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Novel Method to Drive New High Temp FDM Hotend

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Abstract

In recent years, some FDM 3D printer manufacturing companies succeeded in going beyond hotend temperature of 400°C to take advantage of new highly durable materials known as "super engineering plastic". To accomplish the high temperature operation, the de facto industry standard is to employ the high-powered heater and liquid cooling system for their machines.

A new high temperature hotend was developed based on completely different concept has been developed which does not require conventional cooling system to achieve 500°C level temperature. However, it is almost at the high end of the FDM processing temperature limit and extreme care was taken to develop the compact, self-contained, and eco-friendly and heating-on-demand hotend. We had high hopes for the new hotend not only from the industry viewpoint, but also from contribution to minimize global warming.

However, we found a product life issue intermittently with the newly developed hotend. This report is on a novel approach to remedy the problem to extend the new hotend life longer, contributing to longevity of the high temperatures and stable operation with high reliability for 3D printing.

Background

The FDM 3D printer application came out about 3 decades ago. For the low temperature range material such as PCL which requires sub-100°C and mid-range materials like ABS, PLA etc, which are popular for the consumer applications will be adequate if the hotends can handle up to 250°C. Those hotends use heatsinks and some add fans to increase the air-cooling efficiency. However, new the industrial grade materials known as "super engineering plastic" such as PC, TPI and PEEK are becoming more popular and affordable, needs for high temperature capable hotends are getting greater.

The basic technology used for the high temperature hotend which can handle 400°C ~ 500°C range hotend is to use a large heater to raise temperature and large cooling system to lower it. The systems used today are mainly liquid cooled as the forced air is not capable of handling the large amount of heat reduction requirement.

The liquid cooling may be the prevailing way, but we thought it was very wasteful to operate. It is analogous to scooping out the water out of leaking boat with a basket. So, a hotend with a completely new concept was developed.

New Hotend Concept Review

The roots of the concept of new hotend for FDM 3D printer was the thermal printing and erasing technologies [1]. Essence of thermal printhead is resistive heating elements integrated on a ceramic motherboard forming a single assembled part. Although the requirement of thermal printing as well as thermal erasing is less than 200°C, the ceramic and heating resistive materials can handle much higher temperature, double, or even triple of the range. The heating elements can be turned on and off in the mSec order. The thermal erasing technology is lesser known than printing. Thermal rewritable media can be printed and erased when they are heated with different thermal profiles. Thermal erasing head was developed with basic principle as printhead – heating element on a ceramic motherboard. A major difference between two products was that heating process profile. Erasing does not require rapid on and off timing, but it needs to maintain rather tight temperature window of within +/- 10°C during the erasing process due to the rewritable media characteristics.

The idea of heating as needed or heating on demand of erasing head was carried over to the new hotend project. Unlike the prevailing hotend technology which uses a large heater and liquid cooling system, the new hotend utilizes the ceramic heater which can handle the temperature up to the near infrared (IR) range. Previous studies have been reported [2]&[3], but the quick summary about the new hotend characteristics is as follows:

1. Unlike most of the high temperature hotends which are powered by the discrete heaters (called in various names like tube, pipe, sheathed, cartridge -heater), the new hotend is heated with the integrated heating element on the ceramic substrate. The heating element is manufactured 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 (belt furnace) at an excess of 850°C.
2. The new hotend utilizes the resistive heating element which is designed for high temperature usage.
   - The resistive paste material for the heating element has a high positive temperature coefficient of resistance (TCR) of +0.15%/ ℃ ~ +0.33 %/ ℃. This means that when the temperature of the element goes up, so does the resistance value.
   - Since the TCR of the heating element is large, it will be less likely to be damaged by accidental excessive voltage applied or thermal runaway.
   - The current change is proportionally linear with the temperature change up to the high temperature range, the element temperature can be found by measuring the current.
   - The temperature measurement is not a spot like thermistor, but representative of whole heating area.
3. Because it was extremely high temperature application and very wide temperature swing, selection of material and manufacturing process were extra carefully to minimize distortion (immediate as well as latent), residual strain, and thermal fatigue.
4. The body of the hotend is made of a single titanium alloy piece. It was:
   - Less heat conductive compared with other metals.
   - Mechanically very strong.
   - Chosen in consideration of thermal coefficient of expansion compatibility with other materials.

- Considered to help the filament material to flow smoother and less prone for nozzle clogging.

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

Results of New Hotend Project

The results of the new hotend project were previously reported, but the summary is as follows:

- Critical temperature review was cleared as the major objective of the hotend was to operate at 500°C without external cooling system.
- The target material – super engineering plastic such as PEEK filament – was used for sample 3D printing successfully using our bench test printer.
- One of the major failures for higher temperature hotend products is filament material softening before reaching to the heating area and clogging it – phenomenon known as "heat creep". Due to the new design and structure of the hotend, no heat creep failure at high temperature operation is seen.
- Conductivity reduction slits worked well and temperature gradient from the heating section to the filament intake showed no need for large cooling system as seen on Figure 1. Even at high temperature, no sign of "heat creep" was found.

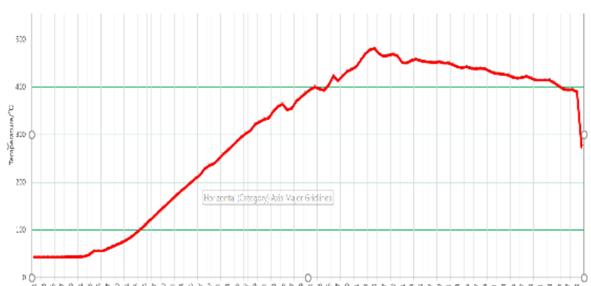

Figure 1
Temperature Distribution of New Hotend

- The goal for the new hotend project was to make a hotend that can handle the temperature range of 400°C~500°C without using a large heater to raise temperature and to lower it without using a large/cumbersome cooling system. The result shows that the goal was met.

New Challenge for New Hotend

The new hotend functioned well at a temperature range operation of 400°C~500°C in the development laboratory setup using the "super engineering plastic" materials such as PEEK filament. However, the product life turned out not to be consistent during the high temperature beta test. Some failed shorter time while others outlasted much longer. The failures did not seem to show the heating element resistance value increase symptom seen in the typical heating element thermal stress malfunctions.

Depending on the product and materials used to manufacture, the maximum usable temperature varies. The new hotend was designed to withstand up to 500°C and the materials to make up the product were selected and assembled for the product to survive the temperature range.

The big challenge for us was to solve the big mystery of why some units perform fine for a long time while others fail prematurely – it seems that there is no consistency in longevity of hotend product life.

Why Hotend Life Not Consistent?

Detailed failure analysis was conducted down to the ceramic motherboard level. It revealed that the major cause of the failure was due to the electrolytic corrosion around the power connecting pads on the ceramic motherboard. This caused the electrode metal to migrate into the resistive element material resulting the resistance value to go up to the point it cannot generate enough heat to melt the filament.

In general, it is true that any electronic product functional capability will degrade as the temperature goes up due to various reasons. It is because at the high temperature environment, various phenomena occur due to the materials change even their phases, their characteristics. In the electronic industry, not many parts exist which are designed for continuous operation at 500°C.

The reason why the failure did not happen to all units went through the test about the same time is because it is caused by the stray current which may be different from a unit to another unit at a higher temperature. The stray current will flow through the path of least resistance which may be different from unit to unit. An approximate analogy may be that lightning seldom strikes same way consistently.

Even if the product is made with the same materials and same process, variation of the product functional capability comes out at the extreme environmental conditions.

Failure Countermeasures

Since the main cause of failure was identified as the electrolytic corrosion and metal migration due to the stray current, the remedy to deal with the issue was studied from hardware and software aspects.

1. **Physical aspect (hardware) improvement:** The main reason why the stray current happens is the contamination during the manufacturing process. If the contamination is garden variety, then it does not cause ill-affect at a lower temperature. When the product is the higher temperature like 500°C, then it will react differently as the hotend material's phase temperature gets close. One way to alleviate the cause and make the hotend performance better.
2. **Non-physical aspect (driving method) improvement:** Since the electrolytic corrosion and metal migration occur in the direct current (DC) environment, the study was conducted using alternate current (AC) including non-sinusoidal alternating current. Since this is a part of the hotend application and usage, the study was mainly to suggest the different type of driving method which would avoid the failure caused by the driving methods.

Hardware Improvement

The concept of high temperature hotend operation without large heating element and heavy-duty cooling system such as liquid-based cooler was verified as previously reported [2].

However, there were some points considered and tested to improve the product life issue. One of the ideas described below turned out to contribute more to the hotend product capability beyond the current life issue. For example, the hotend process speed was limited by the energy delivered from the heating element. This idea will double the power handling capability although it was not addressing the immediate issue only.

The improvement point was as described below:

1. The conductive layer pattern on the ceramic motherboard was redesigned to minimize the voltage differential to adjacent conductive pattern.
2. Though the ceramic motherboard size was not changed, the heating element resistive area was maximized to reduce the load density. The modified ceramic board layout was shown on Figure 2B.
3. The motherboards were doubled up as shown on Figure 2C (increased single to double per side). In addition to the protective layer, an insulative protection board was added (Figure 2D) to minimize the effect of external strain, contamination, heating distortion to stabilize the operation.
4. The single piece hotend body structure including the material supply pipe was redesigned to reach high temperature with minimum power. The improved hotend body only (E) and in the assembled product (F) were shown on Figure 3.
5. Even though the motherboard number doubled, and the body structure was redesigned, the original hotend housing was able to accommodate the improved version of the hotend.

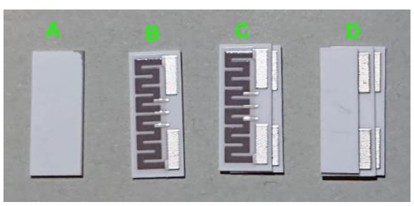

Figure 2 Modified Ceramic Board Layout

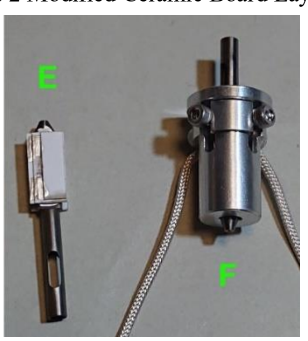

Figure 3 Improved Hotend Body and Completed Unit

Software (hotend driving method) Consideration

It is a generally known fact that electrolytic corrosion and metal migration occur in the direct current (DC) environment. Our hypothesis was that if the new hotend was powered by the alternate current (AC) source including non-sinusoidal alternating current, the failure due to the metal migration and electrolytic corrosion would not happen and the hotend product life would improve. Since this is a part of the hotend usage application and not a part of the product per se, the study was mainly conducted using a simple sinusoidal alternate current.

Hypothesis Verification Test

To verify the benefit of driving voltage source change from DC to AC, a benchmark comparison test was conducted. The test is to see the breaking point by maintain high and constant temperature without any control (ie. Constant DC and AC with no voltage or duty cycle adjustment). An extra thermocouple was added to each unit beside the usual temperature sensing scheme, which was to use the heating element current change as the resistance goes up due to the heating.

It is established empirically that the numerical difference between the heating element temperature sensed value and external thermocouple is about 20°C. So, the voltage was adjusted for both testing hotend unit's thermocouple's temperature at 480°C which is 500°C internally in the beginning of the testing.

Both tests were conducted without the filament fed through the hotend. This would be more stringent condition than the test with the filament running through the hotend as the filament would take the heat away from the hotend and would give the heat sinking effect in the actual operating situation.

1. DC powered unit

- Driving DC voltage was adjusted to produce 500°C and maintained through the testing process.
- Two sample units failed in less than 70 hours with continuous power-on as the resistance value changed drastically.

2. AC powered unit

- Driving AC voltage was adjusted to produce 500°Cand maintained through the testing process.
- Two samples logged 200 hours of continuous power-on with no ill-affect such as change of resistance value.
- The test was stopped after 200 hours as it clearly showed the benefit of AC power driving over DC power.

Since this is the initial test for hypotheses verification using a small quantity sample size, it is not a definitive conclusion. However, it is an indication that the AC power source will help the hotend product life magnitude longer even the AC power voltage was a fixed and no adjustment was made during the test period.

Ongoing Additional Tests

Although the initial verification test result was very favorable for an AC driving method, it did not give the limitation of the new hotend. Some more comprehensive tests have been planned.

One of such tests was known as a step-stress accelerated life test (SST for short) and it has been used widely in the thermal printhead and erasing head industry. It is to determine the limitation of the product by stressing the device to the point of destruction.

The SST test conditions for the new hotend were set to apply power starting from 500°C increase with 5% (25°C) increment every 30 minutes until the test samples unit fail showing such as symptoms as significant resistance or temperature change.

- The AC (regular sinusoidal alternate current) power was applied under the SST conditions to the first unit. The steps were continued until the hotend reached 700°C and the titanium hotend body started to glow red. The hotend did not fail, but the temperature was way beyond the designed level, so the test was terminated. The second unit showed the same result. Those units did not fail during the test and showed no degradation.
- Then the DC source was applied with the same procedures. The units started at 500°C and went up to 550°C, then failures started to occur, and the test stopped. The second unit failed the same way.

The result of SST clearly indicated that the AC driving condition was far superior to the DC condition.

However, the first SST conditions did not adequately force the hotend to the breakdown point and the product limitation was not found under AC condition. The second round of SST was started using the AC power only and the starting temperatures were set to 650°C and 700°C. The result should tell us the failure mode and comparison of product life.

Future Consideration

Despite some obvious advantages of the new hotend technology over the existing liquid cooling technology in the 3D FDM industry, there are some foreseeable issues which need to be dealt with if it usage is limited to the alternate current power source. Some of them can be:

1. Incompatibility with the existing power source, hotend driver circuits, and printer mechanism. The whole printer needs to be redesigned from the beginning.
2. Securing the AC power source with temperature control ability. Possible driving power source may be:
   - Stepdown transformer. The hotend driving voltage is much lower than the commercial power source, this will be the simplest way. The challenge will be that the driving voltage must be controlled according to the temperature.
   - Silicon-controlled rectifier (SCR) related device like thyristor or TRIAC. This will change the effective value of the AC power source rather than the voltage, but the safety issue must be dealt with.
   - AC/AC converter. To reduce the transformer size, convert the supply source frequency to much higher frequency level to use. It would add the complexity to the power supply/driver circuit.
   - DC/AC converter. If the DC power source needs to be used, something like what shown below can be used. This is just an example of potential circuit diagram.

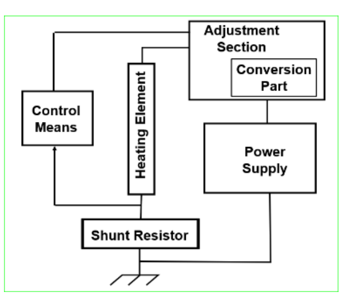

Figure 4 *Example of DC to non-sinusoidal AC Converter*

Conclusion

This report is about the continued study of a revolutionary new concept hotend for the high temperature use which can handle 500°C range. What has been different from the industry de facto product is that the hotend does not use a large heater to raise the temperature and a liquid cooling system to lower the temperature down. The new development and product ran into a foreseen problem of random premature failure of the hotend. The root cause of the failure was identified, and the remedial processes were put in place.

The main idea of countermeasure was to operate the hotend with the alternate current power source. Although the tests are continuing to verify the effectiveness and the merit at this writing, the data obtained so far indicates that it is very effective for improving the product life at a high temperature. The conclusive result should be coming out soon.

We are very optimistic about the future role of the new hotend as small size, light weight, energy-efficient, high-temperature compatible new hotend much more reliable with a long service life.

The concept was new and novel enough that an international patent was applied for [4]. Even if the application usage does not require high temperature operation, small in size, light weight, low energy consumption and prevention of unnecessary heating should be beneficial to all level of 3D printers and open a new possibility of easy multi-hotend applications.

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Author Biography

After retiring from the companies which 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 (currently a part of Arizona State University) in Phoenix, Arizona.