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지그재그 레이어방법을 이용한 적층 HDPE 제조 및 평가

Fabrication and Evaluation of HDPE Additive Manufacturing with Zig-zag Layer Method

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This study aims to optimize the process conditions for high-density polyethylene (HDPE) additive manufacturing through a systematic analysis of key variables, including material selection, layer height, feed rate, melting temperature, and bed temperature. By exercising precise control over these variables, optimal conditions were established, which included a melting temperature of 240°C, a welding speed of 150 cm/min, and a material throughput of 5.66 kg/h. Furthermore, the process was refined by implementing a zig-zag layering method, which significantly improved the stability, bonding strength, and overall mechanical properties of the final HDPE products. The effects of these optimized process conditions were assessed through a series of mechanical tests, such as tensile tests, impact tests, and heat deflection temperature (HDT) tests. As a result, the defined process conditions yielded excellent mechanical performance, achieving a tensile strength of 21.15 MPa, an impact strength of 320 J/m, and an HDT of 93°C. Overall, this study illustrates the enhancement of HDPE additive manufacturing quality through the optimization of process conditions. The strategic implementation of these optimized variables, along with advanced extrusion module design, demonstrates the potential for producing high-quality and cost-effective HDPE products, thereby underscoring their enhanced marketability and performance potential.

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1. Introduction

Three-dimensional printing (3D printing), a representative technology of additive manufacturing, has gained recognition as an innovative manufacturing process in recent years. Its importance has significantly increased across various industrial sectors [1].

In the aerospace industry, 3D printing allows the production of lightweight, high-strength components that enhance fuel efficiency and optimize system performance. This technology maximizes the durability and performance of parts compared to traditional components, thereby significantly improving the overall efficiency of systems.

Additive manufacturing technology is also widely applied in the medical field, where it is used to develop and manufacture customized implants and artificial organs. Additionally, research is underway to develop and apply wearable sensors using 3D printing technology.

Recently, 3D printing has been applied to the production of large structures, including the construction of houses and buildings using cement or composite materials. This technology is also utilized in shipbuilding and the development of automotive parts, including electric vehicles, using metal and polymer materials [2].

The process of 3D printing typically involves the use of thermoplastic materials, which are melted and layered through a high-temperature nozzle. In this process, polymer filaments are

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extruded through a heated nozzle, moved and compressed using a screw, and then layered into the desired shape. To produce high-quality 3D printed products, it is crucial to precisely control the temperature in the melting zone and apply adequate pressure to the extruded material.

However, additive manufacturing using thermoplastics like high-density polyethylene (HDPE) presents challenges such as shrinkage, warping, and insufficient adhesion, making it difficult to achieve high-quality results. HDPE does not adhere well to other surfaces and only bonds effectively to heated HDPE, leading to reduced interlayer adhesion and potentially diminished mechanical performance of the printed product. Additionally, the shrinkage of HDPE during cooling can cause warping of the printed object, negatively impacting the overall quality [3-5].

This study proposes an extrusion module that monitors and maintains a consistent temperature and pressure in the 3D printing nozzle. Specifically, the extrusion module is equipped with a hot air heater that evenly heats the material, improving interlayer adhesion and applying appropriate pressure to the extruded material. This approach has been shown to enhance the performance of HDPE printed products.

2. Development of Process Conditions for HDPE Extrusion Module

2.1 HDPE Extrusion Module

The HDPE extrusion process involves heating HDPE wires or pellets of the same material with a diameter of ∅3 to 6 to a melting temperature of 210-220°C for extrusion. The process also utilizes hot air at temperatures above 300°C and a pressure applicator (Shoe) at the end of the extrusion nozzle to facilitate bonding between the extruded material and the substrate.

As shown in Fig. 1, the HDPE extrusion nozzle was designed based on HDPE extrusion welding methods and was developed to be mounted on a manipulator. The bonding strength between the extruded bead and the substrate determines the quality of 3D printing. Therefore, the nozzle was designed to have a shape that allows for the applied pressure on the extruded bead to enhance bonding strength. To minimize thermal deformation that occurs during the 3D printing process, the nozzle was designed to deliver heated air in all directions using a heater. HDPE is supplied in uniformly shaped pellets to ensure consistent melting, and the pellet supply section was designed considering the flow of the pellets. The extrusion capacity of the nozzle was set to discharge more than 4 kg/h to accommodate the speed requirements of the 3D printing process. Temperature and pressure sensors are attached to the extrusion nozzle to measure the HDPE melting temperature and applied pressure, enabling the monitoring and optimization of the 3D printing process.

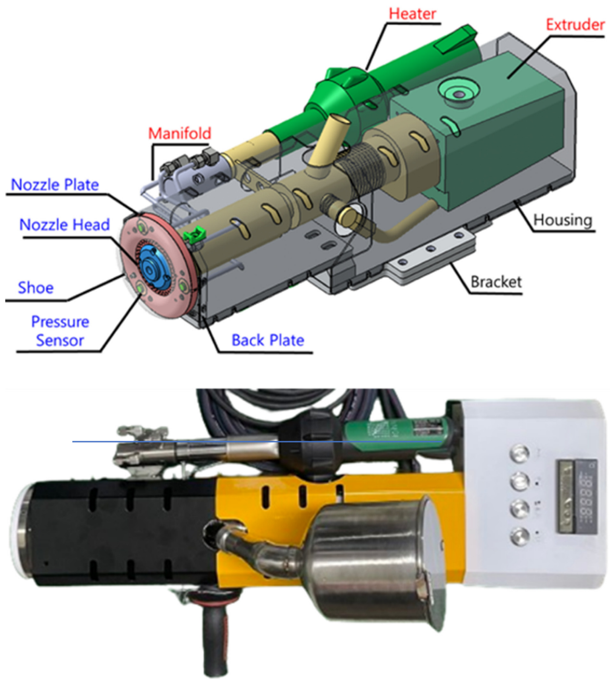

Fig. 1 3D design and picture of 3D printing extrusion module

2.2 Analysis of Process Variables for HDPE Additive Manufacturing

To develop the process conditions for the HDPE extrusion module, various process variables applicable to the additive manufacturing process using HDPE material were identified. The process variables for 3D printing are presented in Table 1. These process variables include material selection, layer height, feed rate, melting temperature, and bed temperature, each of which is closely related to the physical properties of HDPE. Since these variables directly affect the quality and mechanical properties of the product, it is crucial to select process conditions that are suitable for the HDPE additive manufacturing process [6].

Through this research, the process conditions for HDPE additive manufacturing were determined. The impact of each variable on the HDPE additive process was observed, and process optimization was performed to ensure high quality and performance of HDPE-printed products.

This will secure the stability and marketability of products manufactured using the HDPE extrusion module in the future, reduce costs incurred during production, shorten manufacturing times, and overall enhance the efficiency of HDPE additive manufacturing.

Table 1 Process variable for 3d printing

Process variable	Description
Material	Even when using the same HDPE pellets, the properties of HDPE vary by manufacturer, so it's important to select materials suitable for the HDPE additive manufacturing process, along with the appropriate melting temperature and feed rate for the selected material [8]. (Adapted from Ref. 8 on the basis of OA)
Layer height	Layer height is a factor that determines the surface quality and bonding quality of the product. It can be controlled in the additive manufacturing process by measuring the bead height and adjusting the Z-axis offset.
Feed rate	The feed rate affects production time and product quality. If the speed is too high, interlayer bonding may weaken, and if it's too low, productivity decreases. Therefore, it's essential to select a feed rate appropriate for the additive manufacturing conditions.
Melting temperature	The melting temperature determines whether the material can be melted and extruded. The optimal melting temperature varies by material; if the temperature is too low, the material does not flow properly, and if it's too high, the material becomes too fluid, causing the layers to collapse.
Bed temperature	The bed temperature ensures that the material adheres well to the bed during the additive manufacturing process. If the temperature is too low, delamination may occur between the bed and the printed product.

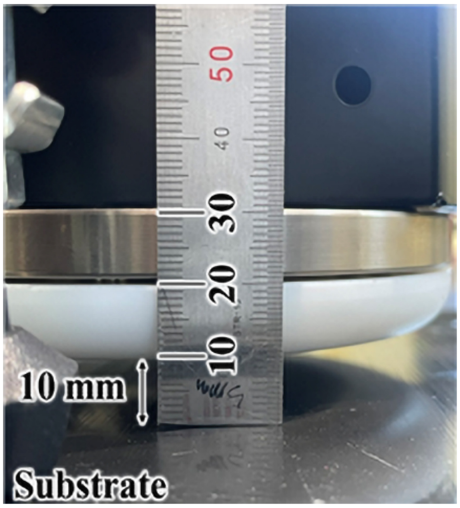

Fig. 2 Determination of layer height from substrate

Table 2 HDPE additive manufacturing process conditions

Melt temperature (°C)	240
Welding speed (cm/min)	150
Preheat (°C)	240
Material throughput (kg/h)	5.66

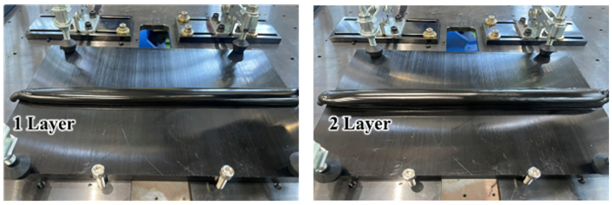

Fig. 3 Experiment of 1st and 2nd layer heights

2.3 Selection of Layer Height in HDPE Additive Manufacturing

In 3D printing, optimizing the layer height is crucial as it significantly influences the quality of the printed product, the process speed, and the consistency of the output. Consequently, it is a key variable that must be thoroughly studied to establish the process conditions for HDPE 3D printing.

Increasing the layer height allows for the creation of products with fewer layers, which can reduce production time and lower the material and costs involved in the process. However, if the layer height is set too high, it may result in decreased product density, leading to a reduction in mechanical properties.

The key factors for controlling layer height include the distance between the substrate and the nozzle, the extrusion rate, and the feed rate. In this study, the layer height was observed when the distance between the substrate and the nozzle was set to 10 mm, as shown in the setup of the substrate and the printing nozzle in Fig. 2.

Under the specified additive manufacturing conditions, the height of the first layer was measured at 10.79 mm, and the height of the second layer was measured at 20.55 mm, indicating that each layer was deposited with a thickness of approximately 10 mm as shown in Fig. 3. This confirms that the layer height can be consistently maintained under the set process conditions as shown in Table 2.

By measuring the height of the bead, an analysis of the bead was conducted for the selected process conditions, and a layer height of 10 mm was chosen to facilitate the control of HDPE 3D printing. Additionally, experiments were conducted to confirm that the layer height remained consistent at 10 mm even during multi-layer printing.

Based on the previously determined layer heights, an experiment was conducted in which a single bead was repeatedly deposited across multiple layers until the shape of each layer was fully maintained.

The experiment showed that structural stability began to fail at the seventh layer, making it difficult to form the bead during the additive process. This phenomenon occurs when a single bead is continuously deposited, leading to a decrease in cooling time between layers and an increase in heat accumulation. As the layer height increases, the HDPE remains in a plasticized state due to the heat, making it challenging to maintain the bead's shape, eventually hindering the additive process.

Therefore, based on the results of this experiment, it is determined that an appropriate cooling time is necessary for successful HDPE layering. Instead of continuously layering a single bead, a surface layering method is likely more suitable. Surface layering allows the bead to naturally cool as it forms the surface, effectively maintaining the bead's shape.

3. Design of HDPE Additive Manufacturing Process

In the previous 7-layer deposition experiment, it was observed that when a single bead was continuously layered as shown in Fig. 4, the layers collapsed, making it difficult to maintain a stable deposition process. To achieve more effective layering, the HDPE additive manufacturing process was redesigned using the zig-zag method [10].

The zig-zag layering method is an effective approach for covering large areas by alternating the layering direction in both horizontal and vertical axes, gradually increasing the height of the layers. This zig-zag method consists of Contour and Pocket layers as shown in Fig. 5. The Contour serves as a guide to prevent the molten resin within the Pocket from flowing outward, thereby enhancing stability during the layering process and allowing for the construction of taller structures with ease. Additionally, the zig-zag layering path ensures the density of the printed product, making it a suitable design path for the additive manufacturing of large-scale structures.

Overlap refers to the intersection between the first bead and the second bead. By controlling the overlap, the bonding strength between beads can be enhanced. Since the beads are circular, if the overlap distance is too large, gaps may form between beads, potentially compromising the mechanical properties of the printed product. Conversely, if the overlap distance is too small, the process time may increase, and excessive overlapping of beads may lead to warping, thereby reducing dimensional accuracy. Therefore, maintaining a consistent overlap distance is crucial. In this study, a 7 mm overlap distance was utilized, as illustrated in Fig. 6. The manufacturing of larger components inherently introduces greater complexity in terms of system configuration, automation, and control mechanisms. To address these challenges, various innovative machine concepts have been developed, including systems incorporating robotic arms. A robotic arm system exemplifies a solution that integrates flexible and cost-effective industrial robots.

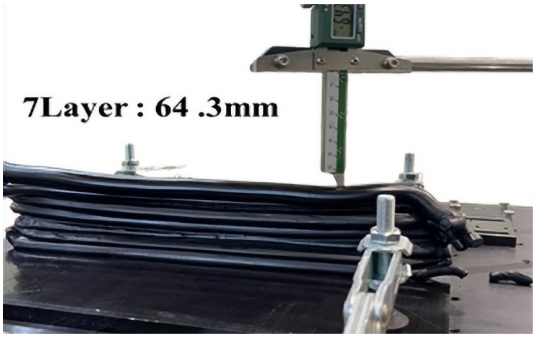

Fig. 4 7-Layer single bead deposition

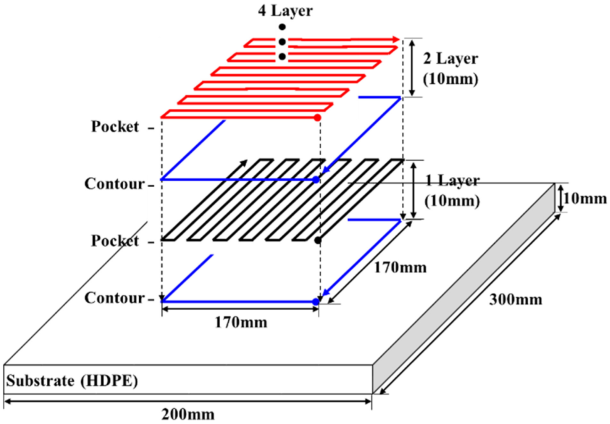

Fig. 5 Schematic diagram of layering path generation

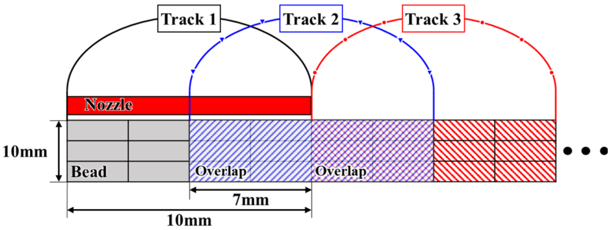

Fig. 6 Schematic diagram of bead formation in layering

The authors conducted an evaluation of this manufacturing technology, focusing on the system architecture and motion planning to optimize performance and ensure precision [11].

4. Experimental and Discussion

4.1 Single Layer Additive Manufacturing Process Test

In the single layer additive manufacturing process, an issue of over-deposition of the bead was observed at points where the zig-zag direction changes as shown in Fig. 7.

This over-deposition likely occurs because the extrusion nozzle remains at one point for a longer duration as the direction changes,

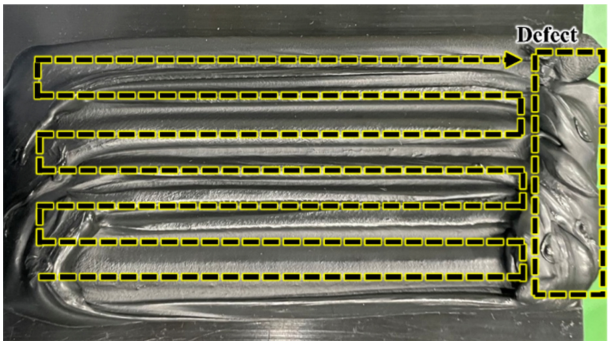

Fig. 7 Over-deposition occurs at path direction changes

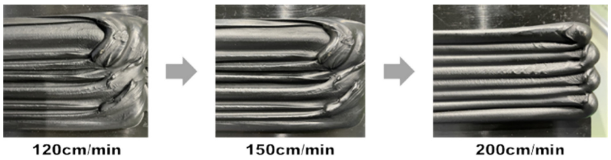

Fig. 8 Changes in extrusion shape depending on speed

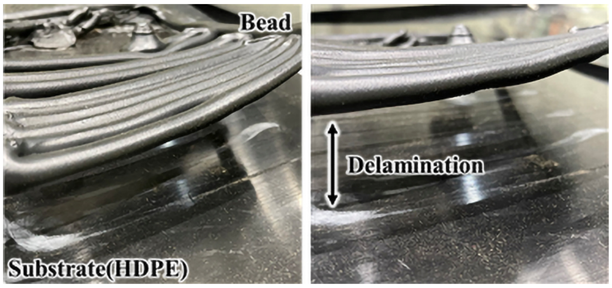

Fig. 9 Delamination occurrence depending on pre-heat temperature of the substrate

leading to an increase in material deposition at that spot. To address this problem, the feed rate at the points where direction changes should be increased, which would reduce the amount of material deposited and prevent over-deposition in those areas. It was observed that increasing the feed rate along the path where the direction changes resulted in a reduction in the amount of over-deposition as shown in Fig. 8. When the feed rate was set to 200 cm/min, no over-deposition occurred, and the layers were successfully deposited without any issues.

In the single layer additive manufacturing process, delamination was observed between the substrate and the bead as shown in Fig. 9. This delamination is likely due to insufficient melting of the substrate, which weakens the bonding strength between the substrate and the bead, leading to separation.

While increasing the preheat temperature of the substrate can enhance bonding, other methods such as reducing the feed rate, decreasing the distance between the substrate and the nozzle, or increasing the heater temperature are also possible solutions. However, reducing the feed rate or the distance between the substrate and the nozzle can affect other process conditions. To avoid these complications, it is recommended to increase the preheat temperature only during the deposition of the first layer to ensure strong bonding between the substrate and the bead, thereby preventing delamination.

Table 3 Process conditions for 3D printing

Melt temperature (^{o}C)	240	Nozzle-Base Distance (mm)	10
Welding speed (cm/min)	150	Contour welding speed (cm/min)	200
Preheat (^{o}C)	240	First layer preheat (^{o}C)	280
Material throughput (kg/h)	5.66	Overlap (mm)	7

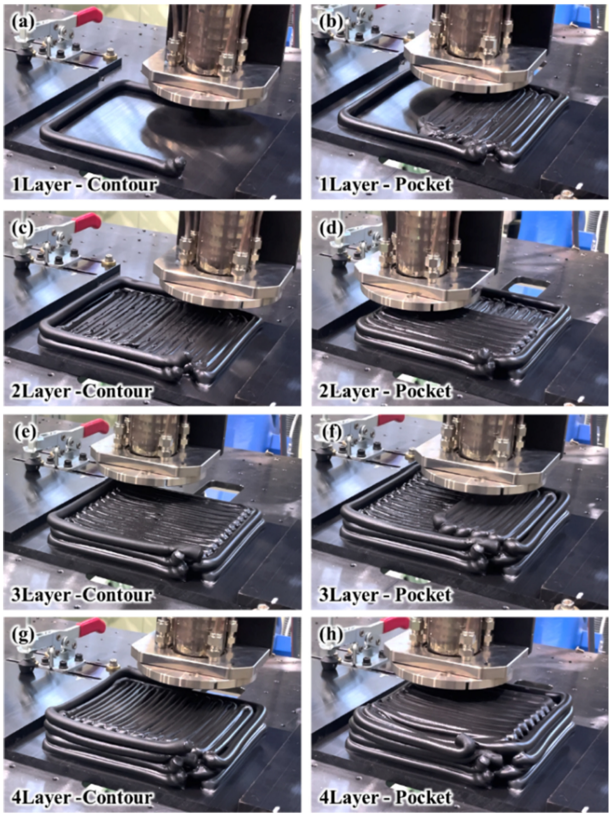

Fig. 10 Picture of the HDPE additive manufacturing process

4.2 Multi-layer Additive Manufacturing Process Test

The evaluation was conducted on the layered product created using the HDPE extrusion module under the process conditions shown in Table 3, and the HDPE additive manufacturing process is shown in Fig. 10. The dimensions of the product, including width, length, and height, were measured and compared to the designed specifications. The designed dimensions of the product were 170 × 170 × 40 mm, but the actual measured dimensions were 180 × 180 × 40.7 mm.

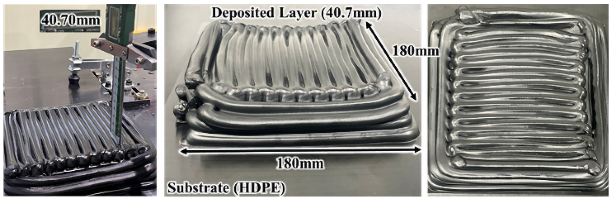

Fig. 11 Picture of HDPE specimens from additive manufacturing

Although the design specified a width and length of 170 mm, this did not account for the width of the bead. Since the layering path follows the center of the bead, an additional 5 mm on each side (half of the bead width) resulted in a total layered dimension of 180 mm.

Therefore, to achieve the intended 170 mm dimension, the design should set the width and length to 160 mm, considering the bead width. This discrepancy arises when the bead width is consistently layered, and this error indicates that the layering process was executed correctly. The layered height was based on a 4-layer structure, with a measured height of 40.7 mm as shown in Fig. 11. This indicates that the beads maintained their shape during the layering process and formed the intended surface.

Additionally, it was observed that uneven beads were formed at the initial stage of the layering process. This phenomenon can be attributed to the findings from the temperature measurement results of the extrusion process in this study. Specifically, the temperature of the molten HDPE resin was observed to rise rapidly during the first 6 seconds after extrusion began, before stabilizing. Therefore, it is believed that the temperature of the HDPE at the beginning of the layering process was not stabilized, leading to the formation of uneven beads.

4.3 Single Layer Additive Manufacturing Process Test

4.3.1 Tensile Test of HDPE

To ensure the quality of HDPE from additive manufacturing, mechanical property evaluations are essential. These evaluations typically involve tensile tests and impact tests, which are commonly utilized in the assessment of polymers. For the evaluation of HDPE from additive manufacturing, test specimens for both tensile and impact tests were extracted from the HDPE-printed surface.

To prepare these specimens, the top surface of the additive manufacturing output was flattened through a facing process, and then the specimens were cut to the required dimensions using precision machining techniques as shown in Fig. 12.

The tensile test on the additive manufacturing output was conducted in accordance with ASTM D 638 standards. The test was performed at a speed of 50 mm/min, with a distance of 65 mm between the grips. The gauge length was set to 25 mm, and a 30 N load cell was used to measure the force during the testing process.

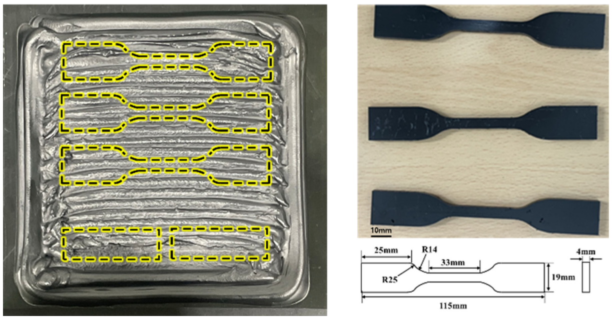

Fig. 12 Picture of HDPE specimens for tensile test

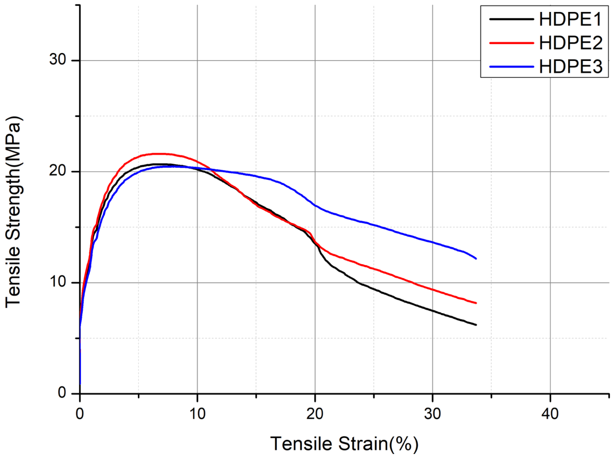

Fig. 13 Tensile test results of HDPE specimens

The results of two tensile tests were measured as follows: 20.7 in the first test, 21.6 in the second test, 20.46 MPa in the third test. The average tensile strength was calculated to be 20.92 MPa as shown in Fig. 13. The elongation at break was measured as 33.3 in the first test, 37.1% in the second test. The first and second tests were conducted on specimens in the longitudinal direction, while the third test was performed on a specimen in the transverse direction. The zigzag layer method was applied to fabricate the additive-manufactured HDPE, and it was observed that the material properties were consistent regardless of the orientation. Considering that the tensile strength of the additive-manufactured HDPE falls within the normal range, as the tensile strength of HDPE is typically above 20 MPa.

4.3.2 Impact Test of HDPE

The impact test of HDPE from additive manufacturing was conducted using the Izod impact test according to ASTM D256 standards as shown in Fig. 14. The impact test specimens were notched to induce stress concentration when an impact occurs,

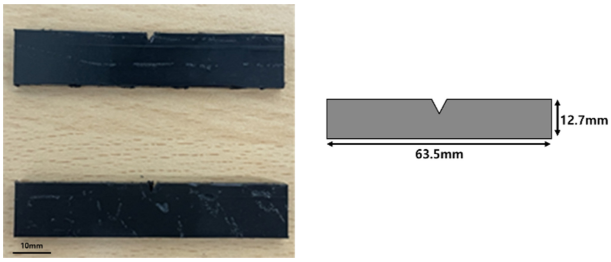

Fig. 14 Picture of HDPE specimens for impact test

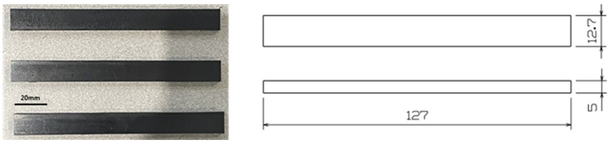

Fig. 15 Picture of HDPE specimens for HDT test

facilitating fracture and allowing the material's impact strength to be evaluated with a lower impact force. The impact test results showed a measurement of 355 J/m in the first test and 284 J/m in the second test, with an average impact strength of 320 J/m.

4.3.3 Heat Deflection Temperature (HDT) Test of HDPE

The heat deflection temperature (HDT) evaluation is used to determine how much thermal load a polymer material can withstand at a given temperature, which is particularly important for assessing the thermal performance of the material. This test measures the extent of deformation that occurs when the material is subjected to mechanical stress at a specific temperature. The test was conducted in accordance with ASTM D648 standards as shown Fig. 15.

The test results showed that thermal deformation began to occur at 93°C, which is higher than the heat deflection temperature of pure HDPE, which is 60°C. This indicates that the material's properties were enhanced through the additive manufacturing process.

The mechanical properties of the additive manufacturing outputs produced with the HDPE-specific extrusion module were evaluated through physical property tests, and it was confirmed that the performance of all specimens was improved compared to pure HDPE material. Therefore, it is believed that the additive manufacturing process proposed in this study effectively improves the properties of HDPE material.

5. Conclusions

In this study, optimal process conditions for HDPE additive manufacturing were established by analyzing critical variables such as material selection, layer height, feed rate, melting temperature, and bed temperature. As a result, the optimal process conditions were determined to include a melting temperature of 240°C, a welding speed of 150 cm/min, and a material throughput of 5.66 kg/h. Additionally, optimizing the layer height at 10 mm played a crucial role in ensuring stability and consistency during the multi-layer 3D printing process. The adoption of a zig-zag layering method further improved the process design, contributing to the stability, bonding strength, and overall mechanical properties of the final product.

These derived process conditions directly contributed to the successful mechanical performance of HDPE products. By optimizing parameters such as melting temperature and feed rate, strong interlayer adhesion was achieved, reducing defects like warping and delamination. In particular, the redesigned process with the zig-zag layering method helped maintain bead shape and structural integrity, allowing for the production of taller and more complex structures without compromising quality.

Such process optimizations played a significant role in improving tensile strength, impact strength, and heat deflection temperature, confirming that the derived process enhances the material properties of HDPE in additive manufacturing. The average tensile strength of the additively manufactured HDPE was found to be 21.15 MPa, with an average elongation at break of 35.2%. Additionally, the average impact strength measured during impact testing was 320 J/m. The heat deflection temperature (HDT) test showed that thermal deformation of HDPE began at 93°C, indicating that the mechanical and chemical properties of HDPE were improved through optimized process conditions and additive manufacturing.

The successful outcomes of this study were largely due to the precise control of process conditions and the innovative design of the extrusion module, which significantly enhanced the quality, stability, and performance of HDPE additive manufacturing products. The effective derivation and implementation of process conditions, along with strategic design improvements, are expected to play a crucial role in achieving high-quality HDPE products with excellent market potential and cost efficiency.

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