot air blower was used to heat up the printed sheets at a temperature of 70°C while the lubricant oil was used to examine the formability of sheets for the incremental forming process. The visual results showed a significant increase in formability. The thickness of the sheet was 3 mm, the interlayer sheet used was rectangular and 80% of density.

2.3. Study on Effect of Interlayering Pattern of Printed Sheet on Formability

In this step, two sheets of thickness of 3 mm and two sheets of thickness of 2 mm were examined. The experiments were carried out using a blower and a lubricant. The results obtained from the tests showed better efficacy and more formability of the triangular pattern than the rectangular pattern.

3 RESULTS AND DISCUSSION

3.1. Investigation on the Effect of the temperature on Formability

The effect of the temperature parameter was performed with two experiments under different temperature conditions. The first experiment was carried out at ambient temperature. The results of this test are shown in “Fig. 6”.

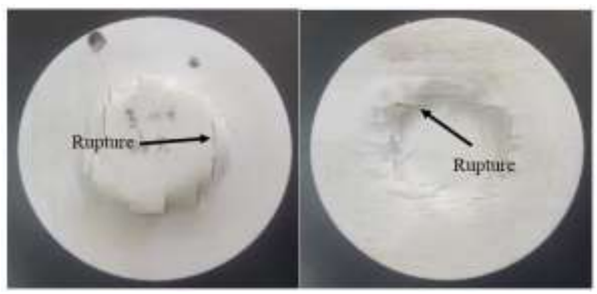

Fig. 6 Sheet formed at ambient temperature.

In the second experiment, the heat was blown by a blower with an industrial blower that shown in “Fig. 7”. The results of the experiments showed that the formability at the ambient temperature was very low, and the surface of the sheet was stringed. Figure 6 shows the strings and large raptures in the sheet. Heating the tools and sheets increased the formality. It was also observed that on the back of the several parts the split failure occurred due to the inadequate transfer of heat to the sub-layers. However, the rupture in the lower layer was very slight, which is the best result of the forming between these experiments.

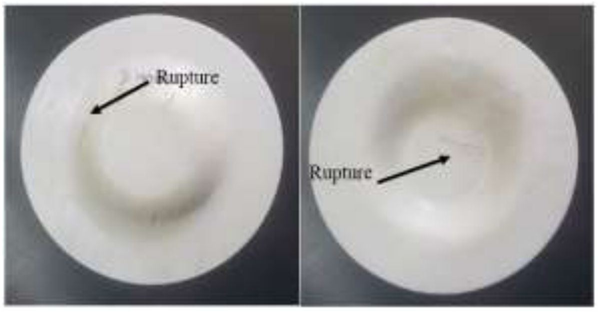

Fig. 7 The sheet formed by the blown heater.

3.2. Investigation of the Effect of Thickness of the Printed Sheet on Formability

Two samples with the thickness of 2 and 3 mm were printed with a triangular interlayer pattern. Figures 8 and 9 show the sheets with a thickness of 3 and 2 mm, respectively. The results of these tests showed that the cracks in 3 mm sample were more than the cracks occurred in the other sample.

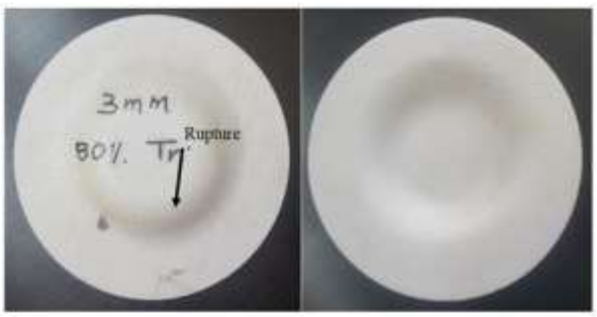

Fig. 8 Triangular layering patterns with a density of 80% and a thickness of 3 mm.

The rupture occurred in the 3 mm sample was around the circle directions. But most of the cracks occurred in the 2 mm sample were created along the length of the layering. The maximum cracks width in 3 mm sample was 1.16 mm and for 2 mm sample, the size was about 0.98 mm that occurred along the length of the gap between close layers. Experimental results showed that the 2 mm sheet formed better than the sheet with the thickness of 3 mm.

Fig. 9 Triangular pattern, density of 80%, thickness of 2 mm.

3.3. Effect of the Interlayer Pattern on Formability

To select the best interlayer pattern for sheet formality, two square, triangular patterns were examined and the results with same density (80%) were analysed. “Table 1” shows the specifications of printed sheets.

Table 1 Specifications of printed sheets with different printing and layering patterns

series	Layering pattern	Thickness	Fig No.
1	Rectangular	3 mm	10
2	Rectangular	2 mm	11
3	Triangular	3 mm	12
4	Triangular	2 mm	13

The results show approximately similar forming conditions. For both sheets the separation of the printed strands at the surface of the first layer were occurred in the upper layer. In addition, rupture phenomenon along the length of the layer were observed. The cracks in the bottom layer of the two sheets are relatively similar and have a long length with the same longitudinal pattern. The maximum tear size in the 3 mm sheet was longitudinally and was 1.88 mm with the length of 28.71 mm. In addition, the largest tear occurred in the 2 mm sheet with the width and the length of 1.85 and 13.92 mm, respectively. Figure 10 illustrates a 3 mm sheet with a rectangular pattern. Figure 11 shows a 2 mm sheet with a square pattern.

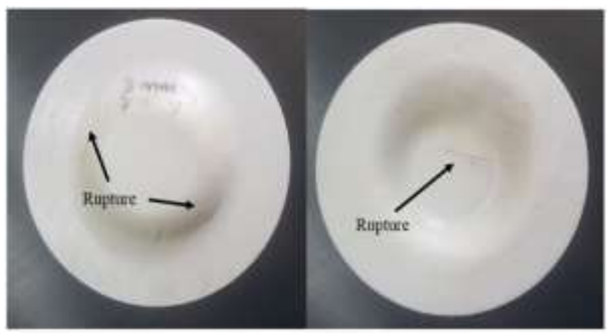

Fig. 10 Thickness 3 mm, Rectangular pattern, Density of 80%.

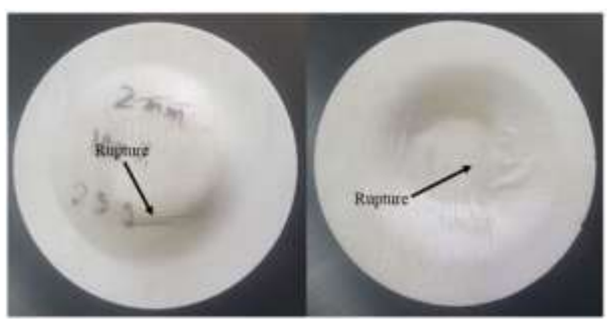

Fig. 11 Thickness of 2 mm, Rectangular pattern, Density of 100%.

Figures 12 and 13 show the sheets with 3 and 2 mm thickness, which were created by triangular internal layering. The Formed sheets show that the tearing of these sheets is less than the rectangular pattern. The vital point in these tests is the splitting of the tear into small portions that is relative to the tear size in the rectangular pattern.

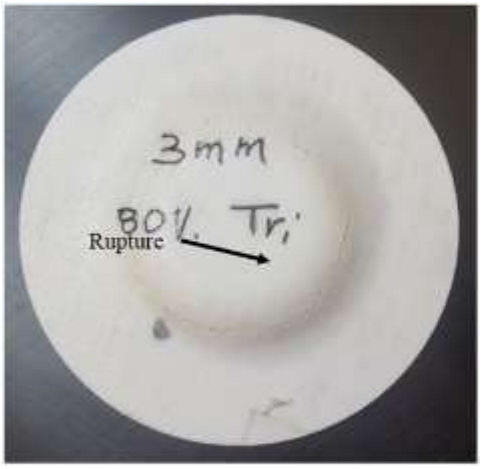

Fig. 12 Thickness 3 mm, Triangular pattern, Density 80%.

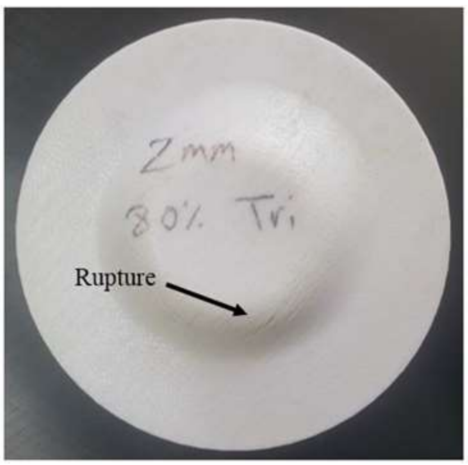

Fig. 13 Thickness 2 mm, Triangular pattern, Density 80%.

Finally, it was concluded that the best performance of the single point incremental formation was related to the blowing hot air with the density of 80% and a thickness of 2 mm using triangular pattern. There was a very small tear on the back of the sheet between the two adjacent layers, which can be ignored according to the application of the sheet. As an important result, the formability was improved efficiently.

Somlo et al. [8] studied the spinal column made of polyethylene. Due to the difference between human body shapes and sizes, the incremental forming technology could be a great method to produce the personalized part for each patient. In their study, single-point forming was done by the KUKA KR6 robot and heated to the surface of the polyethylene sheet. The results showed that this method could be suitable for the production of these kinds of parts with the acceptable quality. Figure 14 shows a spinal cord corset. The present research can improve the result of Somlo study due to utilizing an incremental forming for the production of specific polymeric medical devices using 3D printer technology.

Fig. 14 A patient with spinal disorder [8].

4 CONCLUSION

Incremental forming is a rapid way to form the various parts. This process has lots of advantages such as fast speed, lower cost, etc. 3D printer is one of the rapid prototyping methods. The low cost and producing components with complex design are the benefits of this method. Formability of the polymer sheets, due to their lower internal density during sheet printing, is one of the interesting aspects of this study. This research was conducted in two steps. In the first step, a flat sheet was produced by a 3D printer. Then it was formed by incremental forming method. Subsequently, the forming method was developed by some innovative mechanisms such as hot air blowing and changing interlayering pattern. The obtained results showed that the formability of the sheets increased by decreasing the layering density, and sheet thickness during blowing hot air using a triangular interlayer pattern.

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