High Temperature (500°C) Hotend for FDM 3D Printer

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Abstract

Three dimensional (3D) printing is one of the fast growing printer fields and most widely used process among several processes is known as Fused Deposition Modelling (FDM). The process heats up a thermoplastic filament to the melting point by a heating device and then extrudes the melted material through a small hole. The extruded material is placed, layer by layer, to create a three dimensional object. The heating/extruding device is referred to as "hotend" in industry.

One of the current shortcomings of this process is an inability to use the materials which have a high temperature range (400°C ~ 500°C) such as PEEK (Polyether Ether Ketone) which is so called super engineering plastic. It is at the higher end of the temperature spectrum, generally with very high mechanical strength and thermal resistance. It is used in high temperature, high stress applications, in harsh environments, and low to medium volume production.

We decided to take up the momentous challenge of this high temperature hotend. There have been many problems to be solved to achieve the goal and we are sharing some of the issues we had to deal with.

Background

We have been working on the single component heating devices based on the ceramic substrate over the decade. The major use for that type of device is the application which requires a precise and fast temperature monitor/control in a small package.

The approach we took was to "integrate" the hating and temperature sensing elements a ceramic substrate. This is a new way of making the heating device as a typical product of similar device uses the discrete part such as thermistor mounted on the substrate to monitor the temperature. The benefits for the integrated heating substrate are:

- No extra components or assembly process needed: Since the substrate and heating element/temperature sensor are integrated, those are not required.
- Small and compact: There are no extra components to stick out from the substrate.
- Fast response time: Because the heating element and temperature sensor element are next to each other on the substrate, the thermal response is faster than the added discrete thermistor.
- Withstands high temperature: Since the sensor element is made of the same material as the heating element, it can withstand the same temperature (well excess of 600°C)

It was a very natural fit for the idea of integrated substrate to be utilized for the Fused Deposition Modelling (FDM) 3D hotend project. We have started the 3D hotend project in 2015 and developed "On-demand-like FDM 3D printhead (hotend)" using this idea.

Currently Available Hotend

Hotends currently available on the market are very similar to what is shown on Figure 1 in structure with some minor variances. They are basically made of heating element, often a pipe-shaped "sheath heater", temperature sensor (thermistor), nozzle, metal connecting barrel, coupling and mounting block which mounts those components. Usually a finned heatsink is attached to separate the heated metal block and filament feeding mechanism.

This arrangement works adequately for temperature up to about 250°C. However, it is very difficult to go beyond that temperature range, as the heat has to be dissipated to prevent the coming filament melting before it reaches the hotend. Often some additional cooling device is added, such as a forced air cooling fan. There are some hotends with liquid-cooling system to deal with the excessive heat from the block.

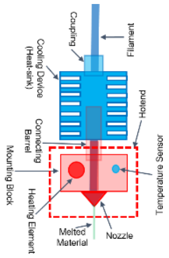


Figure 1
Hotend
drawing

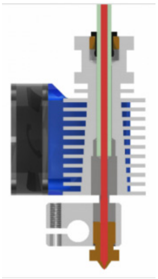


Figure 2
Actural hotend
example

New Hotend Design Philosophy

There is a fundamental philosophical difference between the existing hotends and the new product.

The existing product heats up the metal block which the extruding nozzle and thermistor are mounted. The thermistor can detect the temperature change, but the response is very slow due to the thermal inertia of the metal block mass. In order to prevent the excessive heat to affect the filament fed into the hotend, there is a heatsink to cool off the connecting part.

The new hotend has the integrated temperature sensors which monitor the temperature change in real-time. The information can be fed into the control circuit to maintain the proper operating energy level on the fly so that there is no excessive energy. The unique structure[1] of hotend makes this type of fine temperature adjustment control possible.

The new hotend product is made to heat the necessary the media (filament) as it needs and not to heat if the temperature is high enough – on-demand heating through the temperature sensor feedback (when the additional driver is used).

Since the hotend is heated as it requires, the energy efficiency is very high and it contributes to the energy saving philosophy and makes the 3D printer Eco-friendly.

Heater/sensor Elements Integration

Unlike the commonly available hotend heating section, the new hotend uses two ceramic substrates which sandwich the filament material for extrusion. The multiple heating and temperature sensing elements are integrated on the ceramic substrate as shown graphically on Figure 3.

The front view shows the two uniquely shaped heating elements are connected to the pads.

There are three temperature sensing elements which are very unique as the temperature of three "zones" can be monitored.

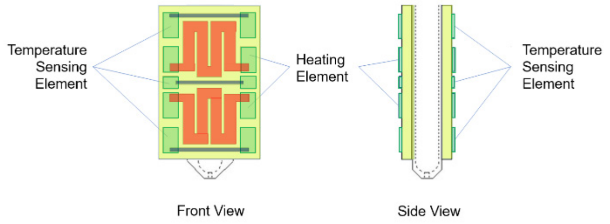


Figure 3 Front/side view of ceramic substrates

Substrate Considerations

Multiple heating and temperature sensor elements are integrated on the ceramic substrate using thick-film technology. The ceramic substrates are sandwiching the filament as seen on Figure 4. The elements are on the "reverse side" of the filament heating surface of the ceramic. There are many benefits for this this structure arrangement as follows:

- Ceramic is extremely hard and abrasion/chemical resistant, so any filament materials will not damage the heating surface even if some additive such as metal particles are contained in the filaments.
- The material flow will be uniform as the surface is smoother than the "front side" where the elements are located and surface is uneven.
- When materials are heated and the physical status changes to the liquid phase, ions in the materials which are "innocuous" at a room temperature or in the solid phase became very chemically active and start attacking the element materials even if they are overcoated with glass. Having the ceramic surfaces avoids this type of problem.
- Having multiple heating and temperature sensor elements can set the suitable temperature profile for specific material requirements.

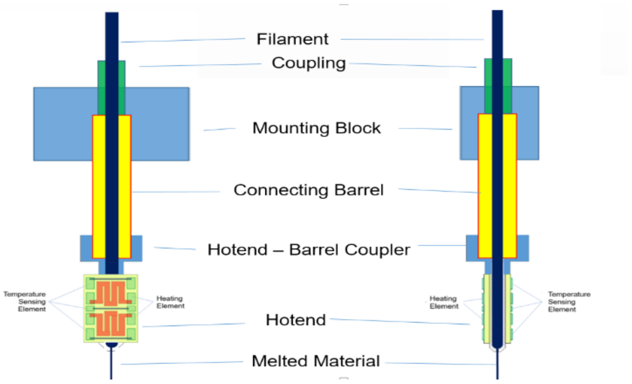


Figure 4 Front/side View of New Hotend Assembly

Temperature Sensing Principle

The temperature sensor elements on the hotend are different from the typical discrete thermistors used on the existing hotends, temperature sensing process is different. The sensor element (R_2) material has the temperature coefficient of resistor (TCR) of plus 1500 PPM per°C (or +0.15%/°C).

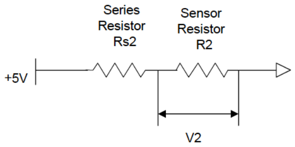


Figure 5 Temperature sensing with resistor

The temperature is calculated as follows:
A high precision resistor (+/- 1% and TCR of +/- 25 or 50 ppm/°C) is added in series.

- The low value reference voltage V_{REF} (such as 5V) is placed across two resistors.
- Since the sensor resistance R_2 at a given time can be defined as R_2=Rs2xV2/(V_{REF}-V2), the temperature change can be calculated as the change from the original resistance value at 20°C.
- Temperature change is found as the ratio of the percentage change of sensor R_2 to the temperature coefficient (0.15)

Making Hotend "Intelligent"

Since the thermal response of the new hotend is much faster than the existing products, it is possible to make the device "intelligent" with the help of external driver circuit. The idea is straight forward – the temperature information from the sensor is fed to the circuit and the driving energy is adjusted according to the preset temperature level.

The driver circuit is not discussed as it is outside of the scope of this paper which is about the hotend, but it is uniquely "intelligence-compatible" hotend. The driver energy can be controlled such method as PWM or PID. Since there are 3 pairs of independent sensors, it is possible to change the temperature profiles within the hotend such as making:

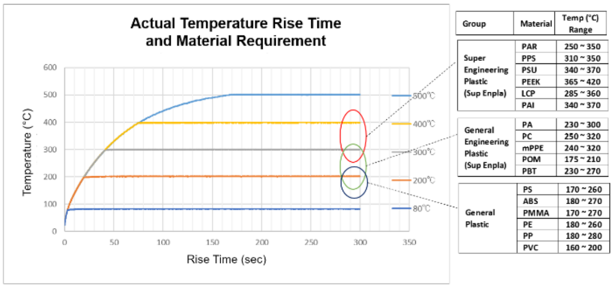
- Extruding side hotter than the barrel side.
- The barrel side hotter than extruding side.
- The temperature even in the hotend.

This makes it possible to establish the suitable temperature profile when the extruding speed is changed (including stopping) and a stable material extruding can be maintained.

New Material Challenge "Super Enpla"

Although FDM printing technology is widely popular[2] and has many advantages over the other 3D technologies due to simplicity, cost and easiness for handling, one of the current shortcomings the inability to use the materials are durable and can withstand high-temperature application.

Our very ambitious goal for the hotend project has been to reach the high temperature (400°C ~ 500°C) often referred to as the super engineering plastic (or sometimes shortened to "super enpla") such as PEEK (Polyether Ether Ketone), PEI (Polyether Imide) and so on as shown on Figure 6 can be used for 3D printers.



Group	Material	Temp (°C) Range
Super Engineering Plastic (Sup Enpla)	PAR	250 ~ 350
	PPS	310 ~ 350
	PSU	340 ~ 370
	PEEK	365 ~ 420
	LCP	285 ~ 360
	PAI	340 ~ 370
General Engineering Plastic (Sup Enpla)	PA	230 ~ 300
	PC	250 ~ 320
	mPPE	240 ~ 320
	POM	175 ~ 210
	PBT	230 ~ 270
General Plastic	PS	170 ~ 260
	ABS	180 ~ 270
	PMMA	170 ~ 270
	PE	180 ~ 260
	PP	180 ~ 280
	PVC	160 ~ 200

Figure 6 Temperature range for materials and new hotend temperature capablity

High Temperature Considerations

In order to achieve the high temperature operation objective, some materials, assembly process and product structure had to be changed as what was usable at 200°C temperature range cannot withstand the high temperature of 500°C. Some obvious changes are:

- Materials such as wires, adhesives, filler and low thermal conductive material
- Processes such as ceramic substrate assembly and connection of wires
- Construction and structure

One example of material and structure changes is shown on Figure 7. The connecting barrel between the hotend and filament coupling is made of machinable and mouldable glass ceramic tube which has a very low thermal conductivity (less than 3 W/m・℃). The barrel is acting as the thermal barrier.

Another example is the wire connection to the ceramic substrate. Conventional connection using high temperature solder may be good enough up to 250°C, but a new process had to be devised using silver-nano paste.

Evaluation of New Hotend (Thermograph)

Thermograph image of the new hotend with power-on state at full temperature level was taken. Since the inner filling of the hotend housing is the thermal insulation material, the image simply shows the outside temperature. The inner temperature is read through the sensor elements.

New Hotend Power Consumption

The power consumption of the new hotend is very low due to high efficiency of the device. Figure 9 shows the actual power consumption in Watts vs. hotend temperature in degree Celsius. Temperature readings were taken through the sensor on the ceramic substrate in the housing.

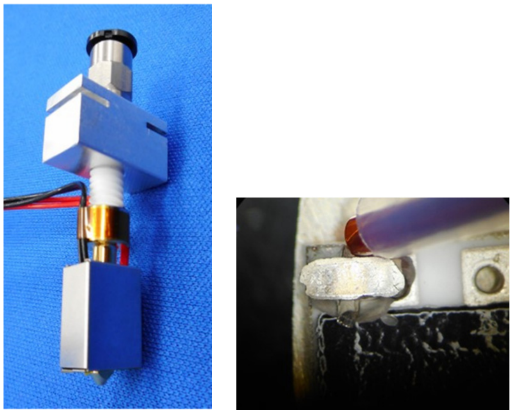


Figure 7 Example of high temperature considerations

Figure 8 Thermograph of new 3D hotend

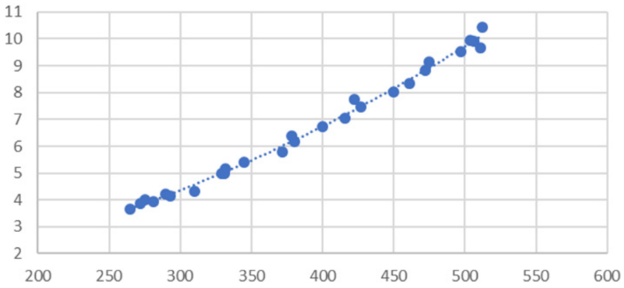


Figure 9 Power consumption vs. hotend temperature

Actual Product Made with New Hotend

The actual product was created with the new hotend using the PEEK material as shown on Figure 10 on our test printer bed setup. The hotend temperature was set at 450°C and the printer environment had to be fine-tuned for the material characteristics. Printer mechanism and setup conditions are not within the scope of this paper, so they will be reserved for the future discussion.

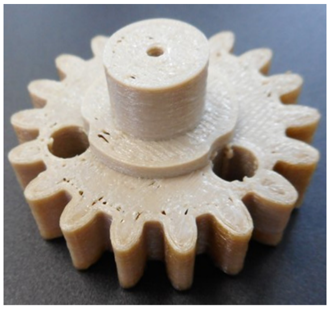


Figure 10 PEEK product sample using new hotend

Multiple Hotends

It is rather difficult to use the existing hotends in multiple manner since they are rather large, although some printer manufacturers are doing so. Also, there are specially made hotends which are designed to feed multiple filaments to a single hotend.

Our approach is a bit different. The hotend assembly is compact and flat, multiple hotends can be grouped as shown on Figure 11. This type of setup is only possible with the new hotend.

When there is a need for different filaments for the process, whether it could be different colors, materials, temperatures or support material, the new hotend makes it easy, simple and compact. Though the tight spacing may restrict the filament feeding method, it will be a joint project with the printer manufacturer.

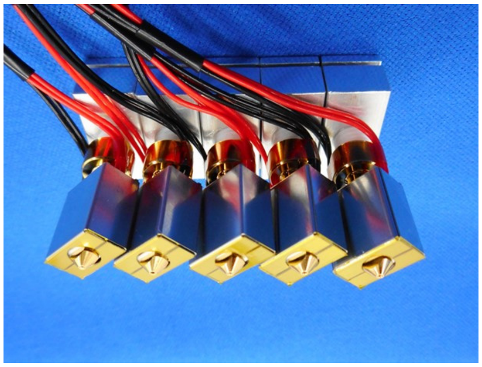


Figure 11 Multiple hotends arrangement

Issues Need To Be Addressed

Potential of FDM high temperature field is wide open. However, there are some issues to be addressed for the technology to be better accepted. Such as:

- Limited availability of high temperature filament material – This may be the function of demand and supply. When the demand of high temperature material increases, the supply should increase, according to the economic theory. It is a bottle neck, currently, nevertheless.
- Cost of material – This is, again, related the demand and supply economics. If the cost comes down for *super enpla*, then it could replace many of the metal part processes because of the easiness of manufacturing process.
- Lack of standardization – This may not be a big issue, but there is no "industry wide" standardization for the 3D printing industry. This may be because the field is in its infancy and so young, and it may take care by itself as the industry mature. It will be helpful to the industry progress and avoid confusions even such thing as terminology if some standard is established.

Future Development

We are looking at the future direction for the FDM 3D hotend in the following areas:

- Multi-nozzle (single unit assembly with multiple hotend nozzles, rather than the multiple single hotend assembly discussed previously) unit development – Single hotend process, especially for larger object printing, is time consuming. This would be beneficial for higher speed and multiple material processes.
- Development of line hotend (like thermal line print head) -- This has to be developed with the printer manufacturers, but the line hotend should speed up the process as it requires single pass for the layer rather than multiple printing process of single hotend.
- Material feeding method development – Currently, including our new hotend, depends on the filament type feeding method. It may be a little stretch and again it will require collaboration with the printer manufacturer, but it will be very useful if the material can be fed in the powder or granule form.
- There are many other possibilities, but we will leave up to the others to explore.

Conclusion

We have achieved our goal -- successfully designed, tested, verified and manufactured the high temperature capable hotends which can be used for Super Engineering Plastic (*Super Enpla)* with the temperature requirement of up to 500°C.

The uniquely structured hotend is truly industry-first and energy-efficient Eco-friendly, compact, small/light weight and intelligent control ready features will be helping the industry moving forward.

We are well aware of the fact that our revolutionary hotend, how wonderful it may be, is just a cog of a gigantic 3D industry wheel and we need to cooperate with the printer manufacturers, filament makers, material companies to improve the industry capabilities. Specifically, it is our hope that the FDM 3D printing industry will keep developing more filaments and supporting materials, the cost will come down and usage goes up.

References

[1] U.S. Patent # 7206009

[2] Nikkei Business Publication Additive manufacturing and 3D printing guide book (in Japanese) 2015, ISBN 978-4-8222-7637-9

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.