Thermal control system for inductive heating for on-orbit 3D printing

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Nov 3, 2024

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Abstract

As human space exploration continues to deepen, 3D printing technology in a vacuum environment has attracted extensive attention from several space agencies around the world. However, the vacuum environment brings many technical challenges and limitations to the 3D printing process, especially in terms of temperature control. The main objective of this paper is to replace the resistance heating nozzle of the Creality Ender 3 3D printer with a new induction heating nozzle, successfully completing the adaptation to ensure that the printer is able to operate properly in a more complex environment. The paper then compares the heating rates of the induction heating nozzles and the conventional resistance heating nozzles, particularly in a vacuum environment. Experiments were conducted to test the heating rate of the nozzles when using induction heating in a vacuum environment, the temperature profiles of the nozzles and heat sinks during the printing process, and the temperature drop profiles of the nozzles and heat sinks after printing was completed. Finally, these data were analyzed in comparison with the temperature change profiles in the ground environment to evaluate the effect of induction heating on temperature control in a vacuum environment. In addition to the temperature tests, comparisons were made between finished products printed under ground conditions and under vacuum conditions. Subsequent attempts will be made to change the printing parameters to improve the print quality and to try printing the finished product using PEEK.

Statement of Contribution

Dr Xiaofeng Wu contributed greatly to the progress of this paper, including sharing resources and providing feedback. The following are the authors' specific contributions to this paper:

- Dr Xiaofeng Wu provided the research direction for this paper.
- I completed a literature review based on the focus of this paper.
- I successfully completed the adaptation of the nozzle to the printer according to the requirements, including the fixing of the nozzle, the design of the circuit, and other requirements.
- Dr. Xiaofeng Wu helped me to learn how to use the vacuum chamber.
- I completed and analyzed the recording of temperature profiles for the nozzle heating and cooling process under ground conditions versus vacuum conditions.
- I completed the process of extruding and printing under vacuum and analyzed the results.

The above is a summary of the contributions made by the students as well as Dr Xiaofeng Wu. I guarantee that the work presented in this post is original and that all citations are appropriate.

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3/11/2024

Acknowledgements

I would like to express my sincerest gratitude to my supervisor, Wu Xiaofeng, for his valuable advice and guidance during the creation of this paper. His professional knowledge and unique analysis have been very helpful to the direction of my research. His enthusiasm for teaching and his patient guidance made me feel warm in the process of my research. He gave me the greatest help in academics, and he also gave me a lot of care in life. Once again, I would like to express my gratitude to my supervisor, Xiaofeng Wu. His passion for academics as well as his passion for life has deeply influenced me and inspired me to move forward in my future.

I would also like to express my heartfelt gratitude to the University of Sydney for providing me with the necessary lab space and resources to complete my experiments more smoothly. The University of Sydney's online library also helped me to access a large amount of literature and deepen my understanding of my research.

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1. Introduction

Since 3D printing was invented over fifty years ago, the technology has evolved rapidly and has a significant impact on the industrial and commercial sectors. Fused deposition modelling, stereolithography was one of the first successful 3D printing methods to be used. 3D printing technology can be widely used for the engineering of highly complex parts, large-scale manufacturing, and plays an important role in many fields[1], including aerospace. And as people explore space more and more, the demand for 3D printing in space is growing. While launching materials from the ground is costly and has strict volume and weight limitations, 3D printing in space allows complex parts to be manufactured on demand. And 3D printing in space can greatly reduce the cost of time. Some complex parts can take more than six months to manufacture, and on-orbit 3D printing can reduce that time to less than a month.In addition to manufacturing mechanical parts, 3D printing in space can also be used to manufacture parts for emergency repair in space, making solutions for some sudden emergencies[2].

Of course, there are some challenges to 3D printing in space. These challenges include microgravity in space, vacuum environments, extreme temperature conditions, and the effects of radiation.

Microgravity can make extrusion printing difficult. In a microgravity environment, the flow of material is impaired and can be hindered in terms of layer build-up.

Vacuum environments affect the dynamics of heat transfer that are critical to the 3D printing process. Convective heat dissipation, which is widely used on the ground, is no longer applicable in a vacuum. The lack of a suitable heat dissipation method poses a great challenge to the control of the printing temperature. Therefore, the ability to stably control the printing temperature in a vacuum is the key to the research in this paper.

Extreme temperature conditions and radiation can also affect the stability of the print, so we need to explore methods of shielding radiation.

1.1. Aim and objective

The goal of this thesis is to successfully adapt an induction heating nozzle to a printer, to test the efficiency of induction heating compared to normal resistance heating, and to measure the temperature profile of induction heating under vacuum conditions, including nozzle temperature, hot bed temperature, and heat sink temperature. A series of temperature tests were conducted to compare the heating curves under ground conditions with those under vacuum conditions, and the heat dissipation curves after the heating was stopped. And print the finished product under ground condition and the finished product under vacuum condition for mechanical property test. As well as changing the printing conditions in the vacuum such as printing speed, printing temperature and other variables to observe whether the printing results are different. The main printing material will be PLA, and after a series of tests, we will try to print PEEK.

1.2 Thesis Structure

- **Part 2:** Provides a review of literature in related fields, including existing types of 3D printing technologies such as FDM, SLA, SLS, DED, 3D printing materials used for experimentation such as PEEK, PLA, nozzle heating methods such as resistive heating, inductive heating, and heat dissipation methods such as fan cooling, hotspot cooling, radiant cooling, and thermal conductivity.
- **Part 3:** Introduces the whole experimental process, including the adaptation process of the new induction heating nozzle and the printer, the installation of the nozzle, the printing under ground conditions, and the printing under vacuum conditions. Temperature curve detection and other processes.
- **Part 4:**Summarize the results of a series of tests.
- **Part 5:**Summarize the work that needs to be done in the follow-up.

2. Literature review

2.1 3D printing technologies

2.1.1 Introduction

The concept of 3D printing first appeared in 1945, while the practice began in 1971 [20].In the 1980s, a new manufacturing method was proposed, unlike the traditional subtractive manufacturing, the new method is called additive manufacturing.The basic principle of additive manufacturing is to deposit material layer by layer according to the design file to gradually form a three-dimensional structure. This manufacturing technique overcomes the limitations of geometry in traditional manufacturing processes, making it possible to produce complex structures and shapes, and is particularly suitable for prototyping, custom manufacturing, etc. [21]. The advantages of 3D printing such as rapid prototyping, cost reduction, and flexibility [22] have led to the rapid development of 3D printing technology in recent years, which has been widely used in a variety of fields, including medical, aerospace, automotive, and architectural industries [1].3D printing has a variety of manufacturing techniques for building parts layer by layer, each of which varies in the way they are formed. Different technologies also vary in terms of manufacturing speed, cost, and durability [1]. Based on the way the 2D material layers are deposited, 3D printing can be categorized into 4 main groups, Figure 1 shows the classification of 3D technologies. The first type is photopolymerization. Photopolymerization uses a light source to cure a liquid resin and is commonly used for high-precision printing. The second type is extrusion molding. Extrusion molding builds up plastic wires layer by layer by heating and extruding them. The third type is powder molding. Powder molding uses laser fusing or sintering of powdered materials. The fourth is laminate manufacturing, which cuts and bonds materials layer by layer, making it suitable for low-cost manufacturing, but with relatively low precision. Subsequent sections will specifically describe the main current 3D printing technologies

[23].

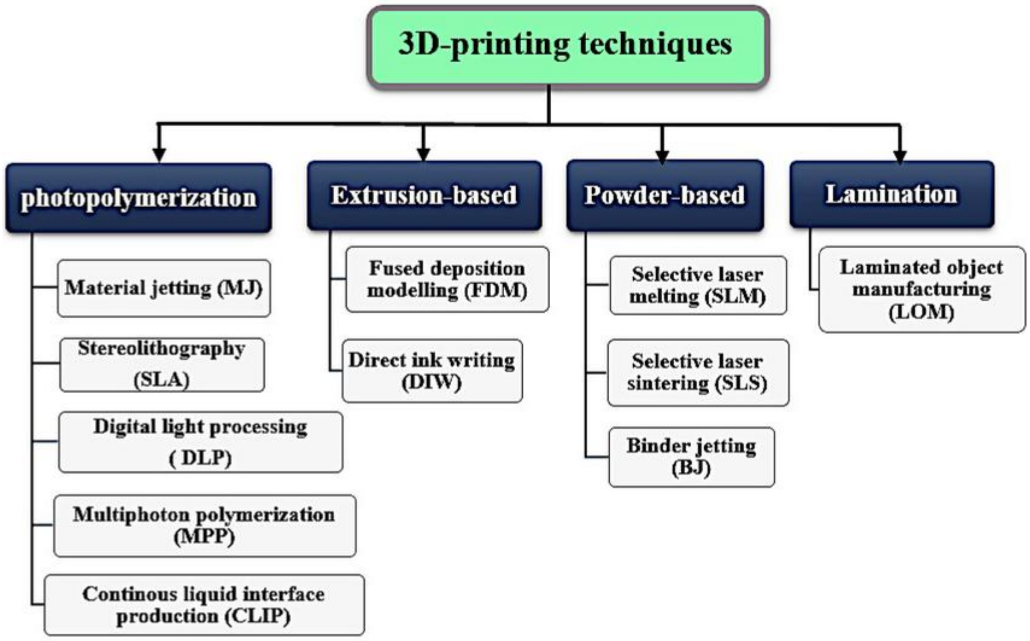

Figure. 1. Classification of 3D printing technology

2.1.2 Fused Deposition Modelling (FDM)

Invented and patented by Crump, fused deposition is the most economical additive technology available. Fused deposition technology is characterized by its simplicity in principle, but is capable of printing complex geometries. Its specific process is shown in Figure 2. The raw material is fed into the machine through a pressure roller mechanism and is melted at high temperatures in the nozzle and extruded through the extruder in the form of a fine filament. Finally the printer controls the nozzle to move on the platform in a pre-designed line so that the melted material is deposited on the floor of the printer and the 3D structure is created in a layer-by-layer fashion until the part build is complete [24].

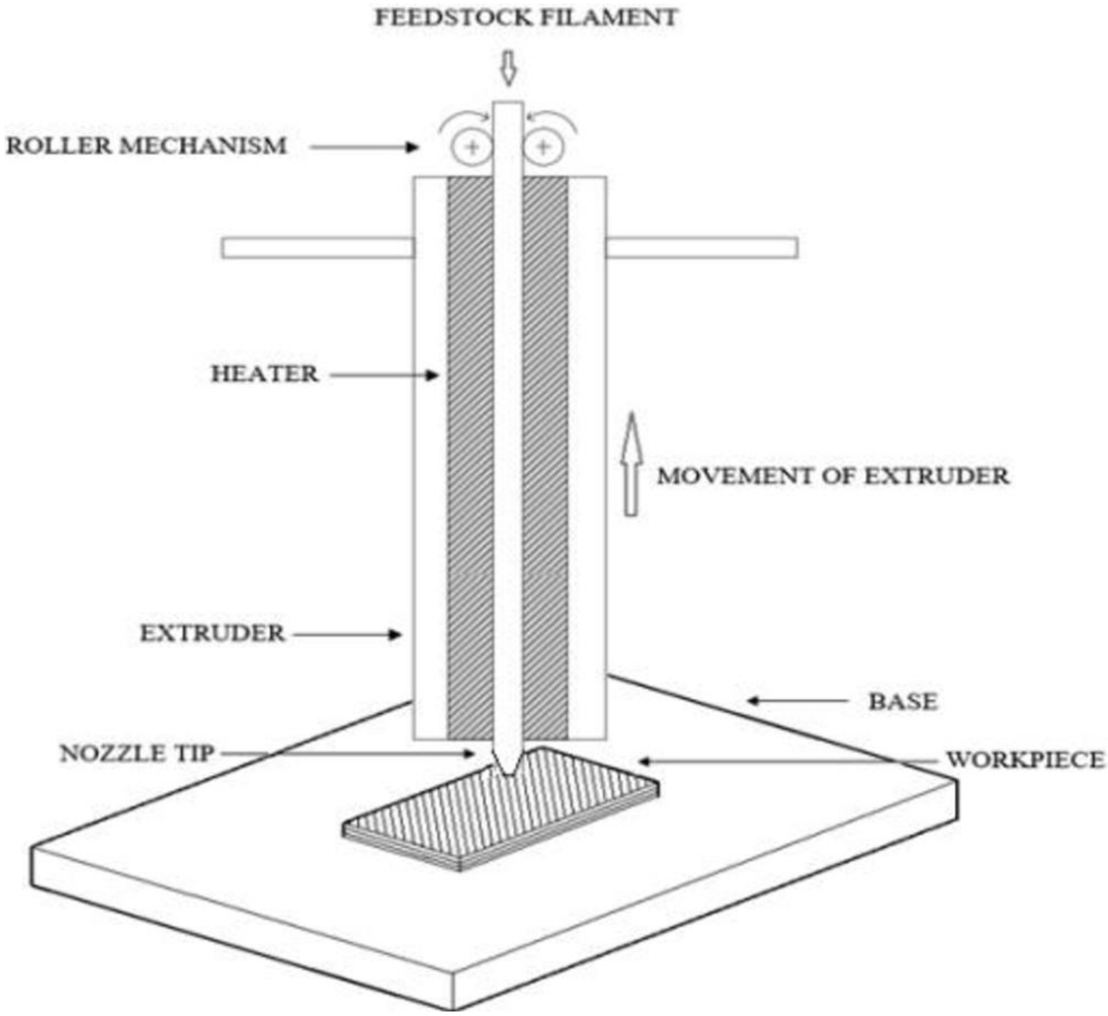

Figure. 2. Fused deposition molding process

FDM has the following advantages:1. FDM printers are low-cost and versatile, suitable for individuals or small businesses.2. Wide variety of materials, FDM mainly uses thermoplastic materials, such as PLA, ABS PETG, etc. Figure 3 summarizes the materials suitable for FDM and their applications.3. Simple to operate, FDM printers are relatively simple to operate, suitable for users who are new to 3D printing.4. Simple to maintain, the structure of FDM printers is simple, and maintenance costs are low. Users who are new to 3D printing.4. Simple maintenance, FDM printers have a simple structure and low maintenance costs. Similarly, FDM has some drawbacks: 1. Compared with other 3D printing, FDM has the lowest dimensional accuracy as well as resolution, and is not suitable for printing items with fine features.2. FDM requires support when printing complex structures, as shown in Figure 4, and removing the support may leave traces on the surface, which affects the aesthetics. Generally in order to save printing time and material, FDM parts are usually not solid, this internal use of low-density structure becomes infill. Figure 5 is a picture of different infill densities.

Material	Applications
ABS (Acrylonitrile Butadiene Styrene)	Prototyping, Automotive Parts, Electronics Casings
PLA (Polylactic Acid)	Prototyping, Medical Devices, Food Packaging
Nylon (Aliphatic Polyamides)	Gears, Bearings, Functional Prototypes
HIPS (High-Impact Polystyrene)	Prototyping, Models, Display Items
TPU (Thermoplastic Polyurethane)	Flexible Components, Phone Cases, Footwear
PEEK (Polyether Ether Ketone)	Aerospace Components, Medical Implants, Automotive
PEI (Polyetherimide)	Electrical Components, Aerospace Parts, Automotive
Carbon Fiber Reinforced Filaments	Automotive Parts, Aerospace Components, Prosthetics
Metal-Infused Filaments	Jewellery, Prototyping for Metal Parts, Decorative Items
Wood-Infused Filaments	Furniture Prototyping, Decorative Objects, Artifacts
Ceramic Filaments	Prototyping for Ceramics, Artwork, Custom Pottery

Figure. 3. Materials and applications suitable for FDM

Figure. 4. FDM support structure

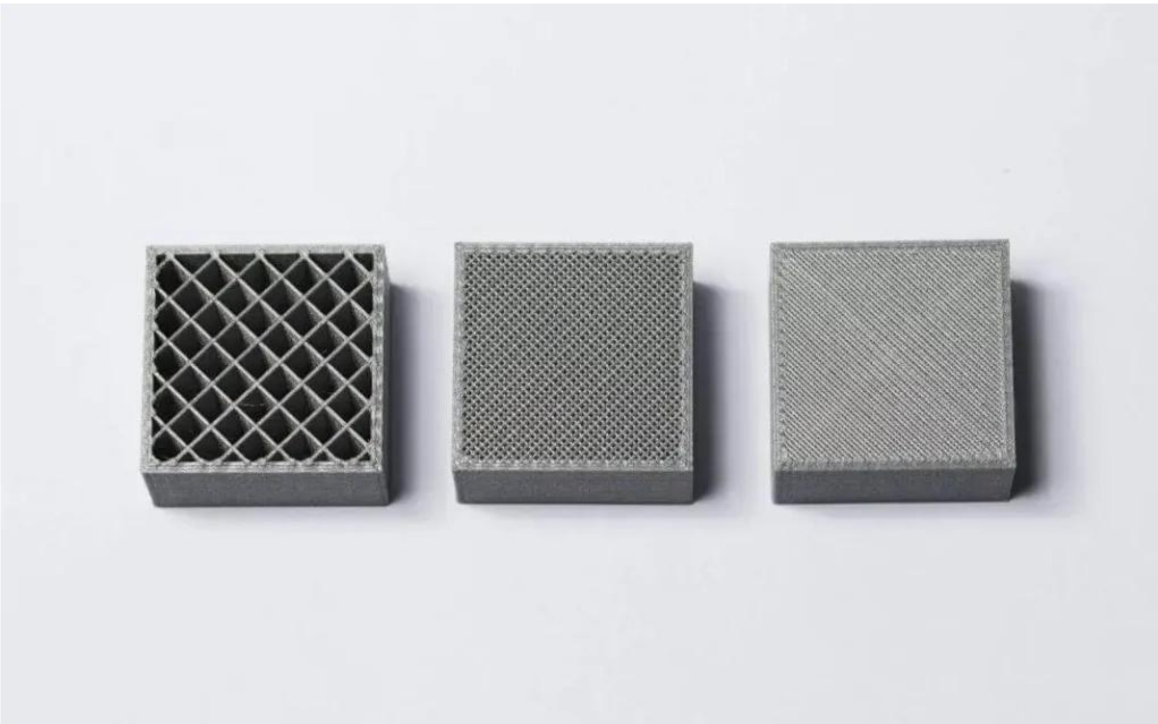

Figure. 5. Fill ratios from left to right are 20%, 50%, and 75%, respectively.

The adjustment of printing parameters has an absolute impact on the final print quality. Figure 6 summarizes the various factors and processing techniques that have an impact on the quality of the finished product, including build time, dimensional accuracy, surface finish, and other influencing factors. By optimizing these process parameters, the print quality of FDM can be effectively improved [24].

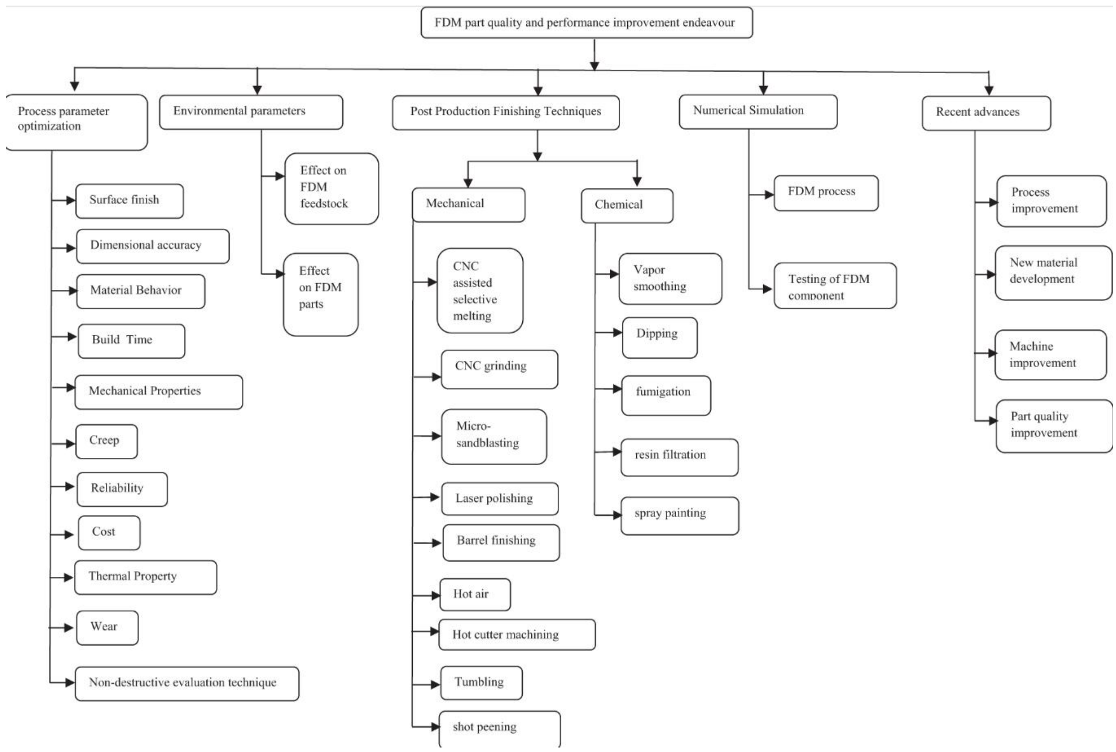

Figure. 6. FDM part quality and performance improvement endeavour

FDM technology has become the most popular type of printing due to its affordability, suitability for a wide range of materials (e.g. PLA, ABS, ASA, etc.) and ease of handling. However, there are some drawbacks, such as limited print detail, which is not suitable for demanding finished products. Moreover, it is often necessary to add some supports when designing models, which will waste some resources and time [25].

2.1.3 Stereolithography(SLA)

Stereolithography was invented in the 1970s, and as one of the earliest and most accurate 3D printing technologies [26], SLA was first patented by Charles Hull in 1986.The basis of SLA is the directional curing of liquid resins through photopolymerization reactions to build three-dimensional objects layer by layer . During the printing process, a laser guided by a galvanometer tracks the first layer in the x- and y-axis and attaches the light-cured layer to the build platform. Thereafter, the liquid resin in the container is dispensed from a new container, allowing it to cure from the bottom up until the print is complete[28]. Depending on the type of light source and curing method, stereolithography can be categorized as follows.

- **Laser Scanning Stereolithography**: Laser Scanning Stereolithography utilizes a focused laser beam to irradiate a resin surface, causing the irradiated resin to cure layer by layer, forming a three-dimensional structure. The advantage of this technique is its precision, which is very effective in the manufacture of microstructures. The process flow of laser scanning stereolithography is shown in Figure 7, the laser emitted from the UV source is focused by the lens and through a series of reflection processes, the laser is precisely irradiated to different positions on the surface of the resin to cure it into specific patterns. When a layer is completed the Z stage will descend layer by layer, thus building a 3D structure layer by layer [27].

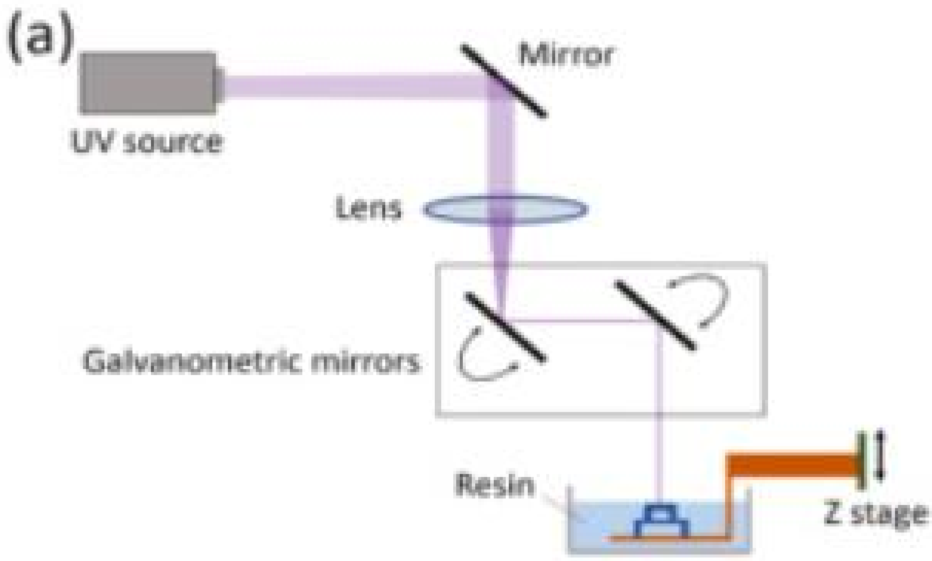

Figure. 7. Laser Scanning Stereolithography Principle of Operation

- **Projected Stereolithography**: In contrast to the process of scanning, projected stereolithography projects an image of each layer onto the surface of the resin by means of a digital processor (DLP), which enables continuous layered printing by means of a single exposure.Fudim proposed the concept of a photomask in the 1980s and developed a system whereby the resin can be cured by irradiating it with ultraviolet light through the mask and a piece of material that is transparent to radiation [29]. As shown in Figure 8, the process can be divided into the following steps: a thin layer of resin is deposited on the surface; the resin is partially cured by irradiating it using an electrostatic photomask with a uniform cross-section; the uncured resin is removed; the empty area is filled with new material; the rest of the layer is further cured; the surface is abraded to form a flat layer structure; and the above steps are repeated until the entire object construction is Completion. Projected stereolithography has the advantages of high speed and high distribution rate, but its distribution rate may be reduced when printing larger objects resulting in less fine details [27].

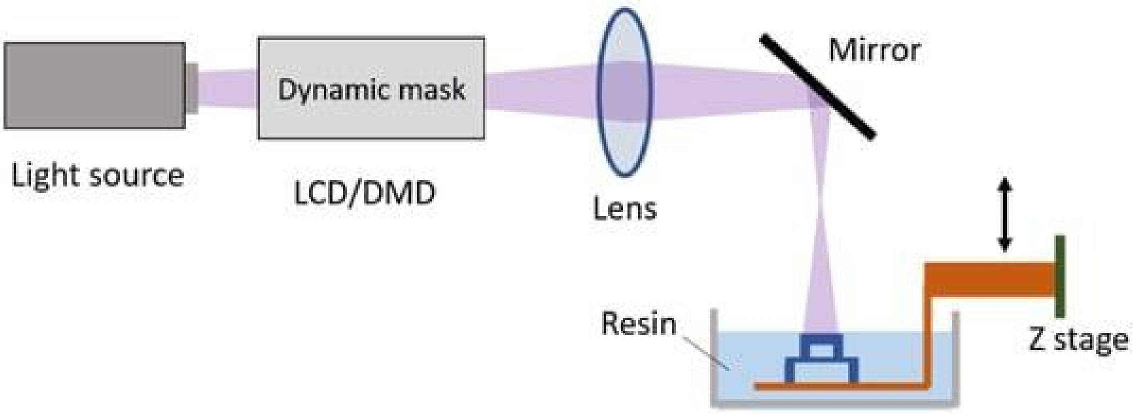

Figure. 8. Top-down projection stereolithography system.

- **Continuous stereolithography**:Although the projected stereolithography above involves each layer, it is not a continuous process, thus leading to drawbacks such as low printing speed and time consuming. To overcome these drawbacks, continuous lithography printing employs the continuous liquid interface production (CLIP) technique [30], as shown in Figure. 9. By generating a stabilized liquid layer with an oxygen-permeable window (oxygen-suppressed layer) underneath the projection plane of the UV image, layer-by-layer printing of the object without stopping can be achieved. The oxygenated dead zone is able to reduce the photopolymerization between the window and the polymerized part, allowing the printed part to be in a continuous exposure state while lifting and lowering, thus eliminating the last two steps in conventional stereolithography, and utilizing the CLIP technique, a continuous printing process can be achieved significantly increasing the printing speed [27].

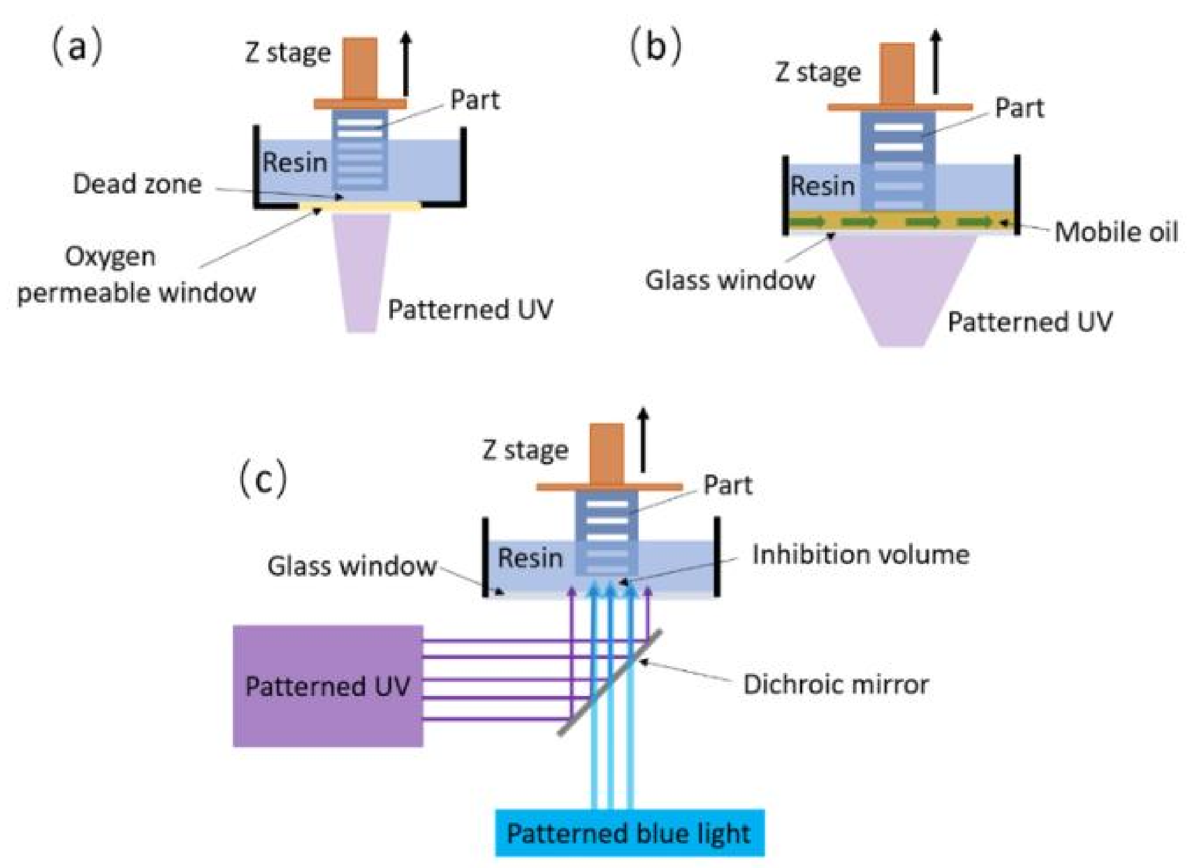

Figure. 9. Continuous Stereolithography Process

- **Volumetric stereolithography**:Unlike the stereolithography process, which fabricates structures layer by layer, volumetric stereolithography is based on the principle of simultaneous formation of three-dimensional structures within a liquid resin container by means of a multidirectional projected light source.Timothy F. Scott's team further extended the concept of dual-wavelengths by employing two perpendicular irradiation modes at blue and near-ultraviolet wavelengths, each of which can initiate or inhibit a polymerization reaction, respectively, to enable volumetric 3D printing [31]. The advantages of volumetric stereolithography include fast printing speeds, smooth surfaces without layer pattern problems, and no need for supports, as it does not require layer-by-layer construction. Since this technique requires more materials, there are fewer materials suitable for volumetric stereolithography. Moreover, because volumetric stereolithography requires precise multi-directional projection, the equipment cost is higher than other stereolithography techniques [27].

2.1.4 Selective Laser Sintering (SLS)

SLS is also one of the earliest additive manufacturing technologies, invented by Dr. Carl Deckard and Dr. Joe Beaman in the mid-1980s. Figure 10 is a schematic of the selective laser sintering process. The printing process is as follows: the powder is uniformly placed on the print table and the printer heats the powder to a temperature slightly below the melting point to make it easier for the laser to heat the powder and cure the part. After preheating the powder to the desired temperature, the laser scans a cross-section of the 3D model and heats the powder to its melting point, causing it to melt and bond into a solid part. The powder that fails to fuse can act as a support part during the printing process, which eliminates the need for a specialized support structure. The platform is then lowered layer by layer and the process is repeated until the print is complete. After printing, the build chamber needs to be initially cooled in the print enclosure to ensure that the part maintains optimal mechanical properties and to avoid warping of the part.SLS has the advantages of eliminating the need for a support structure, design freedom, material utilization, eliminating the need to print a support structure, and reusing the unused powder to reduce material waste. Similarly, due to the high temperature of the powder and the build chamber requires sufficient cooling to ensure mechanical properties, which can lead to longer print times. Moreover, dust may be generated during operation, which is a potential safety risk to the environment and human body.SLS printers and their maintenance are also more expensive and usually suitable for industrial applications, thus having some limitations [32].

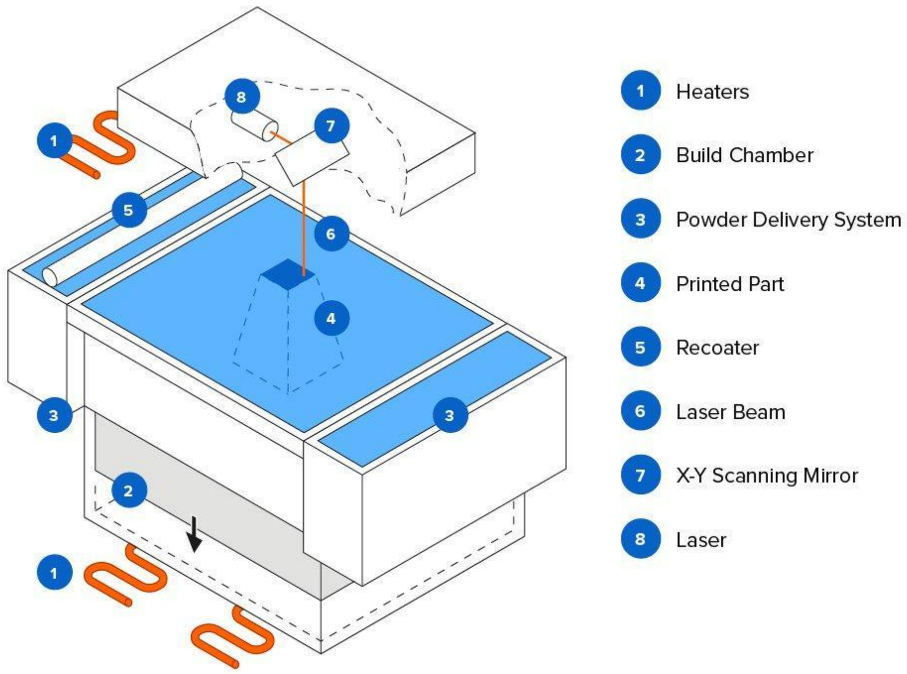

Figure. 10. Schematic diagram of selective laser sintering process

2.1.5 Directed Energy Deposition（DED）

DED is a 3D printing method that uses a focused energy source (e.g., plasma arc, laser, etc.) to melt a material, which is then extruded through a nozzle to deposit the material layer by layer on a floor [33]. A typical DED consists of a nozzle mounted on a multi-axis arm, and unlike the FDM process, the nozzle of a DED can be moved in multiple directions other than the xyz-axis direction, the material can be deposited from any direction, and the deposition is melted with a laser or electron beam. The process is commonly used for metal processing, usually in the form of powder or wire. Figure 11 shows the principle of DED machining.The steps of DED machining are as follows:1. A 4-axis or 4-axis machine with a nozzle moves around a stationary object.2. Material in the form of powder or wire is dispersed from the nozzle onto the surface of the workpiece.3. The material dispersed from the nozzle is melted by means of, for example, lasers or e-beams.4. The material is added layer by layer and solidified, creating or repairing a new structural feature on the workpiece.5. The material is then deposited into the workpiece, which is then deposited into the workpiece. The metals generally used include cobalt chromium and titanium.DED can have the advantages of high precision repair, high flexibility and high utilization, and can repair parts with complex shapes, reduce scrap generation, and can add material to existing structures to create customized shapes and features [34].

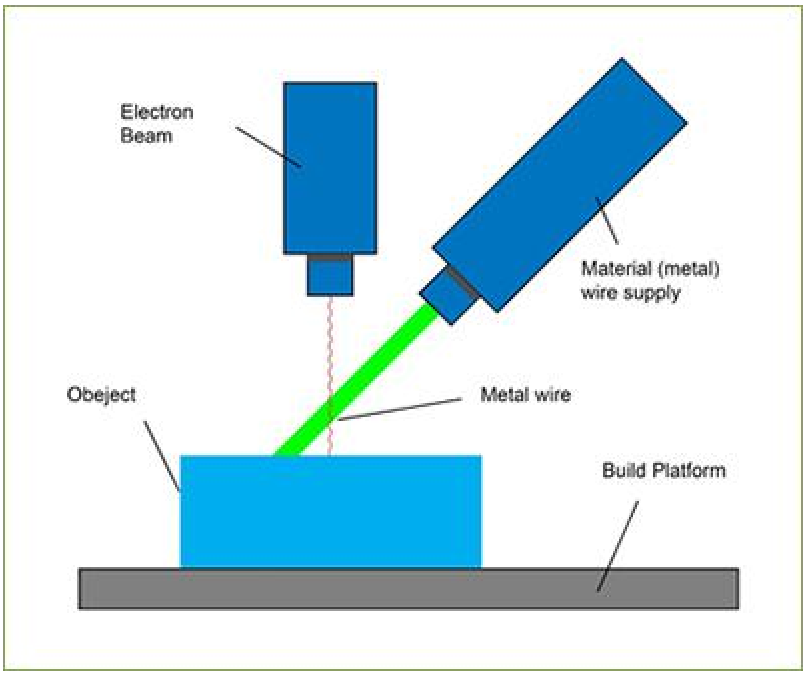

Figure. 11. Processing Schematic of Directed Energy Deposition

2.1. 3D Printing In Space

Launching equipment or spacecraft from the ground into space is limited by weight, size and other factors, which can create many obstacles for the space programme. Also, the transport time is too long, resulting in high time costs. Therefore, the use of in situ materials has become an important part of space missions[3]. And the formulability of 3D printing makes it ideal for formulating materials on demand. Figure 12 demonstrates the advantages of space-based manufacturing over existing methods.

Current Manufacturing Methods	In-Space Manufacturing
Space is isolated yet dependent on earth	Missions have a back up plan building in space
Plan for every "what if" scenario	Build what is needed on demand
"Jerry rig" a solution with parts on hand	Print needed part immediately
Many repairs have no immediate solution	Immediately repair what is broken
Must survive extreme forces of launch	Build for main use in space, not launch
Conform to fairing of launch vehicle	Build large structures that can only be built in space
Requires a large workforce	Less hands-on work needed

Figure. 12. Advantages of Space Based Manufacturing Over Current Methods

3D printing can solve three problems currently faced by the space industry: the size problem, the excessive resource waste problem, and the time delay problem[3]. 3D printing can not only improve the efficiency of space missions, but also promote the further development of human exploration of space. Therefore, the development of space 3D printing technology is an indispensable step for human deep space exploration.

2.2. Resistance Heating

The principle of contact resistance heating is to use the cutting tool and the workpiece together to form a circuit with a high electric current, which generates a large amount of heat when passing through the resistance. Contact resistance heating has the advantages of low energy consumption and high thermal efficiency. Since metal materials generally have high melting points, contact resistance heating can be chosen to heat the nozzle and melt the material[4].

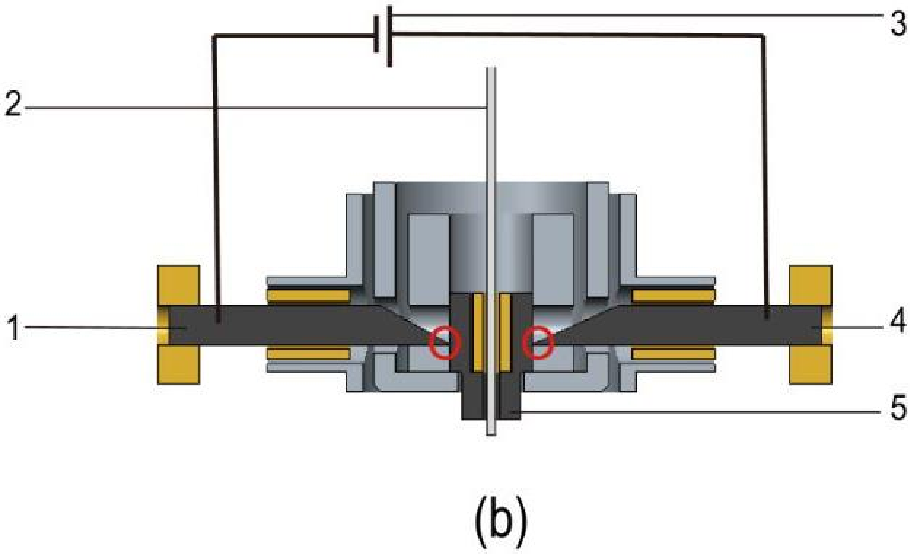

Figure. 13. (b) macroscopic schematic (1: heating cathode; 2: metal wire; 3: DC power supply; 4: heating anode; and 5: printing nozzle).

The heated cathode and heated anode are connected to the positive and negative terminals of the power supply, respectively, forming a closed circuit with the nozzle.The DC power supply provides low voltage and current. A large amount of heat is generated when the current passes through the resistor, which increases the temperature of the nozzle and melts the wire to print the desired item.

2.3. Induction Heating

Induction heating is a heating method. As shown in figure 3. By connecting an induction coil to a high-frequency current, a rapidly changing magnetic field is created around it. When a conductive material is placed in the magnetic field, the changing magnetic field will generate an electric current inside the conductive material thus producing heat[5]. Induction heating has many advantages over resistance heating. Firstly, induction heating is non-contact and the heat is generated inside the heated material, which reduces losses due to heat conduction. Secondly, induction heating allows for precise control of the heating zone and temperature, whereas in FDM 3D printing, where indirect resistance heating is mostly used, this can lead to unstable temperature control and thus affect the material's non-uniformity. Therefore, using induction heating to heat the nozzle may improve the print quality.

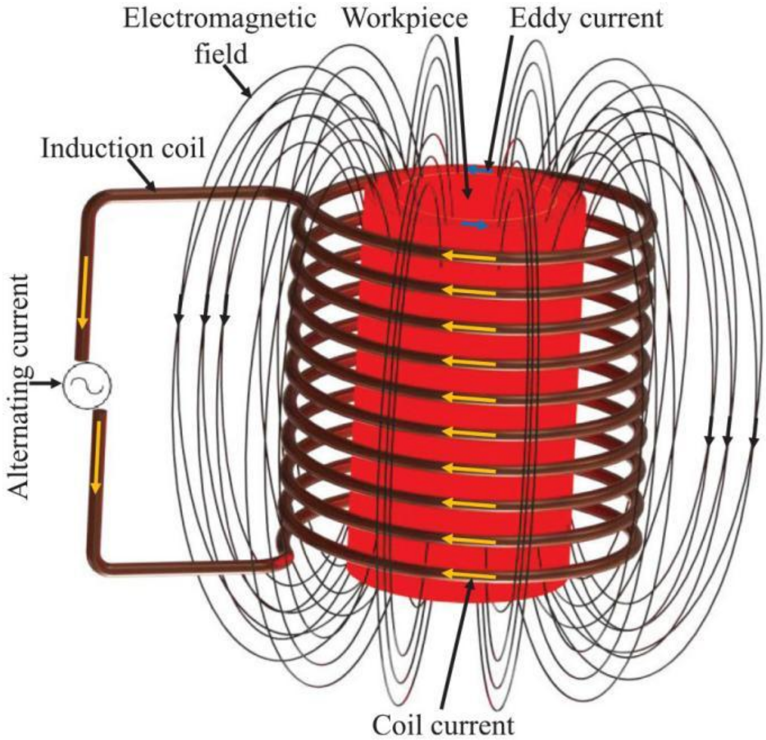

Figure. 14. Typical induction heating principle[6]

In order to heat the metal to a certain temperature using induction heating, the process structure as shown in Figure. 4 is designed in this paper. The coil is wound around the extruder. The induction heater provides a 1 KW DC power supply to give heat to the extruder. Water cooling is used to dissipate the heat and temperature is controlled using proportional integral differential. Finally aluminium was used as the printing material and an infrared pyrometer was used to measure the temperature. The final results of the experiment showed that it was possible to melt and extrude the metal using induction heating, but some problems such as filament breakage and material clogging were encountered[6]. Therefore, more precise temperature control and more accurate structural design are needed.

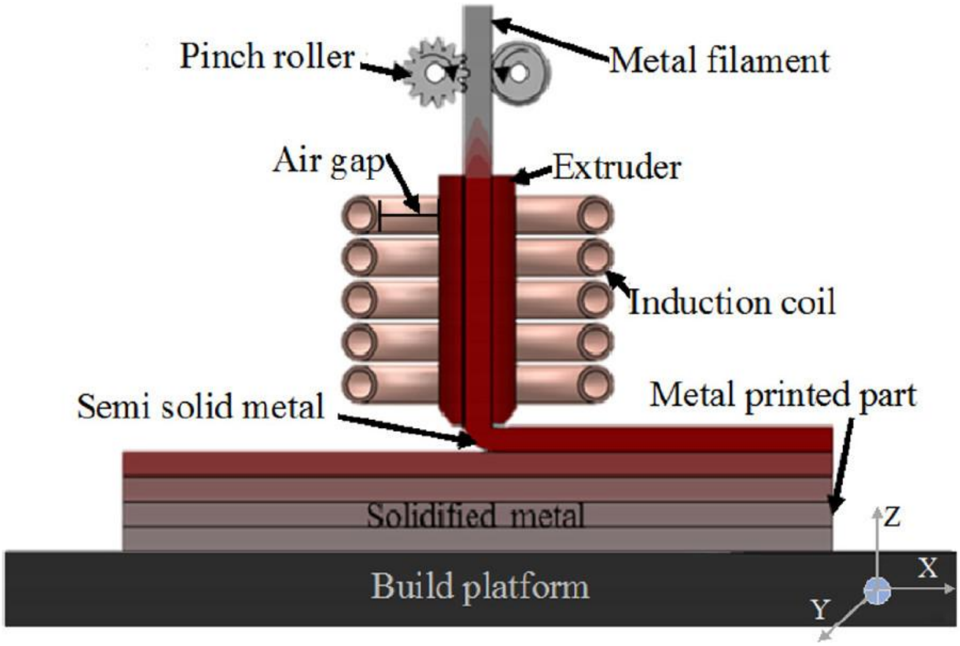

Figure. 15. Schematic of induction-based metal additive manufacturing process[6]

2.4. Proportional-Integral-Derivative (PID) algorithm

PID control achieves precise control by regulating the control output of the system[7]. The following are the formulas for the proportional algorithm, the proportional integral algorithm, and the proportional integral derivative algorithm[7].

The formula for the proportionality algorithm is：

$$\frac{mv(s)}{e(s)} = k_c \text{ or } mv(t) = mv_{ss} + k_c e(t)$$

Where the adjustable parameter to be specified is the controller gain. Proportional control is characterised by a fast response time and the size of the adjusted system output is proportional to the error.

The formula for the proportional integral algorithm is：

$$\frac{mv(s)}{e(s)} = k_c[1+\frac{1}{sT_i}]$$

PI control is characterised by providing fast response times and eliminating steady-state errors.

The formula for the proportional integral derivative algorithm is：

$$\frac{mv(s)}{e(s)} = k_c[1+ \frac{1}{sT_i} + T_d s]$$

Where TD is the rate time. PID control is suitable for more complex systems. PID control is required for high precision and for environments that require fast response times.

PID controllers, on the other hand, are used to regulate a range of process variables such as flow, pressure, speed, temperature, etc. in industrial control systems.PID controls process variables through a feedback mechanism in the control loop, which accomplishes this through three mechanisms: proportional control, which responds to current errors; integral control, which resolves accumulated past errors; and differential control, which predicts future errors. The stability of the system is maintained by adding up these three components to calculate the output. The core formula is as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}$$

where u(t) is the control output

e(t)=r(t)−y(t) is the error，

K_P is the proportional gain

K_i is the integral gain

K_d is the differential gain

The proportional P is proportional to the current error, and increasing it can increase the response speed of the system, but too large can also lead to overshooting.

Integral I can eliminate the steady state error, increasing it can increase the speed of eliminating the steady state error, but too large will cause oscillation.

Differential D can predict the trend of the error, increasing it can reduce the overshoot, but too large will amplify the noise[35].

Because precise control of the nozzle temperature is required during the induction heating process. Therefore, we can choose to use PID control to control the nozzle temperature.

2.5. Fuzzy Logic Control

The structure of a fuzzy logic control system contains three steps: fuzzification, fuzzy inference and defuzzification. Where fuzzification is the conversion of conventional or explicit data into fuzzy data. The fuzzy inference process generates fuzzy outputs by combining the affiliation functions and control rules. Defuzzification then calculates each relevant output by various methods and records the results in a lookup table. In practical applications, the corresponding outputs are extracted from the lookup table based on the current input values[8].

The advantages of fuzzy logic control are that it is suitable for dealing with non-linear and uncertain systems, it does not require an exact mathematical model, it is suitable for complex systems, and the rules are simpler to write, which saves a lot of time.

When fuzzy logic is used to control the 3D printer nozzle temperature, the following steps can be taken:

1. Define the fuzzy logic control system:

Input variables: Temperature error E (difference between set temperature and actual temperature)

Rate of change of error ΔE (rate of change of temperature error in time)

Output variable: output power adjustment (increase or decrease power according to temperature demand)

2.Fuzzification:

Convert the input variables into fuzzy sets and design the affiliation function.

Temperature error E: can be classified as high, medium or low

Rate of change of error E: can be classified as small, medium, large

Power output: can be categorised as increasing, constant, decreasing

3. Establishment of fuzzy rule base: determine the relationship between input variables and output variables.

4. Fuzzy inference: based on the current input values, using the rule base to reason

5. Defuzzification: Convert the values derived from fuzzy reasoning into precise variables.

Finally, the temperature is controlled within the desired range through continuous adjustment.

2.6. PEEK

Polyetheretherketone (PEEK) is a semi-crystalline thermoplastic with excellent mechanical properties. The following are some of the properties of PEEK materials[9]:

1. Thermal stability and high heat resistance: PEEK has a high melting point of 343° c, and can be used in a 260° c environment after 5,000 hours with the same initial state, is a high-performance plastics in one of the best heat-resistant materials.

2. Excellent mechanical properties: PEEK has high modulus of elasticity, high toughness, impact resistance and other characteristics. In addition, PEEK also has the characteristic of bending resistance.

3. Chemical resistance: PEEK can resist the erosion of most organic and inorganic chemicals, and show good resistance to acids, alkalis and many other solvents. And it can maintain its strength under different concentrations of solvents.

4. Radiation Resistance: Due to its stable chemical molecular structure, PEEK is one of the most radiation resistant thermoplastics.

Due to these excellent properties, PEEK is widely used in aerospace, petroleum, automotive, military, chemical industry and other fields[10].

2.7. Heat dissipation

Layer cooling fans

Layer cooling fans are often used in FDM3D printing for heat dissipation to control issues such as warpage or deposition quality. Typically cooling fans are small fans attached to the 3D printer head that serve to cool the extruded material to control a range of problems that may be caused by high material temperatures[11].When printing parts that have a small cross-sectional area, the underlying material may not have enough time to cool before extruding additional hot material. This leads to an increase in temperature and softening of the part. This is where cooling fans can be used to cool down the material, allowing it to cure more quickly and thus maintain the extruded geometry[12]. Figure 1 shows how the fan works. Due to the lack of air in a vacuum, this convective heat transfer may be less applicable in on-orbit 3D printing.

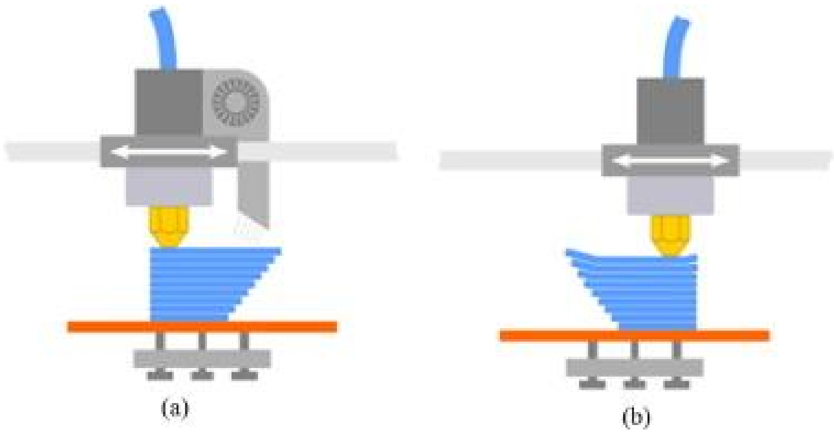

Figure. 16. Schematic of the layer deposition process in 3D printing: (a) With part cooling fan, and (b) Without part cooling fan

Thermo-electric cooling

The Peltier effect is the phenomenon where a potential difference across a thermocouple causes a temperature difference between the different connection points of the thermocouple. Therefore, a thermoelectric cooler (TEC) can be used to cool an object.Pelier elements are often used in computers, especially CPUs.The most common material combinations are two semiconductors, bismuth and telluride, and the temperature of the connection between the two conductors changes when a DC voltage is applied and a DC current flows from one conductor to the other.The internal view of a TEC is shown in Figure 1[13]. Although thermoelectric cooling has the advantages of being noiseless and simple in construction, there are some limitations. Thermoelectric cooling is more costly and has some limitations in temperature regulation. Thermoelectric cooling is usually applied to a small range of temperature control, if the temperature difference is too large will lead to a reduction in the efficiency of heat transfer[14].

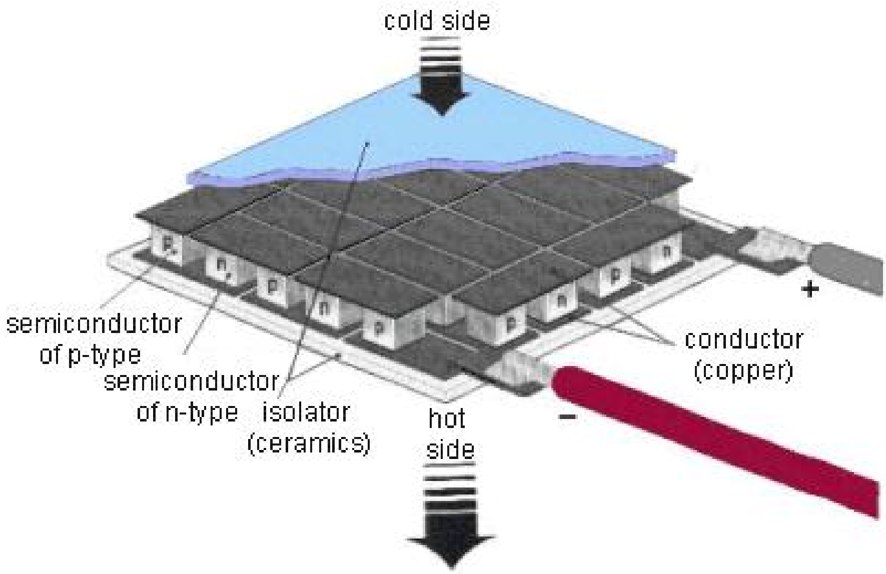

Figure. 17. An inside view of TEC

Radiation cooling

Any object that exceeds absolute zero will emit energy in the form of electromagnetic radiation, which is Planck's Law. Planck's radiation is also known as thermal radiation because of its relation to temperature. The higher the temperature of an object, the more radiation it emits at each wavelength. Planck's law expressed in terms of different spectral variables is shown in Figure 8[15]. Whereas in a vacuum, heat can only be transferred by radiation or conduction. Therefore many satellites transfer heat to the external environment by thermal radiation. Figure 5 shows the wavelengths of the thermal radiation band of the electromagnetic spectrum. The ability to transfer heat by thermal radiation is related to the optical properties of the material, i.e., solar absorptivity versus IR emissivity. Therefore radiative heat transfer is widely used in small satellites and other types of spacecraft. Depending on the requirements, specific paints or coatings can be added to modify the surface properties of spacecraft[16].

Planck's law expressed in terms of different spectral variables			
with h		**with $\hbar$**	
variable	**Distribution**	**variable**	**distribution**
Frequency ν	$B_\nu(\nu,T)=\frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/(k_BT)}}$	Angular frequency ω	$B_\omega(\omega,T)=\frac{\hbar\omega^3}{4\pi^3c^2}\frac{1}{e^{\hbar\omega/(k_BT}}$
Wavelength λ	$B_\lambda(\lambda,T)=\frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/(\lambda k_BT)}}$	Angular wavelength y	$B_y(y,T)=\frac{\hbar c^2}{4\pi^3y^5}\frac{1}{e^{\hbar c/(yk_BT}}$
Wavenumber $\tilde{\nu}$	$B_{\tilde{\nu}}(\tilde{\nu},T)=2hc^2\tilde{\nu}^3\frac{1}{e^{hc\tilde{\nu}/(k_BT}}$	Angular wavenumber k	$B_k(k,T)=\frac{\hbar c^2k^3}{4\pi^3}\frac{1}{e^{\hbar ck/(k_BT}}$

Figure. 18. Several forms of Planck's law

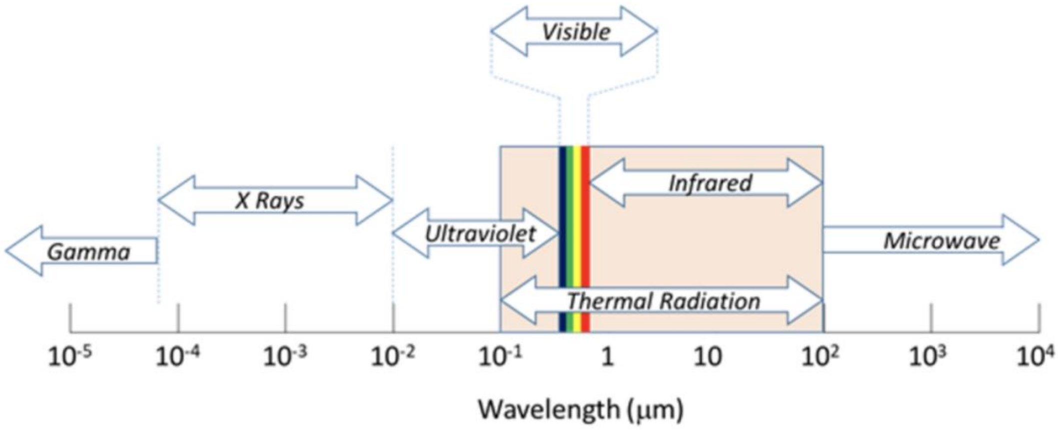

Figure. 19. Electromagnetic spectrum showing the range of Thermal Radiation.

Heat Pipe Cooling

Heat pipe technology was created in 1983 and is essentially a passive heat transfer device with high thermal conductivity. Heat pipes can transfer heat from one point to another through a two-phase flow pattern. Two phase flow is an interactive flow of two different phases having a common interface in the same channel, containing solid-gas, solid-liquid, and liquid-gas[18]. The concept of heat pipe is shown in Figure. 10. Heat pipes have extremely high thermal conductivity in steady state operation and are relatively space efficient compared to conventional methods. Due to the extremely high thermal conductivity of heat pipes, they can operate well under microgravity conditions. Moreover, heat pipes have no moving parts, no wear and tear, and low maintenance costs. Therefore, the French National Centre for Space Research (CNS), the National Aeronautics and Space Administration (NASA) and other units are committed to the research and development of heat pipes in space, and have achieved positive results[17].

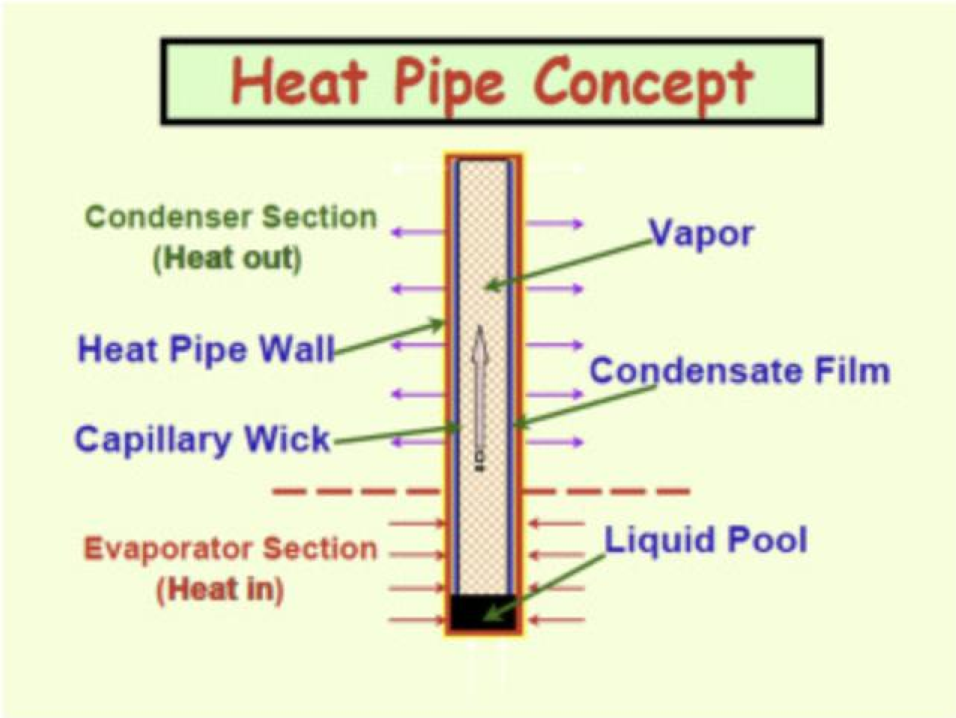

Figure. 20. Heat Pipe Concept

3. Experimental processes

In order for the nozzle to work properly, we first need to understand the components we need and what they do. After a number of debugging sessions, all the devices needed to make the nozzle work properly were finalized. Here we need the following devices:

1. A printer motherboard, as shown in Figure 21. The printer motherboard is the core control unit of the 3D printer, which is responsible for the movement of the motor, power distribution and the control of external accessories.

Figure. 21 Printer motherboards

2. One INO board, as shown in Figure 22. The role of the INO main control board is to combine with the Raspberry Pi to realize precise control of the nozzle temperature through the PID control algorithm and PWM control.The left USB is the interface used

to connect to the Raspberry Pi, allowing the Raspberry Pi to act as a host computer to calculate the heating power and control the INO board. The right interface is the power supply, the induction heating coil, and the K-type thermocouple connected to the nozzle, in that order.

Figure. 22 The structure of INO Board

3. Raspberry Pi, as in Figure. 23. The Raspberry Pi acts as the main controller here, controlling both the printer motherboard and the INO main control board through the serial port, realizing the synergistic control of printing and temperature.

Figure. 23. Raspberry Pi

4. One Converter Step-Down Power Supply, as shown in Figure 24.Since the power supply required for the motherboard and INO board is 24V, and the power supply required for the Raspberry Pi is 5V. and the vacuum bin only has four ports that can access the power supply, it is not possible to use three power supplies to provide voltage for the three boards. Here we use a parallel method to provide voltage to all three boards at the same time using a 24 power supply. Here we need a voltage reducer to step down the 24V to 5V.

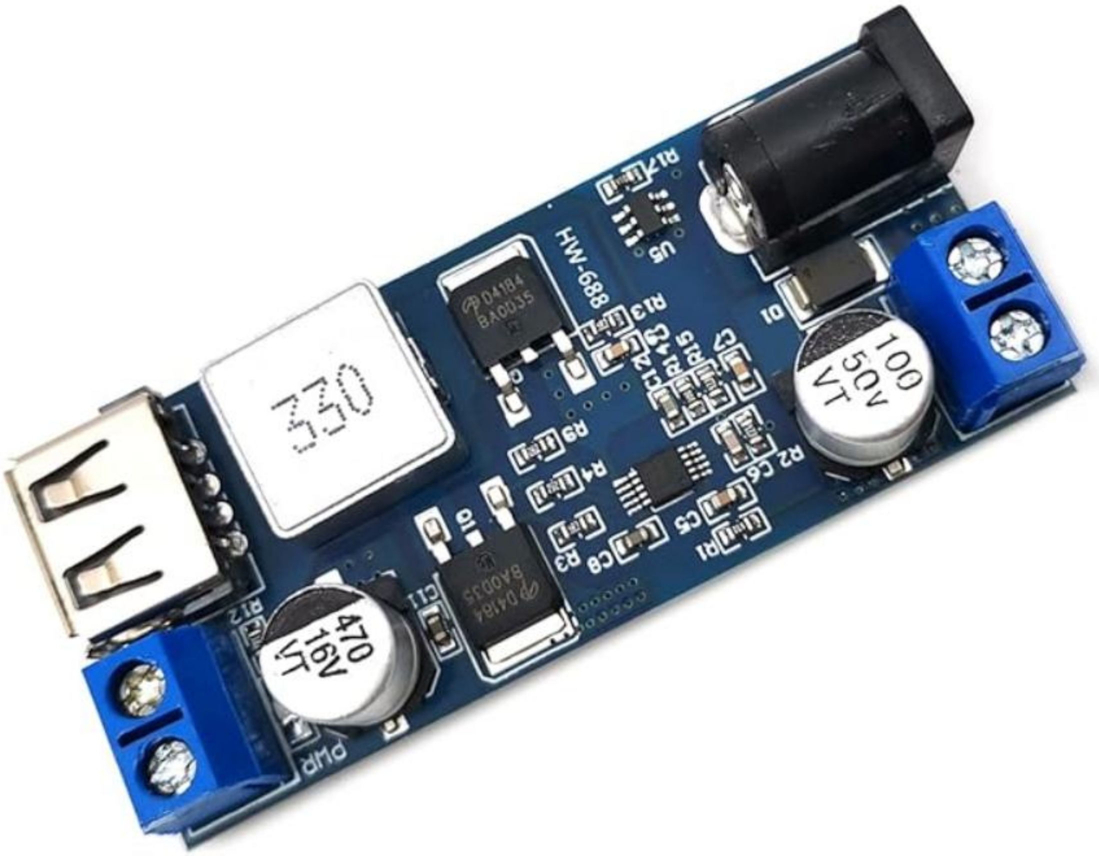

Figure. 24. Converter Step-Down Power Supply

- **Working principles of the nozzle**

In the whole 3D printing process, the Raspberry Pi acts as the upper computer, and the printer motherboard and INO control board act as the lower computer. First, the Raspberry Pi is responsible for parsing the G code of the slice file and sending the parsed motion control commands to the printer main board, which controls the operation of the stepper motors based on these commands to complete the precise movement of the print head in the XYZ axes so as to execute the printing task. In this process, Raspberry Pi is also responsible for nozzle temperature control. Through real-time acquisition of the nozzle temperature feedback, the Raspberry Pi runs a PID control algorithm to calculate the required heating power. After the calculation is completed, the Raspberry Pi transmits the heating power data through the serial port to the INO main control board, which uses PWM signals to adjust the heater power of the nozzle according to the received power data, thus accurately controlling the rise and fall of the nozzle temperature. This centralized control by Raspberry Pi not only improves the resolution of the slice file and the efficiency of motion control, but also optimizes the temperature regulation through the PID algorithm to ensure the temperature stability and printing accuracy during the printing process, effectively improving the performance and output quality of the entire 3D printing system.

The combination of electromagnetic induction heating head with PID control and PWM control forms an efficient and precise temperature control system with multiple significant advantages. First, the electromagnetic induction heating head is capable of rapid warming and efficient heat transfer, responding quickly to dynamic changes in temperature. By combining with PID control, the system is able to regulate the heating power in real time to avoid overshoot and fluctuation of the temperature, thus realizing stable temperature control.The PID control algorithm utilizes proportional, integral and differential links to precisely regulate the heating power to ensure that the temperature is maintained near the set value, which significantly improves the efficiency of energy utilization and reduces the unnecessary energy loss. In addition, PWM (Pulse Width Modulation) control further enhances the flexibility and accuracy of the system. By adjusting the duty cycle of the PWM signal, the heating power of the induction heating head can be carefully controlled to achieve more precise temperature regulation. Figure 25 shows the temperature control system architecture.

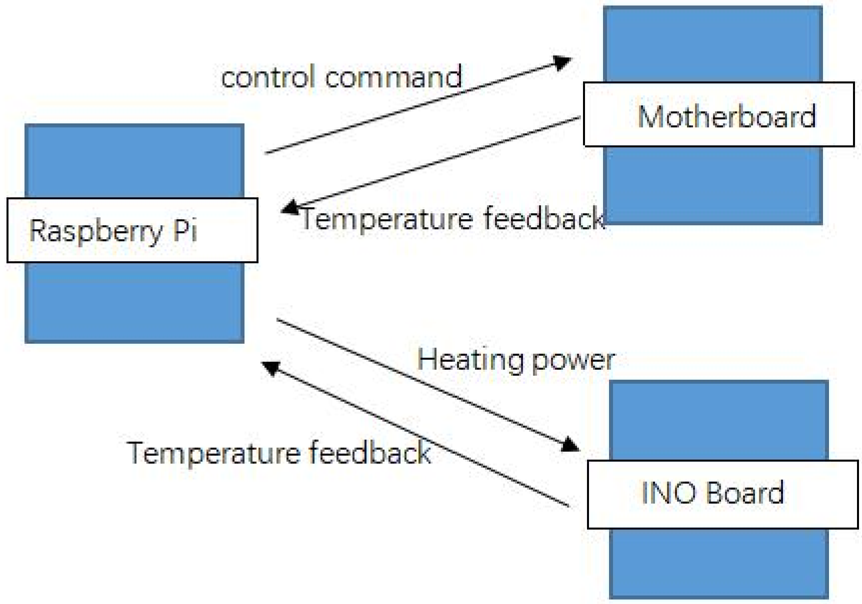

Figure. 25. Temperature control system architecture

- **Fixing of nozzle**

After confirming that the printer motherboard and INO control board are connected into the Raspberry Pi. We need to finish securing the nozzle. Since the printer's xy-axis printhead slider bracket does not have a suitable screw capable of holding the nozzle in place, I initially decided to use a strap to hold it in place, as shown in Figure 26. However, after trying to extrude and move the nozzle, I realized that fixing it with the tape was not strong enough, and the nozzle showed signs of relative movement, which, although small, would affect the print accuracy and print quality. So after some consideration I decided to drill two more screw holes in the original slider bracket and secure the nozzle with screws. Figure 27 shows the before and after pictures of the slider bracket with screw holes. With the two screws, the nozzle can be firmly fixed to the mobile bracket, as shown in Figure 28.Because of the subsequent need for heating and printing tests in a vacuum, we need to detect the temperature of the heatsink, and if the temperature of the heatsink is too high, we need to consider adding other ways of heat dissipation. Therefore, I chose the HT-NTC100K Thermistor Temperature Sensor to measure the temperature of the heatsink, and the fixing method is shown in Figure 29. After making sure that the HT-NTC100K Thermistor Temperature Sensor is in contact with the heatsink, I used a strap and tape to fix it to the slider bracket. After making sure that the HT-NTC100K Thermistor Temperature Sensor is in contact with the heatsink, the HT-NTC100K Thermistor Temperature Sensor is fixed to the slider bracket using a tie and tape.

Figure. 26. Fixing of the nozzle by means of a strap

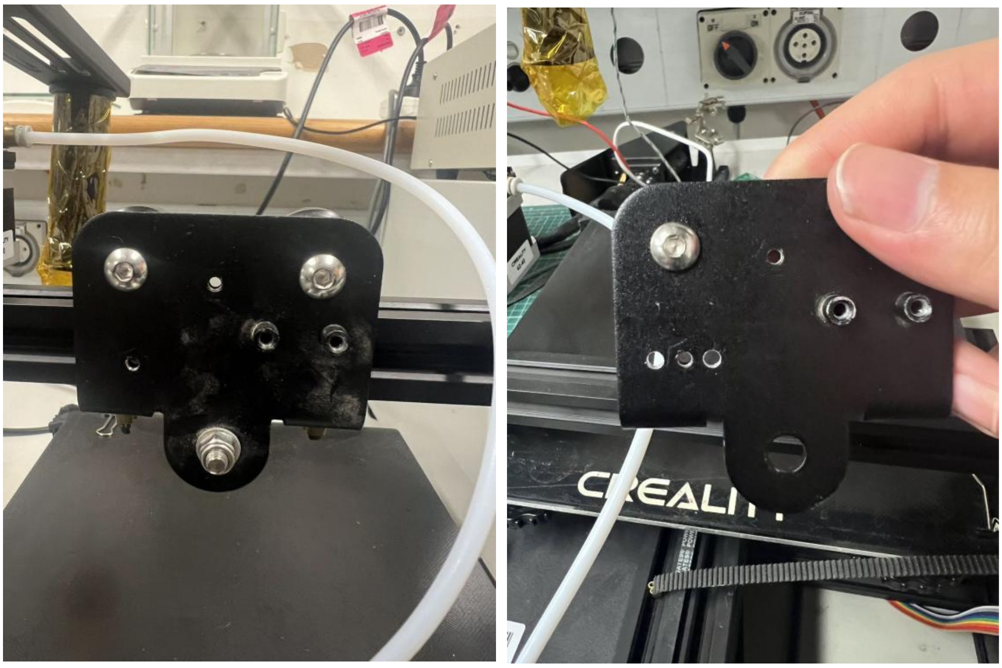

Figure. 27. Screw holes before and after comparison

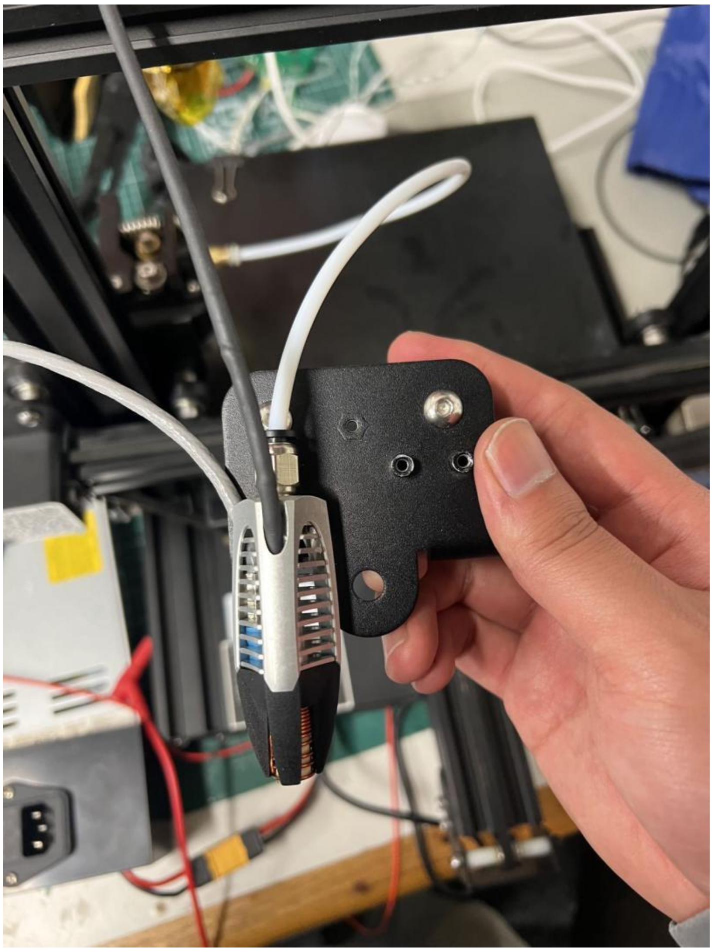

Figure. 28. Final nozzle fixing position

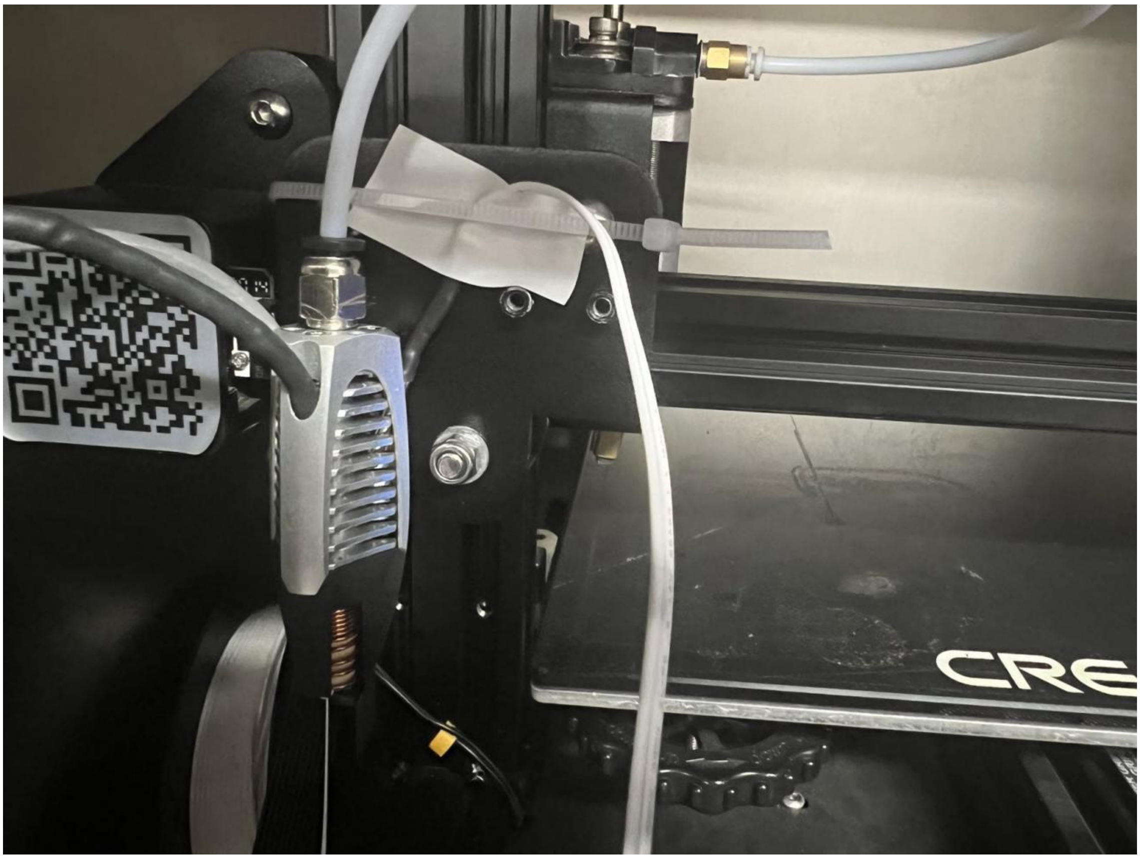

Figure. 29. HT-NTC100K Thermistor Temperature Sensor Fixing

- **Temperature test**

After the nozzle is fixed, the next step will be to test the nozzle's heating speed at room temperature and its ability to print. Before performing the temperature test, we need to place the printer in the vacuum bin. Since the inside of the vacuum chamber is connected to the outside world there are only 4 ports. There are three devices that need to provide power: the INO control board, the Raspberry Pi and the printer motherboard. Therefore if three power supplies were used to power each of the three boards it would result in insufficient interfaces. As the printer board and the INO control board need a voltage of 24V, here I used a parallel connection to provide 24V to the three boards, to the Raspberry Pi additional connection to a voltage reducer, so that the voltage supplied to the Raspberry Pi from 24V down to 5V. specific connection circuit diagram as shown in Figure 30. The physical connection diagram is shown in Figure 31.

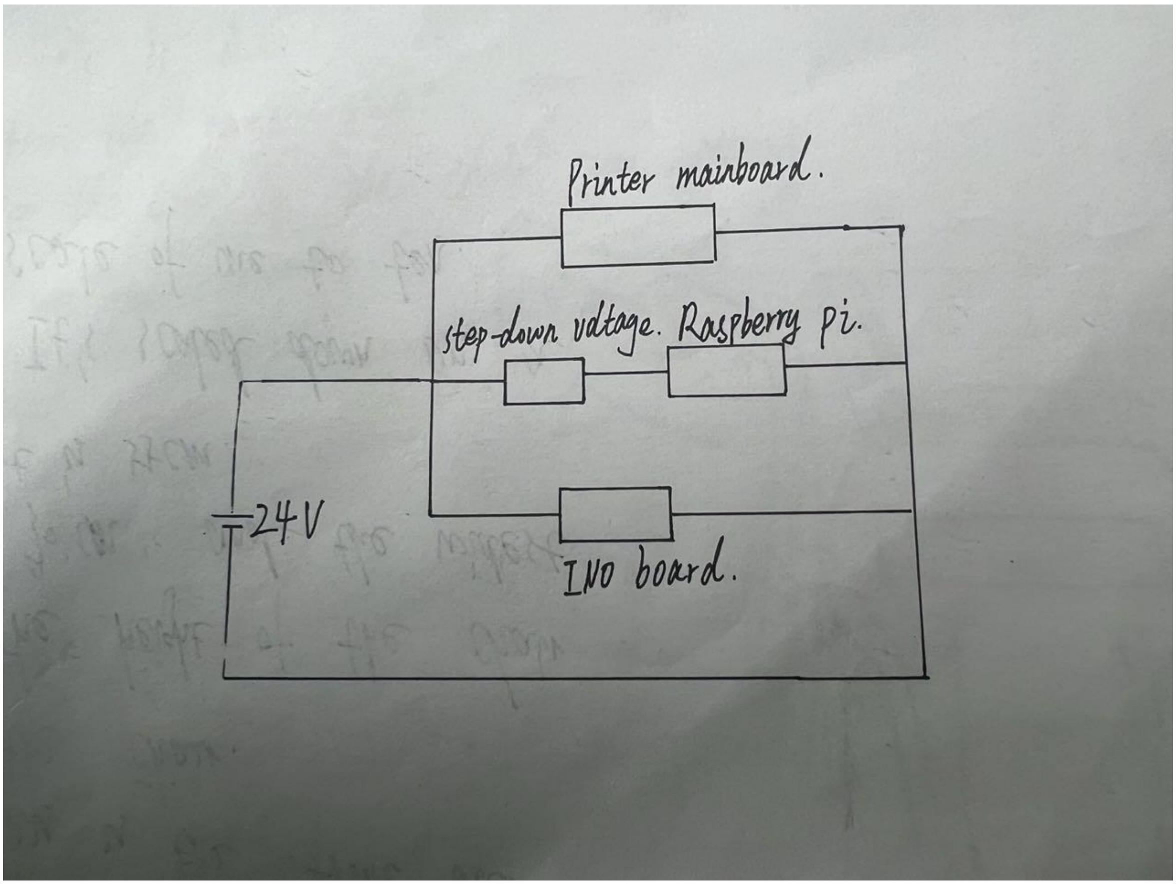

Figure. 30. Printer Control Board Connection Circuit Diagram

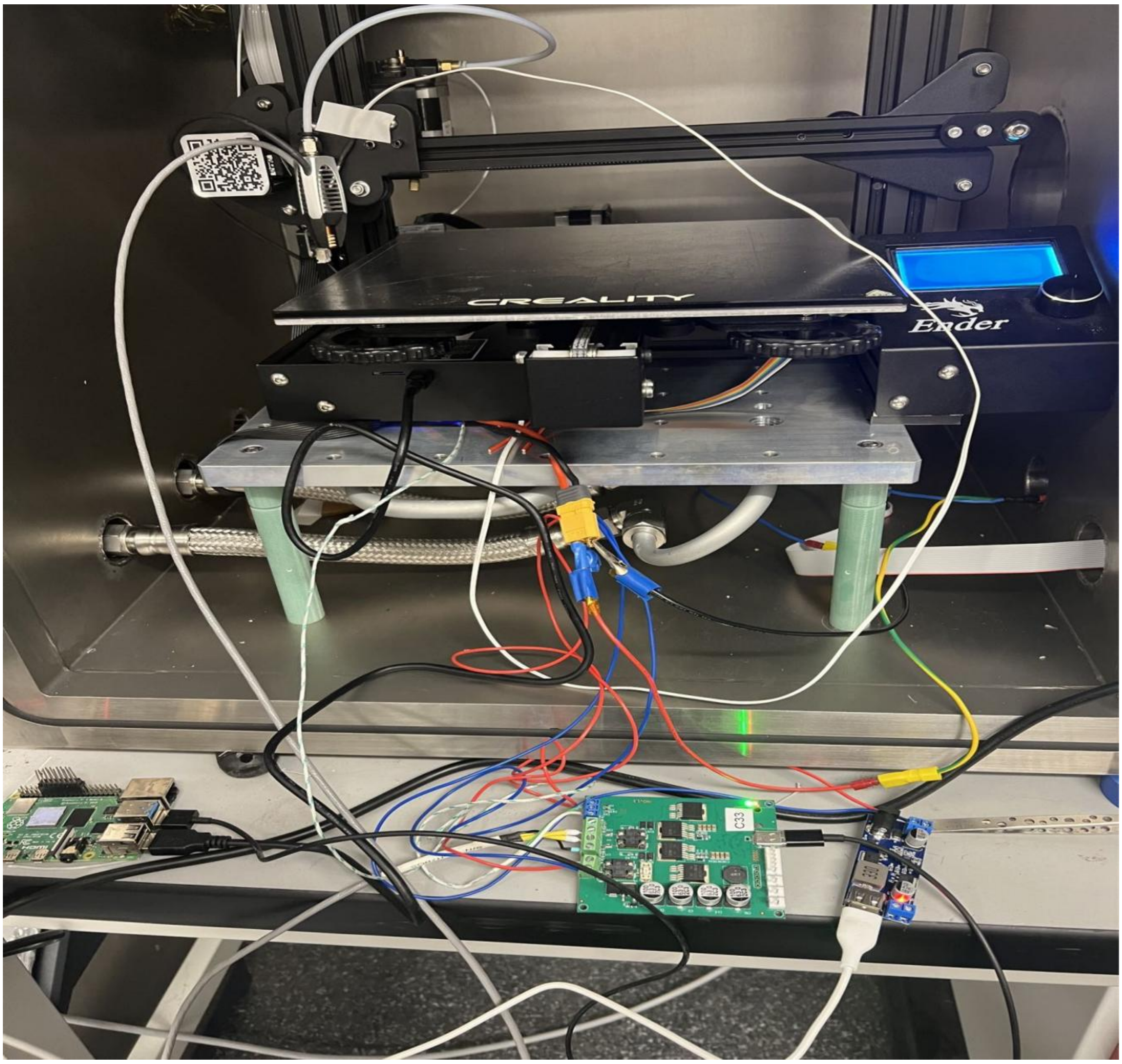

Figure. 31. Circuit connection diagram

First test nozzle heating speed. In the control interface to the expected temperature to 240 degrees, select the heating, and finally get the heating curve as shown in Figure 32. In order to more intuitively observe the changes in temperature, I exported the data using matlab to plot the temperature change curve over time, as shown in Figure 33. From the figure can be observed, after the start of heating the nozzle temperature changes very quickly, the nozzle temperature from the beginning of about 20 degrees to 240 degrees just less than 10s of time, and after reaching the predetermined temperature, the temperature change is very small, indicating that the thermal control of the system is very good to ensure the stability of the temperature of the print. After testing the temperature change curve of induction heating, I recorded the temperature change curve of ordinary resistance heating as shown in Figure 34. From the figure can be seen through the resistance heating of the nozzle from room temperature to 200 degrees heating takes about two and a half minutes, and reached a predetermined temperature, there is a more obvious fluctuations in change, indicating that the stability of the resistance heating performance is poorer. Through the comparison of the two heating methods we can conclude that the rate of induction heating is much greater than the rate of resistance heating.

Figure. 32.Temperature change curve for heating the nozzle to 240°

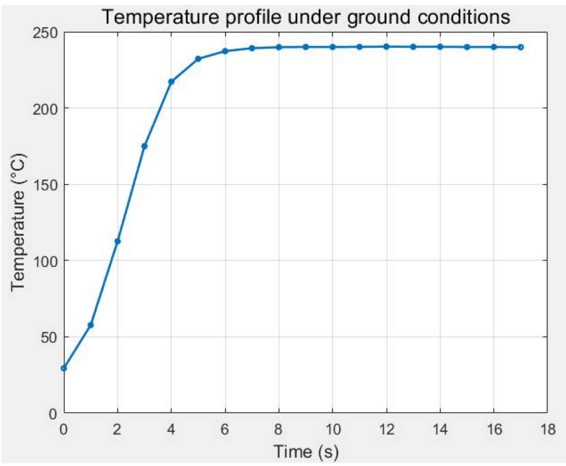

Figure.33. Image of nozzle temperature variation with time

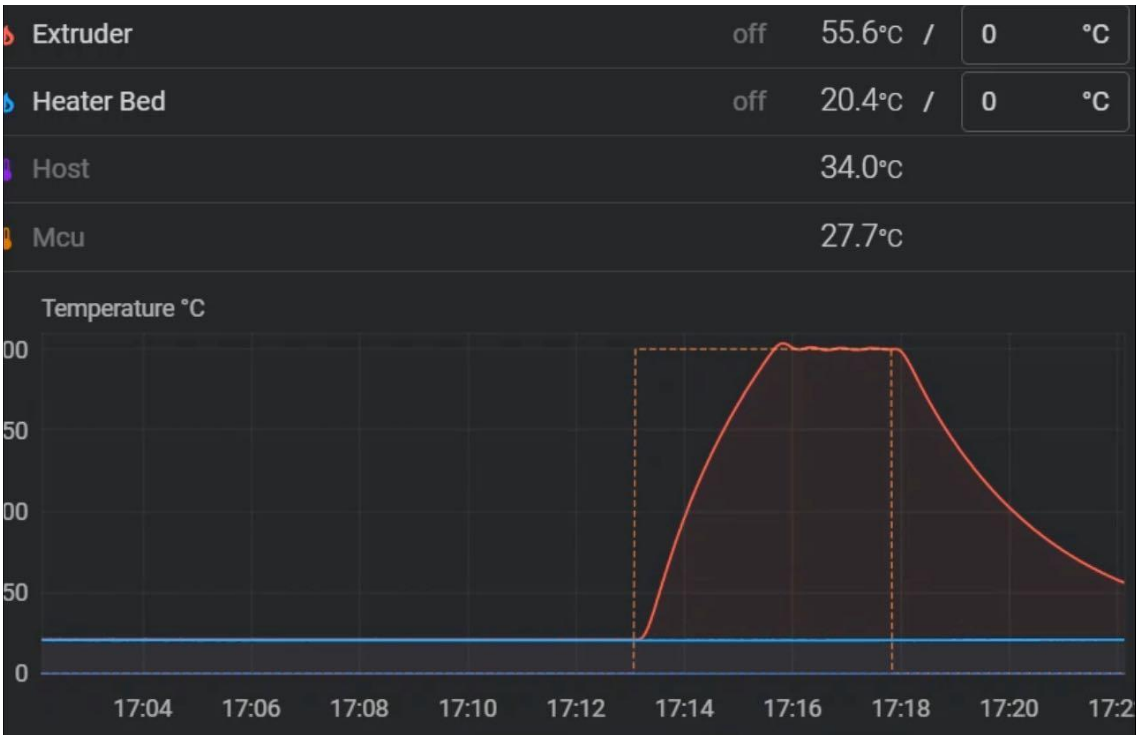

Figure. 34. Temperature change curve of resistance heating

After completing the heating rate test under ground condition, we tried to test the heating rate under vacuum condition, after exporting the data, we plotted the curve of temperature change with time under vacuum condition through matlab as shown in Figure. 34, and compared the heating rate under vacuum condition with that under ground condition as shown in Figure. 35. It can be seen through Figure. 34 that the heating rate of the nozzle in vacuum is also very fast, and the nozzle temperature can reach 240 degrees in 10 seconds and stabilize. The temperature change curves highly overlap under different conditions as shown in Figure 35, which shows that the heating rate of the nozzle is not affected by the environment.

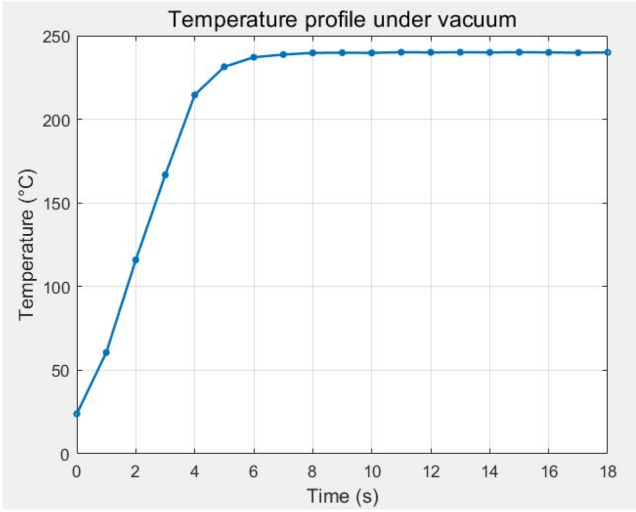

Figure. 34. Curve of temperature variation with time in vacuum

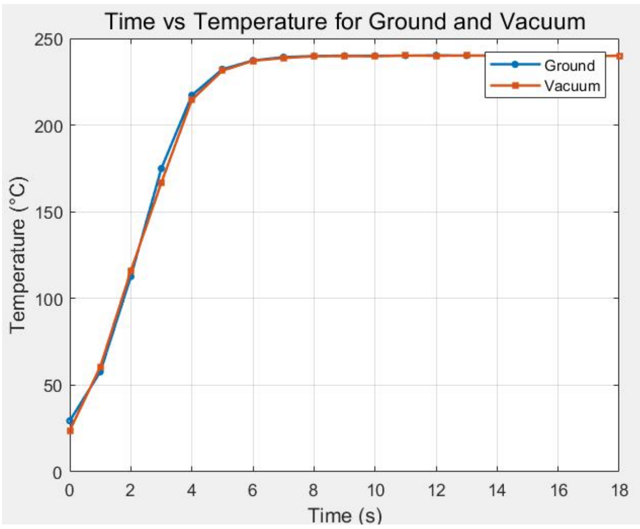

Figure. 35. Temperature profiles for two different conditions

Similarly, we recorded the temperature change curves of the nozzle after stopping heating, as shown in Figures 36 and 37. The comparison shows that the cooling rate of the nozzle is more rapid after stopping heating in the ground condition. We believe that this is due to the lack of air in the vacuum condition, where the heat dissipation efficiency is too low, resulting in a much slower cooling rate of the nozzle.

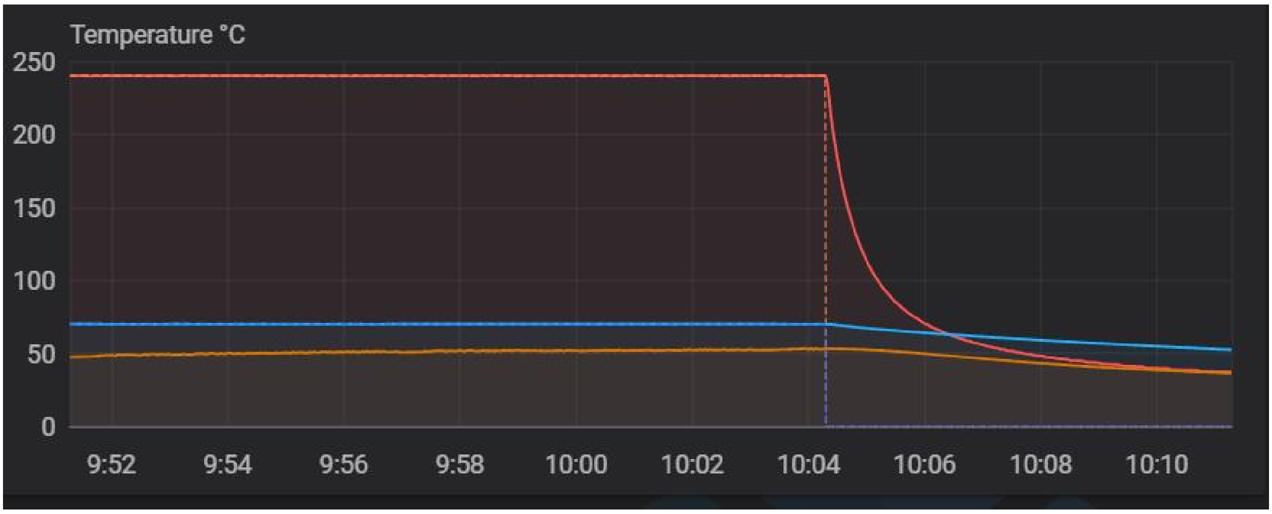

Figure. 36. Temperature profile after stopping heating in the ground environment

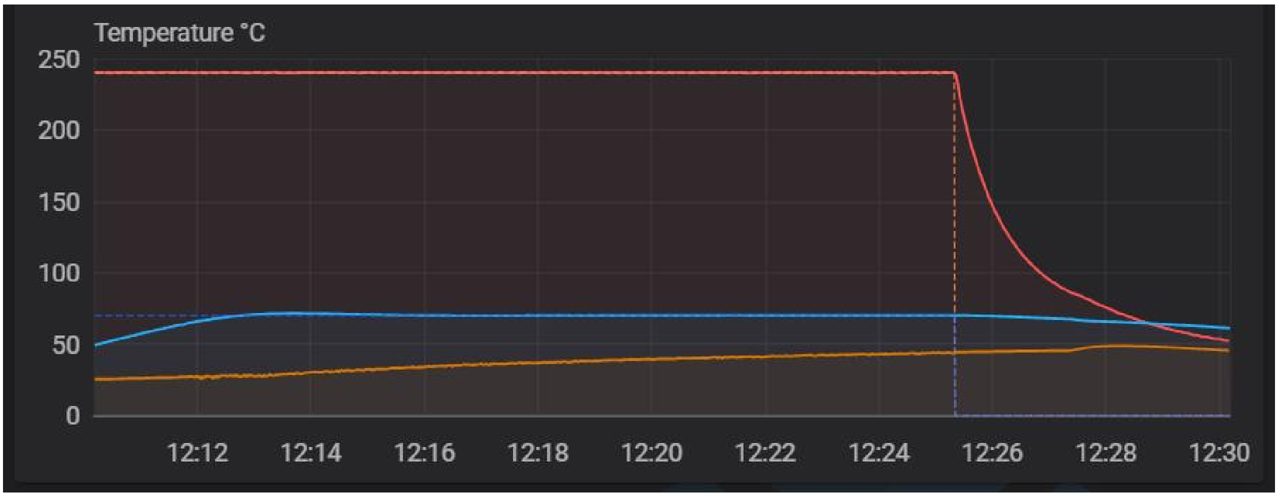

Figure. 37. Temperature profile after stopping heating in vacuum environment

- ## Print Test

After completing the temperature test, I next performed a print test. The print material I chose here is PLA. The first attempt was to print a square with a length, width and height of 1cm under vacuum conditions, and the print results are shown in Figure 38. A clear print quality problem can be seen in the figure. While the bottom buildup was normal, significant material buildup occurred on the top layer, resulting in a protruding surface and failure to mold. I believe this is due to the slow dissipation of heat from the print material. While the nozzle temperature is stable, the temperature of the extruded material does not drop quickly enough, which causes the material to start printing the next layer before it has cooled and cured completely, resulting in material buildup. I think this phenomenon can be improved in the following ways: 1. Reduce the printing speed, we can reduce the speed of the nozzle to increase the printing time, so that the material has more time to fully cool down. 2. Reduce the printing temperature, here I set the printing temperature of 240 degrees, you can try to reduce the temperature by 10-20 degrees to see if there is a change. 3. Reduce the temperature of the hot bed, the heat transfer of the hot bed is also a cause of the temperature can not be reduced quickly. Heat transfer from the heat bed is also one of the reasons why the temperature can not drop quickly, you can reduce the temperature of the heat bed to see if the print quality has improved. 4. Increasing the print cross-sectional area, as well as decreasing the print speed, will give the material more time to cool by increasing the print time for each layer.

Figure. 38. Finished print under vacuum

Due to time constraints, I doubled the cross-sectional area of the print and reduced the print speed by 20% to try the print again. At the same time, I printed an identical object under ground conditions to compare with the finished product printed under vacuum conditions. The finished print is shown in Figure 39. As you can see from the figure, the quality of the print was significantly improved compared to the previous one. From the side view, it can be seen that the edge of the finished product printed under vacuum has obvious warping, which is still due to the lack of timely heat dissipation. This is still due to the lack of heat dissipation, but it is much better than the previous print. From the top view, it can be seen that the top part of the finished product was not fully molded under vacuum conditions, which means that the material was not cooled and shaped well at the end of the printing process. Therefore, it is necessary to continue to reduce the printing speed in the next experiment to observe the print quality.

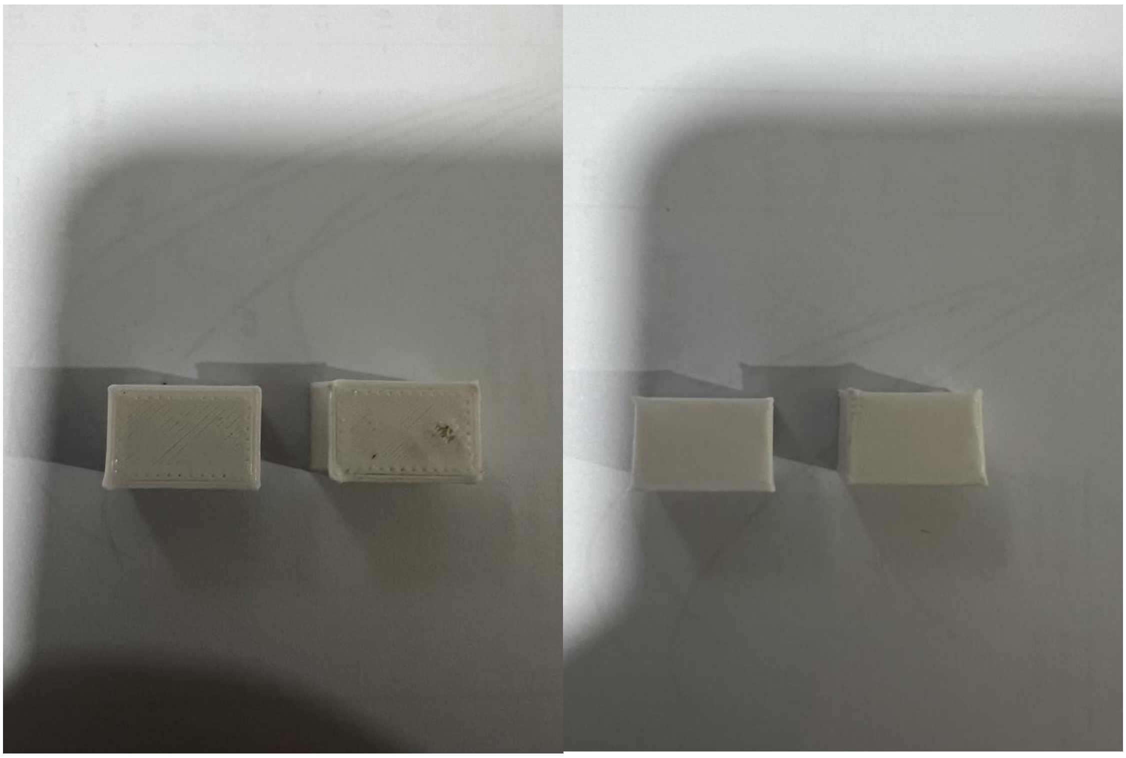

Figure. 39. Finished prints under different conditions (ground conditions on the left)

During the printing process, I recorded the temperature profiles of the nozzle, the hotbed, and the heat sink, and it can be seen in Figures 36 and 37 that the nozzle and hotbed temperatures remained stable during the printing process, with only minor variations, under both ground and vacuum conditions. And the temperature of the heat sink is increasing all the time with the change of time. However, as the temperature increases, the temperature of the heat sink slows down and eventually reaches about 50 degrees. This is due to the fact that our print time was short, only about 15 minutes, and if the print time increases, the temperature of the heat sink will continue to increase. So in the next experiment I need to increase the printing time to observe the temperature of the heatsink, if the temperature of the heatsink increases to a certain value, we need to consider adding other cooling methods to increase the cooling efficiency.

After completing the extrusion and printing of the PLA material, I attempted the extrusion and printing of the PEEK material. After heating the nozzle to 400 degrees Celsius to extrude the PEEK, I found that it would not come out, and after trying to increase the temperature to 450 degrees Celsius, the result remained the same. I thought the reason might be that the extruder's extrusion force was not enough, so I tried to extrude it manually, which eventually proved to be successful. The extrusion result is shown in Figure 40.This proves that the temperature is sufficient, but the material cannot be successfully extruded due to insufficient extrusion force. Therefore, the extrusion and printing of PEEK could not be completed for the time being.

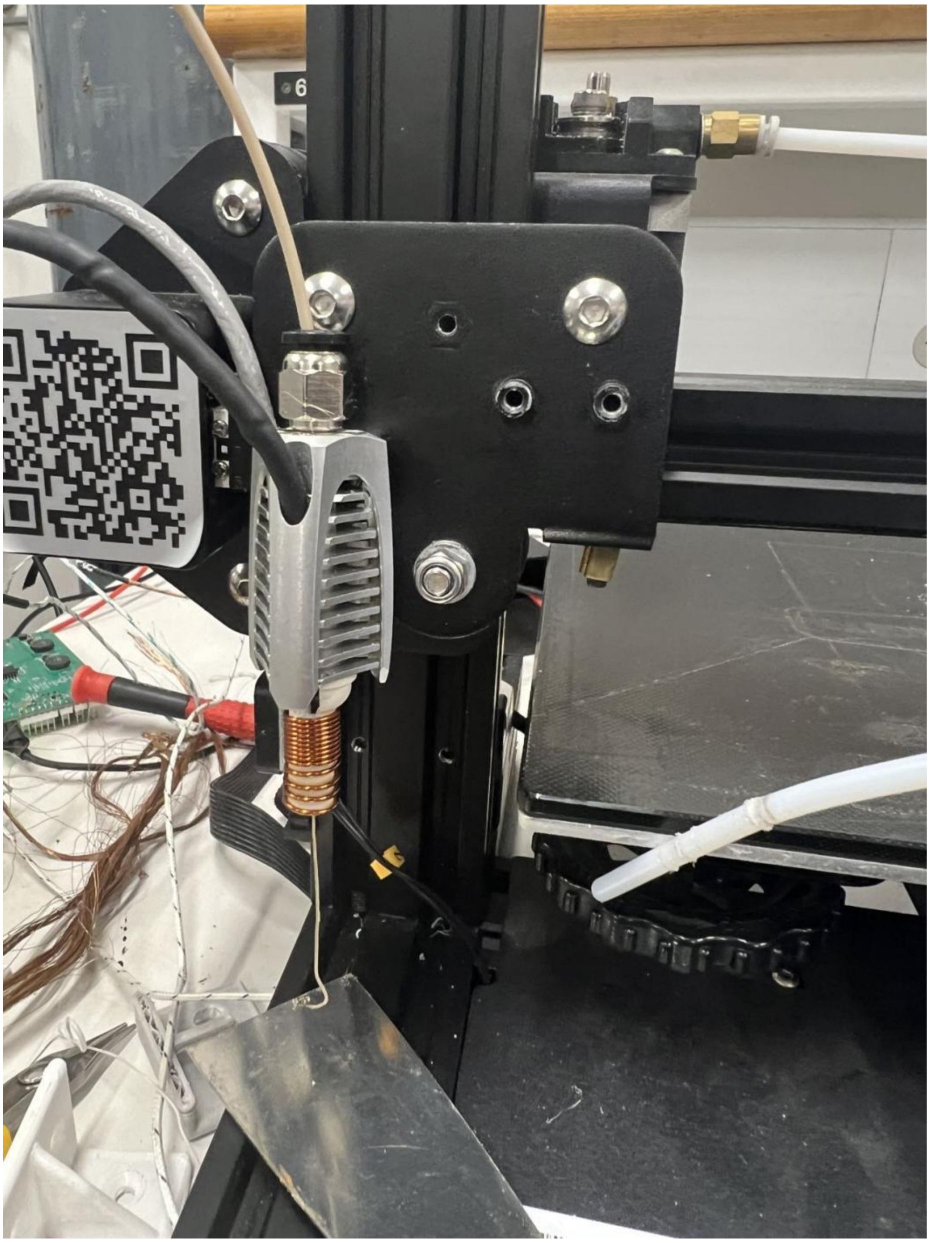

Figure. 40. PEEK Extrusion

4. Conclusion

After a series of temperature tests as well as print tests, these conclusions can be drawn. The induction heating rate is much higher than the resistance heating rate, which can realize the nozzle temperature from room temperature to 450 degrees in 20s. The vacuum environment does not affect the heating rate of the nozzle. However, the cooling rate of the nozzle after the heating is stopped in the vacuum is lower than the cooling rate in the ground environment. The temperature of the nozzle can be stabilized during the printing process in both ground and vacuum conditions. The problem is that the material does not dissipate heat quickly enough, and although it is possible to improve the print quality by reducing the print speed, this will take more time. How to solve the problem of material heat dissipation while keeping the print temperature and heat sink temperature stable is a problem that needs to be investigated next.

5. Future work

In response to the results we have obtained so far, our future research direction mainly includes the following points:

1. Increase the printing time to obtain an optimal printed finished product by varying conditions such as print speed, print temperature, and interlayer wait time. Determine the conditions under which or optimal printed finished product can be obtained. And find other methods suitable for dissipating heat from the material.
2. Conduct tensile and compression tests on finished products printed under vacuum conditions and on finished products printed under normal conditions to evaluate the mechanical properties of the material such as tensile strength and yield strength. Measure the hardness of the finished product using hardness testing equipment, and use abrasion resistance tests to evaluate the abrasion resistance of the material. This series of tests is used to compare the mechanical properties of the finished product printed under vacuum conditions with the finished product printed under ground conditions.
3. After determining that the nozzle temperature was sufficient to melt the PEEK material, we needed to find out why the material could not be extruded so that the nozzle could successfully extrude the PEEK material. After the PEEK was able to be extruded, the process was repeated and a series of tensile and compression tests were performed on the PEEK and PLA prints to evaluate the differences in mechanical properties and abrasion resistance.

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