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New and Unique Hotend for 500 °C Range 3D FDM/FFF Usage

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Abstract

Three-dimensional (3D) printing is one of the fast-growing printer fields and the most popular & simplest method is known as Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF). The process is to heat up a thermoplastic material to the melting point by a heating device and extrudes the melted material through a small hole. The extruded material is placed, layer by layer, to create a three-dimensional object. The heating device is referred to as a "hotend" in industry. We found our patented temperature-controllable heating devices to be an excellent match for this application.

There are many hotends on market today for the materials with lower (low to mid-200℃) temperature range. However, the market is in need for high temperature (400℃~500℃) hotend which is compatible with the materials with higher mechanical strength and durability. This type of material is known as super engineering plastic such as PEEK (Polyether Ether Ketone), TPI (Thermoplastic Polyimide) and so on.

We developed a unique heater which is the hotend key part for the high temperature application. Our heating element is integrated on a ceramic substrate and it doubles as the temperature sensor. The heating element has a high TCR (Temperature Coefficient of Resistance) – positive 3300 ppm/°C. The temperature change can be detected easily by monitoring the driving current of the element. Another part is that the hotend body is made of single low thermal conductive metal (Titanium-alloy) piece rather than multiple materials. Heating is done "as needed" base since the characteristics of the heater is "on-demand-heating-like" and the Titanium-alloy body acts as the heat-break so that the big cooling system is not required,

Introduction

There are more than half a dozen technologies in the three-dimensional (3D) printing industry. To those of us whose background is "traditional" printing industry, 3D printing is understood as a process which creates a stereographic object in principle by stacking flat 2-dimensional (X-Y) printed images in Z direction. In the earlier days, the term "3D printing" appeared in the technical field as a process that deposits a binder material onto a powder bed with an inkjet printhead layer by layer. In general, today the term is used in wider sense as it goes beyond the "traditional" printing process and it is used interchangeably with the term additive manufacturing (AM) and there are several different technologies to accomplish the process.

The specific technology we are addressing in our report is FDM/FFF. The term FDM was trademarked by Stratasys Inc. originally. The process is to heat up a thermoplastic material (usually in the filament form) to the melting point by a heating device and extrudes the melted material through a small hole. It is like how the hot glue gun for handicraft work in principle. The extruded material while it is still in the liquid phase is placed, layer by layer, to create a three-dimensional object. The heating device is referred to as a "hotend" in industry. Our report is focused on our recent and newest unique hotend research study.

About Hotend

The hotend part of this technology has changed very little well over 3 decades since the patent[1] for FDM was issued. The basic components which make up the hotend are heater,

temperature sensor, mounting block, nozzle, heat break and connecting wires. Hotends which are available on market today may be adequate for the materials with lower (low to mid-200℃) temperature range such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) and so forth, but the formed products are lacking durability and mechanical strength for actual usage as the working parts. The market is in need, as we understood, for the materials which can be manufactured into parts which can be placed in practical and actual working machines. This type of materials is known as super engineering plastic and representative materials are PEEK, TPI and so on.

The hotend for super engineering plastic material requires a higher temperature range (400°C~500°C) and its components must to withstand that heat level. Regular thermistor, for example, is rated up to around 350℃ maximum, so an alternative temperature sensor such as a thermocouple must be used. Although alternative component can be used, it lacks the wide part selection, easiness of usage and cost advantage of thermistors. Other commonly used building components for the off-the-shelf hotends such as wires, insulation and solder become problem as they all have maximum operating temperature of about 250℃ usually.

For those reasons, making a high temperature compatible hotend was not simple, so we took a different approach for the concept, material, design, structure and assembly.

Existing High-temperature Hotends

The high-temperature hotends currently used by the 3D printer manufacturers have very similar structures to the low-temperature ones as shown on Figure 1, though the heaters and cooling systems are much larger to meet the high temperature needs.

The way we may refer to as "Brute Force Method" which heats up the hotend to high temperature with a large heater then it is cooled off immediately after heating with high volume forced-air or sometimes liquid cooling system. The temperature is monitored with a discrete sensor device attached on the heating device.

The devices are typically heavy, cumbersome and bulky, especially if the liquid cooling systems are used. As the systems, they are very inefficient since heating and cooling are at the same time.

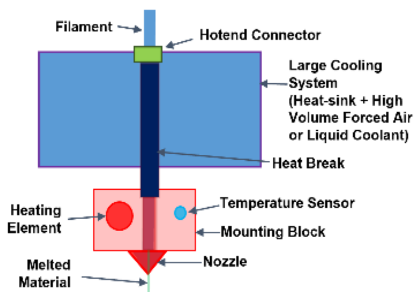


***Figure 1**. Current high-temperature hotend*

New Approach to High Temperature Hotend

We decided to select PEEK which is the representative of the super engineering plastic materials for the structural design and material selection target. The basic philosophy is to economize the heating energy "To heat the required location for the required time and required temperature and to recapture the unused heat"

A new concept hotend based on the ceramic-substrate integrated temperature sensor and heater developed for the heating head patent[2] was conceived and research started a couple of years ago. We presented a paper in 2016[3] and 2017[4] with completely different approach from the existing hotends on the market using the integrated sensor/heater substrate on the hotend. The paper of this year is continuation of the new concept with major new ideas and improvements incorporated.

PEEK is a crystalline resin and the melting point is 343℃, but we set the heater temperature to be 425℃~450℃ for better fluidity after liquefaction and formation of objects. The maximum operation temperature is set to be 500℃.

Figure 2 shows the graphic explanation of the new hotend. Unlike the existing hotend, the high temperature hotend developed requires no cooling system, much smaller in size and lighter in weight and much more energy efficient. All of those improvements are based on the factors discussed in the following section and we have applied for the international patent[5].

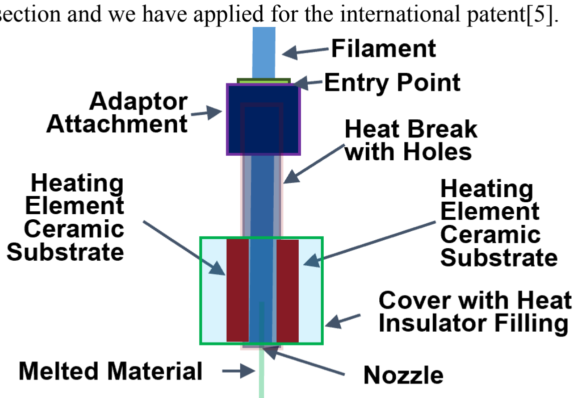


Figure 2. New high-temperature hotend

Single piece body construction

The body of the hotend is uniquely made of a single metal piece - Titanium alloy – which has very high thermal resistivity and mechanical strength. Since there is no need for complicated assembly process of multiple materials, it will help increase of productivity and reliability.

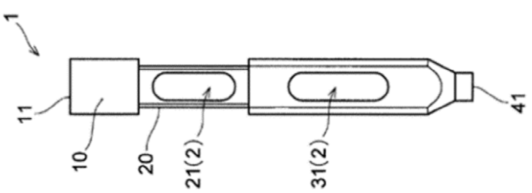


Figure 3. Single piece construction

This is the industry first construction method and very effective way to isolate the hot section and cold section.

Explanation of Figure 3 (The drawing is shown sideways in order to save the page space)

1. Complete hotend body
10. Adaptor attachment
11. Filament entry point
20. Heat break section
21. Heat reduction openings
31. Heating openings
41. Nozzle

New construction materials and method

The hotend body is made of a single Titanium alloy as stated before. Because of the mechanical strength ability of the alloy, the body can be machined to thin wall with holes to reduce the thermal conduction.

The heat break section on Figure 3 has the wall thickness of 0.5mm and the openings were made to reduce the heat conduction from the heating substrate. Due to the low thermal conductivity of the alloy and reduced thermal path, the thermal resistance of the hotend through the heat break is about 600 ℃/W.

No separate temperature sensor element

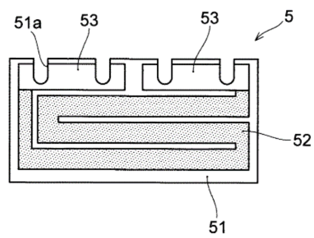
Another unique feature of the new hotend is the resistive heating element. It has a very high positive temperature coefficient of resistance (TCR) of 3300 parts per million (PPM) per ℃. When the temperature goes up, so does the resistance value. This characteristic has been utilized two ways in the hotend.

1. The resistive element heats the hotend as well as to read the temperature if the drive current is monitored. There is no need for the separate temperature measurement part or wires if this characteristic is utilized.
2. Since the resistance goes up when the temperature goes up, there is "self-regulating" ability and the "snowball effect" (as the temperature goes up, resistance goes down in the case of negative TCR) type of damage is unlikely to occur.

Newly designed heater ceramic substrate

The heater consists of the heating resistive element on the alumina zirconia substrate. Unlike existing hotends on the market which use discrete heater elements, the new heating element is integrated on the ceramic substrate with thick film technology.

The heating resistive element pattern was designed to utilize all the substrate footprint so that the heat generation is maximized. The notching is for the connecting wire to have a good contact and to relieve the stress on the electrode on the substrate.



Explanation of Figure 4
5. Heater
51. Alumina zirconia substrate
51a. Notching
52. Heating resistive element
53. Electrodes

Figure 4. Heaater substrate

New heating element energy control circuit

The temperature sensing is very different from the existing hotends which typically use thermistors, thermocouples and the like, so the block diagram shown on Figure 5 is suggested for controlling the hotend energy as an example.

In practice, this is the part of printer manufacturer's know-how and we do not get involved with the actual individual circuit.

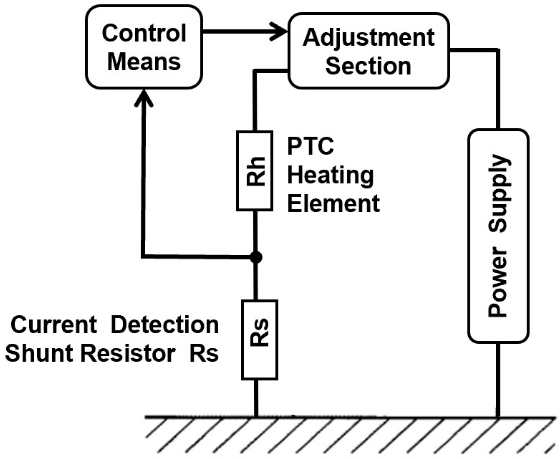


Figure 5. Example of energy control block diagram

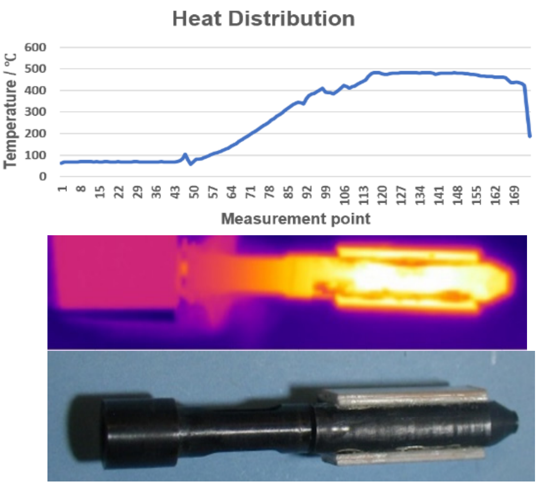
Verification of new hotend performance

In order to verify the new hotend performance, especially operation without any cooling system while the heating section reaches the high temperature, a thermograph image was taken as shown on Figure 6.

Since the final completed product has the stainless-steel cover over the heating part, it is difficult to see the true image of thermal profile. For that reason, the cover was removed to obtain an accurate temperature reading.

The measurement point table is too large to include in this report, so simplified table is shown below. The position on the table corresponds to the heat distribution measurement point on the distribution graph.

The thermographic image does not show the shape of the hotend, so the picture of actual unit is added for reference without the cover.



Position	Temp
1	64.1
8	69.4
15	69.3
22	69.4
29	69.5
36	69.1
43	69.2
50	69.2
57	103.6
64	139.8
71	195.0
78	253.1
85	316.1
92	363.9
99	392.1
106	422.0
113	441.9
120	476.4
127	481.1
134	480.3
141	476.3
148	480.0
155	471.2
162	462.6
169	435.3

Figure 6. Verification of hotend performance

Completed Product

The completed final hotend is shown on Figure 7.

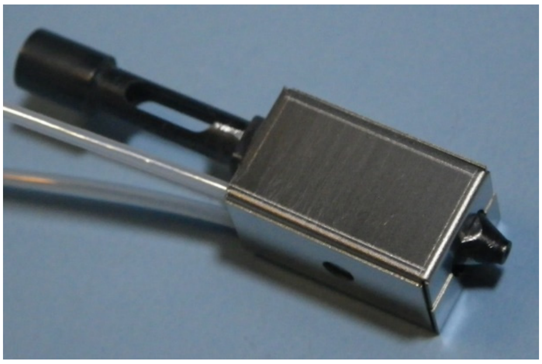


Figure 7. Completed new hotend

Quick product specification summary is:

- No external cooling system is required for continuous 500℃ operation
- External dimensions: Total length 32 mm
- Heating part (cover size): 7 x 7 x 15 mm
- Weight: Less than 3 grams
- Thermal capacity: 1.5 J/℃
- Maximum operating temperature: 500℃
- Heater resistance @ 25 °C: 18Ω± 15%
- Heater TCR: Positive 3300 PPM/ ℃
- Power requirement: 24V DC (standard) about 14 W
- Connecting wires: 2 wires only
- Filament diameter: 1.75 mm
- Nozzle diameter: 0.6 mm
- Heat break: 10 mm long x 3 mm OD
- Thermal resistance 600 °C/W

Actual Operational Test

Off-the-shelf 3D printer was modified to accommodate the new hotend for actual manufacturing testing as shown on Figure 8. The purpose of this experiment was to verify the operation of the hotend for the high temperature required super engineering plastic materials and not to fine-tune the printer. For that reason, the experiment was done in the open setting and the print stage was not in the closure.

If more sophisticated printed object evaluation is required, the closed print chamber setup will be better and we will leave that type of test to the printer manufacturers.

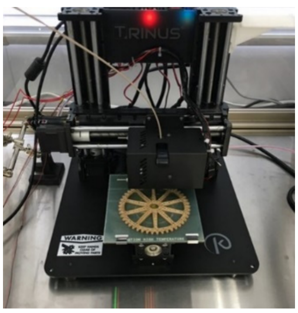


Figure 8. Actual manufacturing test

Test Results

New hotend operational tests were run for several materials using the printer shown on Figure 8 and some examples were as shown on Figure 9. The materials used were:

PEEK (polyether ether ketone)
TPI (thermoplastic polyimide)
PEEK/CF (PEEK with carbon fiber)

The reason why this test was done is to show that the new hotend really does work for the super engineering plastic filament rather than just a product on the paper.

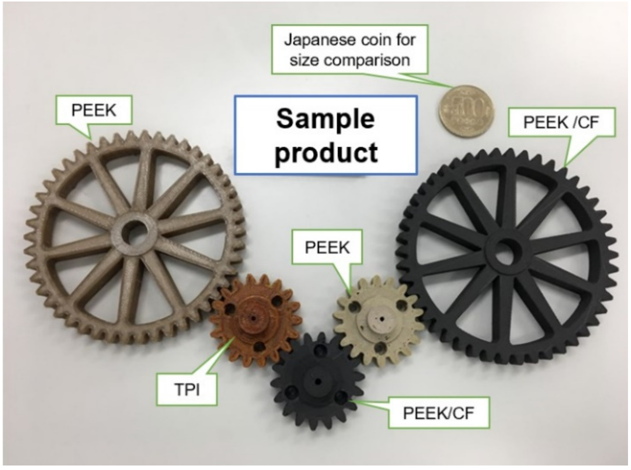


Figure 9. *Sample printed products*

Conclusion

This has been the third-year report on the unique 3D hotend study. The incremental improvement of materials and methods led us to the super engineering plastic compatible high-temperature hotend report.

The result of this study shows that the small (less than 3 grams) hotend which does not require the large heater and huge cooling system performs well. In comparison with the existing high temperature hotends, advantages are obvious from the space (footprint as well as the volume) and efficiency view point, not mentioning the "on-demand like" heating characteristics.

We believe that this is market ready product for the 3D FDM/FFF printer market now we are happy to contribute to the betterment of exiting industry.

Future Outlook

With the characteristics of new hotend, we foresee new activities in various applications especially in the following areas:

- Simultaneous multiple object forming: Short-run medium quantity production application.
- Supplemental forming: Forming additional object on the ready-made object
- Non-filament usage: Other type of material than filament, such as pellet for own "blend" material
- Higher speed forming
- Multi-functional product forming
- Multi-nozzle hotend
- Multi-material forming (including non-resin materials)

We have been working on the continuous improvement (*kaizen*) for the hotend performance and one of the areas is to study the liquid / solid boarder line control for higher process speed and reduction of clogging incidents.

References

[1] US Patent "Apparatus and method for creating three-dimensional objects", US5121329A, Inventor S. Scott Crump

[2] US Patent "Heating head for erasing a printed image on re-writable media", US7612790B2, Inventor Hideo Taniguchi

[3] Hideo Taniguchi, Nobuhisa Ishida & Jiro Oi, On-demand-like FDM 3D printhead consideration, Proceeding 2016 IS&T's NIP32 pg. 37

[4] Hideo Taniguchi, Nobuhisa Ishida & Jiro Oi, High Temperature (500°C) Hotend for FDM 3D Printer, Proceeding 2017 IS&T's NIP33 pg. 166

[5] International application applied for "Discharge head of molding materials for three-dimensional molding devices" based on the Patent Cooperation Treaty FP11381WO, Inventors Hideo Taniguchi & Nobuhisa Ishida

Author Biography

Before founding HIT Research Corporation (HRC) and HIT Devices Ltd., in Kyoto, Hideo Taniguchi worked for ROHM Co., Ltd. for over 40 years where he was responsible for the products including items relevant to the printing industry like thermal printheads (printhead with partial glaze layer, development / implementation of driver ICs on substrate for printhead) and development / mass-production of LED printheads. He received his BS from Ritsumeikan University in Kyoto (in the field of Applied Chemistry) with additional study in Electrical Engineering.

Nobuhisa Ishida has been with HRC from its inception in 2015 and working mainly with the 3D printhead development. Prior to HRC, he worked for ROHM Co. Ltd., in Kyoto and Konica Minolta, Inc in Osaka/Tokyo. Through his career, he had been in the developmental in such field as thermal printhead, inkjet printhead, MEMS micro pump, fuel cell and printed electronics. He graduated from Kansai University in Osaka, Department of Applied Chemistry with BS degree.

Jiro Oi works for HRC since 2015. Prior to joining HRC, he worked for HIT Devices Ltd US Office, ROHM Co. Ltd., US Office and Hitachi, Ltd., in Japan and US. He received his BSEE from California Polytechnic State University in San Luis Obispo, California and MBA from Thunderbird School of Global Management in Glendale, Arizona.