https://doi.org/10.2352/ISSN.2169-4451.2019.35.34

Application Kaizen for FDM 3D High Temp (500°C) Hotend

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Abstract

As the FFF/FDM 3D fabrication process becomes more accepted and popular in industry, the demand for products with higher anti-abrasion capability, higher durability as well as the ability to withstand higher temperature is growing fast. The materials for this type of product are known as "super engineering plastic" and materials such as PEEK and TPI are the examples.

Due to the high temperature requirements, the existing hotends which are made for lower temperature materials like PLA and ABS are not capable to handle the material. A revolutionary new concept hotend for high-temperature usage in the range of 300 °C to 500 °C has been developed specifically designed for the super engineering plastic materials.

The new hotend is compact in size and the thermal capacity is small accordingly compared with the conventional units, but it can follow the precise temperature requirements and fine adjustments as needed. Unlike the others, this hotend does not need a large cooling system (either forced air or liquid coolant) to prevent the heat creep on the cool end of the extruder. It is more energy efficient and eco-friendly as it heats when it is needed. Also, thanks to the size and weight, multi-nozzle device will be feasible in the near future.

With the new design improvement and ability to monitor-control the hotend temperature more accurately, it is much more clogging-resistant of filament material than existing or even our own previous year's hotend.

Introduction

There has been a great amount of advancement in the three-dimensional (3D) printing industry in the last three decades. There are various technologies, but we have been focusing our study to the technology known as the FFF/FDM 3D fabrication process. Our interest, more precisely, is the hotend part of the extruding mechanism where the sold material (usually in the form of filament) goes in and comes out melted.

The hotend is one of the key 3D printer parts because it affects the printer performance and capability. If it does not deliver enough heat to melt the filament, the 3D formation of the product will not happen. On the other hand, if it gets too much heat without adequate cooling, the filament becomes too soft to be pushed in – the phenomenon called "heat creep".

Various filament materials have the suitable operating temperature ranges and characteristics. The materials such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) and so forth will work in the range of low to mid-200℃ and relatively easy to work with, but they lack durability and mechanical strength. The materials which are durable and strong enough to be manufactured into the parts for the actual working machines are known as super engineering plastic (super enpla, for short). They are represented by such substances as polyether ether ketone (PEEK), thermoplastic polyimide (TPI) and so on.

There are new applications for the super enpla beyond just rapid prototyping. PEEK, for example, can be used for medical purposes such as dentures and artificial joints. 3D printers will be perfect match for this type of application.

The super enpla materials require a processing temperature range of mid-300℃ to 500℃ which is substantially higher than the aforementioned materials. The hotends used for the mid-200℃ materials cannot handle this temperature range, even if the heaters are beefed up as other components such as thermistors and wires are not rated at that temperature range. But, one of the most difficult issues is how to avoid the heat creep as discussed in the following sections. We have approached the higher temperature hotend design from the heating device point of view using the knowledge and know-how of ceramic board used for thermal printhead and heating head[1] as discussed in the following sections.

Existing High-temperature Hotends

Following is a brief explanation of how the high temperature hotends works in general. This type of hotends are currently available on the market and used by many 3D printer manufacturers.

They have very similar structures to the low-temperature (mid-200℃) hotend, though the heating element and cooling system are much larger to meet the high temperature requirements. One example of typical hotend available on the market (or through internet sales channel) is shown on Figure 1A picture and 1B drawing.

The way we may refer to jokingly 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 liquid cooling system. The temperature is monitored with a discrete sensor device such as a thermocouple attached on the heating block.

The devices are bulky, heavy and cumbersome, especially if the liquid cooling systems are used. In case of liquid cooling, there is a need for a separate circulation and heat radiation system with a liquid reservoir though we are not including it as a part of our discussion in this paper. As systems either forced air or liquid cooling, they are not very efficient as the systems must be cooled at the same time as they are heated in order to prevent the heat creep.

Figure 1A
Picture of off-the-shelf
high temperature hotend

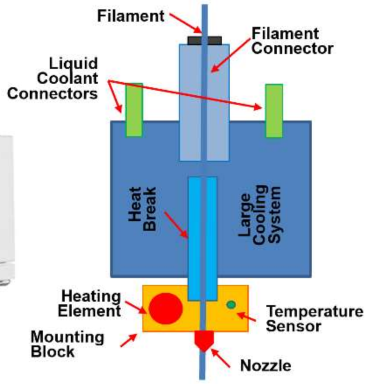

Figure 1B
Drawing of off-the-shelf
high temperature hotend

Our Approach to the Hotend

We have approached the hotend design from a different viewpoint. In contrast with the existing high temperature hotend design philosophy, we believe the forced air/liquid cooling system right after the high temperature heating block is a big waste of energy. The better way is to heat on demand so that the energy is applied when and where it is needed[2]. There is a big challenge of how to take care of the issue of "heat creep" without the large cooling system. The different components/ideas are discussed in the following sections.

Integrated heating element on to the ceramic substrate

Most of the high temperature hotends are powered by the sheathed heaters. Our hotend is heated with the integrated heating element on the ceramic substrate. This is the same technology used to manufacture the printhead for thermal printer. The reason why our hotend has the fast heating response is due to this technology.

The making the heating element is done by the process known in the industry as thick film technology – the resistive material is screened on the ceramic substrate in the paste form and fired in the oven at a very high temperature. Heating characteristics can be changed by the paste material as well as the screen pattern according to the need for the heating profile.

Figure 2 is the actual screen pattern for the heating element for the hotend. There are 5 rectangles in the lower end of the pattern indicating the connecting pads. Heating profile can be changed by selecting a pair of pads based on the requirement.

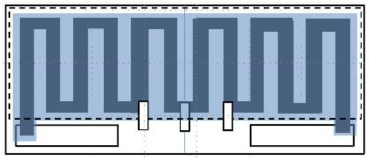

Figure 2
Screen printing pattern of heating element
on the ceramic substrate

Unique heating element

As shown on Figure 2, heating profile can be changed depending on the application requirement. The hotend is designed for mainly high temperature usage, but the selection gives the choice of application without making major change.

The resistive paste material for the heating element has a very high positive temperature coefficient of resistance (TCR) of +0.33 %/ °C. This means that when the temperature of the element goes up, so does the resistance value. The heating element has the following features[3].

1. Since the TCR of the heating element is large, it will be less likely to be damaged by accidental excessive voltage applied.
2. Since the current change is linear up to the high temperature range, the temperature can be found by measuring the current.
3. The temperature is not a spot like thermistor, but representative of whole heating area.
4. Thanks to the resistive material characteristics, the saturation temperature is self-regulating with heating and cooling balance.

Single piece hotend body construction

The body of the hotend is made of a single titanium alloy piece. This material is less heat conductive compared with other metals such as stainless steel (SUS), brass and aluminum which are commonly used for hotends. It is mechanically much stronger. Since it is a single piece, the internal material flow structure is straight and it is less prone to nozzle clogging.

There is a pair of slits between the heating section and the mounting block as shown on Figure 3. This reduces the conductive heat as the cross section is cutback. The heat reduction is such that the only passive heatsinking is necessary. This is the industry first construction method and very effective way to isolate the hot section and cold section. This has been applied for the international patent[4].

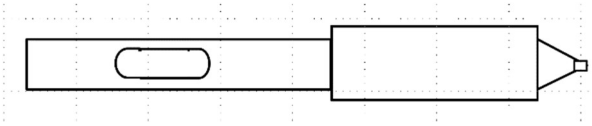

Figure 3
Drawing of single piece
hotend body construction with slits

Effectiveness of new hotend design

To verify the effectiveness of the new hotend design and construction, a thermograph shot was taken and compared to the regular and the temperature profile as shown on Figure 4. Since any external attachments to the hotend will interfere with the thermography, the hotend was stripped down to the body and ceramic substrates with the heating elements.

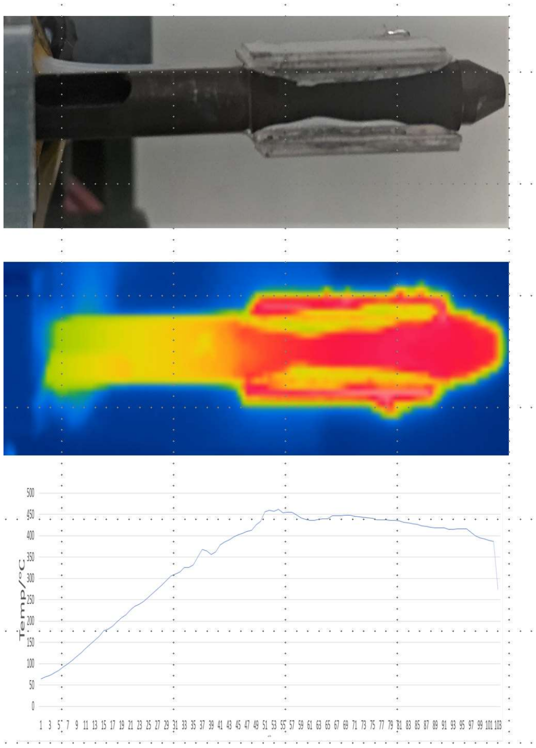

Figure 4
Actual heating profile and
thermograph verification of effectiveness

As it can be seen from the picture, the material used to attach the ceramic substrates to the body was oozing out around the edges a little which made the two lines due to emissivity difference of two materials on the thermograph. An important point here is to note that the temperature reduction from the peak point (about 450°C to the mounting/cooling block about 60°C) is in a linear fashion which is the validation of the titanium alloy body and structural design/construction effectiveness for temperature reduction. This thermograph was taken with the infrared emissivity 0.85 and applied power at 10.0 W at the saturated state.

Actual hotend heating operation

Figure 4 was taken with the main components of the hotend, but it did not include such things as outer casing which will affect the ultimate hotend performance. The completed hotend cutaway drawing is shown on Figure 5.

Figure 5
Completed hotend

In order to measure internal temperature of hotend, three (3) discrete thermocouples were attached on the hotend as shown on Figure 6.

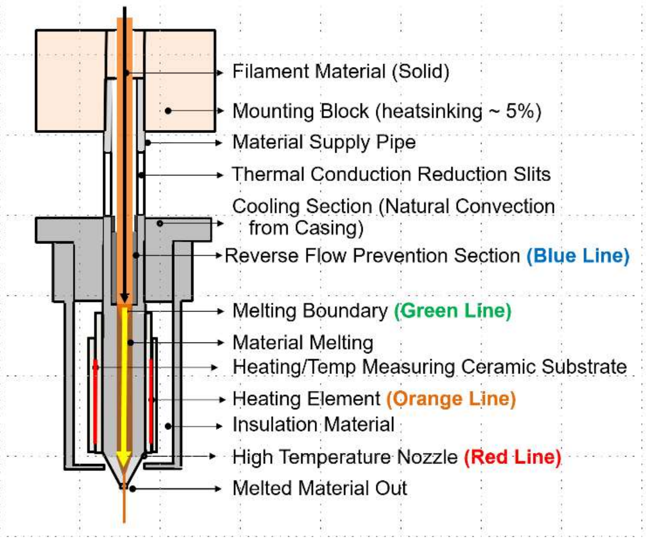

Figure 6
Cutaway drawing of completed hotend

Along with the thermocouples, the heating element is used to measure the temperature making four (4) test points. They were plotted on Figure 7. There is a slight difference between Line 1 and Line 2 which is coming from probably by the placement and characteristic of two components. The applied power at the highest temperature on the graph was 8.5 W.

The discrepancy between the red line (nozzle temperature) and orange line (heating element temperature) may be due to the type of measurement method (thermocouple vs. heating element resistance monitoring) and also location of the measurements were taken could be the causes.

The importance of this temperature measurement is the reverse flow prevention section temperature (Line 4 – blue line) stays blew 300 °C and the heat creep (reverse flow of material) does not occur.

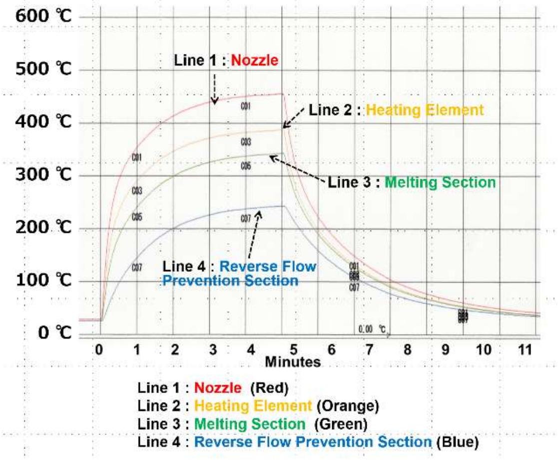

Figure 7
Completed hotend temperature distribution

Critical temperature review

Required operating temperatures are different from material to material. Since we are targeting the high temperature material mainly PEEK, Line 1 and 2 show the temperature of melted material leaving the hotend. The most critical temperature, we determine, is the reverse flow prevention section shown on Line 4 (blue line on the graph) because this is the point should never go beyond the melting point of the material.

Green line (Line 3) indicates the temperature which the material (the filament) of solid phase changes over to the liquid phase when it melts.

Temperature drops in the reverse flow prevention section such that the filament retains the solid-state characteristics. If this section becomes too hot beyond the melting point of the material, then the melted material may overflow out of the slits.

The hotend reacts much faster than the conventional products as it can be seen from Figure 8. It is taking less than 3 minutes to reach mid-400 ℃ in the heating element/nozzle, so it is extremely important to monitor the temperature via heating element current and control the required temperature for the operation.

Evaluation of new hotend

Our involvement of 3D printing has been the hotend only and we are not expert of other components or the whole printer mechanism. However, the hotend needs to be incorporated into the printer with an appropriate filament in order to be evaluated in order to see if the hotend is working as it was designed and manufactured. Fortunately, off-the-shelf 3D printers are plentiful and it is easy to obtain. We modified one unit to accept the hotend mechanically and electronically.

The electronic hotend control circuit had to be modified to drive our hotend as the hotend does not use either thermistor nor thermocouple for temperature monitoring. The block diagram of the hotend temperature control is shown in Figure 8.

Mechanical modification was straight forward to replace the existing hotend with our product.

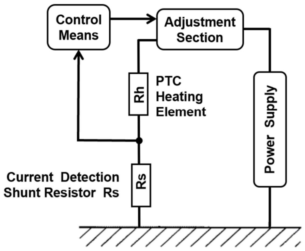

Figure 8
Block diagram of control circuit

Actual printed product using the hotend

After the modification of a off-the-shelf 3D printer, some sample prints (products) were made using PEEK filament. The data used for the sample shown in Figure 8 was available in the public domain from the internet – part of a drone.

Figure 9
Sample product using new hotend
in a modified 3D printer with PEEK filament

Outlook

Because the hotend we have been studying is small, light, high-performance, efficient and does not require the extra cumbersome cooling system, we believe the outlook for the future development is very promising.

One immediate possibility is a multiple nozzle hotend. This will enable for a printer to use different type of filament materials, different colors, different nozzle diameter, different heating temperatures and so on.

Another possibility is to increase the heating temperature higher by changing the number of heating element substrates from two (2) currently to four (4). This will open a possibility of using the materials which are not possible in the today's FFF/FDM world like metal and glass, or inorganic/organic compounds of low-melting points.

If the process speed needs to be increased, four-sided heating substrate model will be very useful as amount of heat generated can be doubled. (If the voltage is increased with the current heating element, the self-regulating characteristics will kick in and the resistance value will go up and the temperature will not go up).

We will be adding hotends with nozzle opening diameter of 0.2 and 0.3 mm. This will be welcomed addition to the high procession applications. Also, the heat requirement goes down as the hole gets smaller. When the diameter decreases, the clogging becomes less which is a good trend.

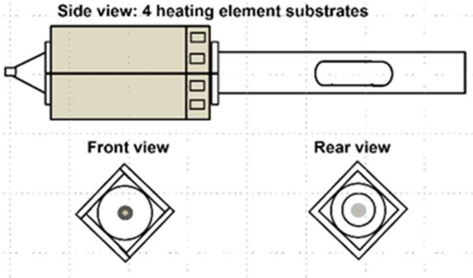

Figure 10
Potential future hotend

Conclusion

We have been studying the new concept 3D hotend in the last few years. Some improvement/kaizen points have been incidental, but the main idea has been the same – How to improve the efficiency of hotends and expand the FDM printing technology field. This year's challenge was to reduce the frequently occurring problem for the high temperature 3D printer – nozzle clogging.

The issue was addressed by studying the clogging causes, changing the design of heating element pattern and hotend body, etc.

Thanks to the public interests in high end 3D products, the supplies of PEEK, TPI and alike are becoming more available and the costs are coming down.

References

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

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

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

[4] 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

After retiring from the companies he founded (HIT Research Corporation and HIT Devices Ltd., both in Kyoto), Hideo Taniguchi is continuing the research of hotend in Kyoto for FDM 3D printing by forming KHR Center. Previously, he worked for ROHM Co., Ltd. for over 40 years where he was responsible for the printing industry related products like thermal printheads and LED printheads. He received his BS from Ritsumeikan University in Kyoto with additional study in Electrical Engineering.

Jiro Oi works for KHR Center (US Office) in the field of FDM 3D printer hotend. His prior experiences are with HIT Research / HIT Devices, 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.