High Speed Sintering of New Materials

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April 2017

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# Table of Contents

Table of Figures .................................................................................................................................................. 3

Abstract .............................................................................................................................................................. 4

1.0 Introduction .................................................................................................................................................. 4

1.1 Overview of Additive Manufacturing .......................................................................................................... 5
1.2 Problem Statement ......................................................................................................................................... 7
1.3 Literature Survey .......................................................................................................................................... 8
1.4 Objectives .................................................................................................................................................. 10

2.0 Experimental Procedure .............................................................................................................................. 11

2.1 Machine Specifications and Setup ............................................................................................................... 12
  2.1.1 General Procedure for Printing Specimens ......................................................................................... 13
2.2 Temperature Study of HSS Machine ........................................................................................................... 15
2.3 Design of Experiment with NYLON 12 ....................................................................................................... 16
2.5 Design of Experiment for PMMA and PEEK ............................................................................................. 16

3.0 Results and Discussion .................................................................................................................................. 17

3.1 Temperature Study ..................................................................................................................................... 17
3.2 Nylon 12 Design of Experiment .................................................................................................................. 18
3.4 PMMA and PEEK Experiments .................................................................................................................. 19
3.5 Future Work ................................................................................................................................................. 23

4.0 Conclusion .................................................................................................................................................... 24

References ......................................................................................................................................................... 26
Table of Figures
Figure 1: Principle of High Speed Sintering ................................................................. 10
Figure 2: The HSS machine as viewed from above ....................................................... 13
Figure 3: Placement of temperature sensors for heat study ....................................... 15
Figure 4: Temperature study graph .............................................................................. 17
Figure 5: Nylon 12 Design of Experiment Results ..................................................... 18
Figure 6: Picture of PMMA samples ............................................................................... 20
Figure 7: Mass and sinter speed of PMMA samples .................................................... 20
Figure 8: Picture of PEEK samples ................................................................................ 22
Figure 9: Mass and sinter speed of PEEK samples ...................................................... 22
Figure 10: Tensile test and microscope sample ......................................................... 23
Figure 11: The next iteration of HSS machine ............................................................. 23
Abstract

Additive manufacturing, also called 3D printing, is a technology undergoing development which holds the potential for rapid and cheap production of complicated and exotic parts. Particularly, it is an excellent method of manufacturing when one wishes to minimize material wastage, and it can be used to produce geometries that would otherwise be difficult or impossible with conventional manufacturing techniques. One of the newest 3D printing technologies for thermoplastics is high speed sintering (HSS), which uses infrared light to sinter layers of thermoplastic powder coated in radiation-absorbent material with an ink-jet printer head. HSS is promising in that it has material requirements similar to that of selective laser sintering (SLS). Selective laser sintering is well established for many thermoplastics but is extremely expensive. Most thermoplastics have not been applied to HSS due to a lack of understanding of the science behind HSS. This research aims to investigate the relationship between ink-jet printed thermoplastic powders and infrared light in order to test the versatility of HSS. Three thermoplastic powders, including Nylon 12, Polymethylmethacrylate (PMMA), and Polyether ketone (PEEK), were used for the experiments. PMMA and PEEK samples of one layer were printed well below their recommended processing temperatures by existing publications; however, they were successfully sintered, indicating the viability of PMMA and PEEK with HSS.

1.0 Introduction

Given the unconventional nature of additive manufacturing, it is prudent to review modern literature on the subject to determine what has and hasn’t been done, especially in regards to the particular subject of interest in this research, which is HSS. An overview of additive manufacturing and the specific focus of this research preludes that literature review.
1.1 Overview of Additive Manufacturing

We live in a world where technology is advancing at an exponential rate. Inevitably, this means that the demands of society are evolving in a similar way. Manufacturing as an industry has been affected both by the new kinds of demands, as well as the speed at which these demands change. In order to keep up with the pace of modern industry, it is becoming necessary to speed up the design and manufacturing process. In today’s evolving world, demands of building parts in a less centralized manner are also growing. With traditional manufacturing techniques, however, it is cheapest to build many identical parts in a centralized location. Last but not least, end users want custom-built parts on a more frequent basis. Prosthetics, for instance, are built to fit their individual wearers, and therefore cannot be made inexpensively using traditional manufacturing techniques.

Three dimensional printing is a new manufacturing technique that has been in development since the 1980’s and has been growing in popularity in the last decade (Maxey, 2013). The process begins with the creation of a 3D model in CAD software. The 3D model is then transferred to a 3D printer where it is digitally deconstructed, or ‘sliced,’ into a large sum of tiny layers. Once this is done, the 3D printer lays physical material down, one layer at a time, until a complete three dimensional part is produced. Each layer usually has a thickness of about 100µm (Ellis, 2014).

Three dimensional printing addresses all of the aforementioned issues regarding modern industry. There is almost no waste material, it is remarkably easy to produce parts quickly, and building custom parts is a simple matter of altering the digital 3D model that is used by the 3D printer. With 3D printing, there is no need to fabricate molds or machine tools to manufacture products with. Parts made using 3D printing can also be stronger and lighter, since 3D printing enables the creation of complex geometries that are otherwise difficult or even impossible.
The simplicity of 3D printing technology also means that 3D printing has the potential to fill a local manufacturing model in which products are built on demand at the location where they are needed (3dprintingindustry.com). Perhaps the most extreme example is in space, where presently, ships and space stations can only have broken parts or systems replaced by a ship launched from Earth. Carrying a 3D printer in space would eliminate the need to carry redundant systems, and it would reduce the frequency of resupply missions from Earth. With fewer redundant systems, ships would be lighter, cheaper to launch, less expensive to maintain, and therefore easier to send on missions into deep space. Given all of these advantages, however, 3D printing is still limited in the known materials it can work with. Additionally, the 3D printing of products can sometimes result in poor mechanical properties and a bad surface finish. There is also a limit on the size of 3D printed parts, since they must be contained within the 3D printer while being constructed (Cornell).

Three of the most popular technologies are stereolithography (SLA), fusion deposition modeling (FDM), and selective laser sintering (SLS). Stereolithography starts with a vat of liquid resin. This liquid resin hardens into a solid when exposed to laser light. With a building platform positioned just beneath the liquid resin’s surface, a laser is used to harden the first layer onto the building platform. The platform is then lowered by a small increment, allowing the next layer to be made, and so on until the part is complete. Fusion deposition modeling begins with a spool of filament made from a thermoplastic. The filament is fed into a heated extrusion head, which then melts the filament and lays down the material layer by layer. In selective laser sintering, the base material is a powder, which can be made from a variety of substances. A roller distributes a thin layer of powder from a feed bed onto a building platform, and a laser is focused onto the powder to sinter the part’s first layer. The building platform is then lowered, the feed bed is raised, the roller rolls out another thin layer of powder, and the process is repeated until a completed part can be removed from the unsintered powder (3dprintingindustry.com).
While these methods are effective, there are certain challenges associated with them. Selective laser sintering is time-consuming since the laser beam has such a small contact area. Only certain polymers can be used with fusion deposition modeling and stereolithography. Parts made using stereolithography can become brittle over time, and adhesion between layers can be a challenge in fusion deposition modeling (3dprintingindustry.com).

HSS, a 3D printing technology similar to selective laser sintering, has been in development since its inception in 2003 (Ellis, 2014). It is similar to SLS in that it starts with layers of a powdered material. Instead of a laser, however, an infrared heat lamp is used in conjunction with a black ink-jet printer head to sinter the powder. Once a new layer of powder is rolled out, the printer head prints the geometry of a slice of the part onto the powder. The infrared lamp passes over the powder, and only the powder coated in ink absorbs enough energy to be sintered. HSS is promising in that it has material requirements similar to that of SLS, and it is significantly faster in generating a final product using thermoplastics (Ellis, 2014).

1.2 Problem Statement

Three dimensional printing in general has the potential to revolutionize and streamline many aspects of modern industry. Companies will be able to manufacture replacement parts without any concern for shipping logistics or waiting periods, and consumers in retail will be able to customize the products they purchase. Not only would HSS be faster at this than other 3D printing technologies, but it would be cheaper and more user-friendly as well. The lasers used in SLS are very expensive and dangerous if not used properly. An infrared lamp, on the other hand, is cheap and easy to use.

HSS would especially benefit the aerospace and medical fields. The aerospace industry is always looking for ways to more quickly and inexpensively manufacture lighter and stronger parts. As companies and nations extend their presence in space, faster 3D printing technologies will bolster the ability to have a
local manufacturing model in space, allowing more to be achieved with fewer resources. The medical industry will benefit from the ability to more quickly 3D print customized medical implants and prosthetics, which is especially appealing to the recipients of such implants, as it means they can receive them in a shorter time frame and at a lower cost. Currently, however, the list of materials that have been tested with HSS is very limited.

In this research, multiple thermoplastic powders with applications in the medical and aerospace fields will be selected and obtained to be 3D printed with HSS. By varying certain parameters of the HSS process, such as infrared lamp power, overhead and jacket temperatures of the build and feed beds, and stroke speed, it is expected that a combination of parameters can be found which produces dimensionally accurate specimens with mechanical properties similar to that of the same thermoplastic parts made with conventional manufacturing methods.

1.3 Literature Survey

Three dimensional printing first entered the scene in 1984 when Charles Hull invented a 3D printing process called stereolithography. The first 3D printing machine, a stereolithographic apparatus (SLA), was made in 1992, and was able to build objects out of a photopolymer. The photopolymer was the color and consistency of honey, and was solidified by a UV laser layer by layer to create a solid part. The year 1999 sees the first human organ made with the assistance of 3D printing. Young patients underwent urinary bladder augmentation using a 3D printed scaffold coated in their own cells. In 2006, selective laser sintering (SLS) becomes viable in manufacturing. This leads to the ability to print a wide range of materials, including various thermoplastics, elastomers, and metals (Maxey, 2013). SLS has become a popular choice when it comes to the ability to customize in manufacturing, and this research aims to further the investigation into HSS as a similar but faster means to manufacturing parts.
When it comes to the 3D printing of thermoplastics, much of the research in the topic of SLS involves exploring the mechanical and thermal properties of the polymer powder. Grain size and shape are input variables considered. The crystallization temperature ($T_c$) and melting temperature ($T_m$) are of critical importance. In order for the polymer to be successfully 3D printed with the SLS method, the material must have a crystallization temperature lower than the melting temperature. During the printing process, the ambient temperature in the 3D printing apparatus is kept at a temperature between these two temperatures. Any unsintered powder will remain in a solid state, while the powder which receives energy from the laser will melt. It is critical that the build temperature remain higher than the crystallization temperature until the printing process is complete. Otherwise, the unfinished part will solidify, shrink, and fail (Ellis et al, 2014). This applies to HSS as well as SLS.

The determination of crystallization and melting temperature can be achieved by way of differential scanning calorimetry (DSC). Yusoff et al. (2014) used DSC to discern thermal properties of five different polymers for use in SLS in order to help users create high quality parts with better finish quality. While this research will not aim specifically to achieve better surface finish quality, knowing the melting and crystallization temperatures is important for HSS of a thermoplastic to be successful.

Parameters of interest when investigating the viability of HSS with a particular thermoplastic are the sintering stroke speed, preheat stroke speed, infrared lamp power, and build/feed overhead and jacket temperatures (Ellis et al, 2014). In the HSS process, an ink-jet printer deposits radiation absorbing material (RAM) onto the powder’s surface based on the desired part geometry. The entire build surface is then irradiated by an infrared lamp. The build area coated in RAM absorbs significantly more energy than the area without and is sintered as a result (Ellis et al, 2014). Once the powder has been sintered, it must not cool down below its crystallization temperature, as this will result in thermal stresses and shrinkage, causing the part to fail. This is why it is critical for the crystallization temperature of the
thermoplastic powder to be lower than the melting temperature. Once one layer has been sintered, the process is repeated until the part is finished and can be removed from the unsintered powder. Figure 1 illustrates this process.

Three dimensional printing has been developed in both depth and breadth, in terms of varied methods and the understanding of those methods. As we improve our understanding of the science behind 3D printing processes such as HSS, we increase 3D printing’s competitiveness and viability in the market. Much of the research presently focuses on understanding the crystallization/melting temperatures, heat flow, and improving the mechanical properties of 3D printed parts.

1.4 Objectives
Thus far, only Nylon 12 has been tested with HSS. The goal of this research is to attempt HSS with PMMA and PEEK, two thermoplastics that have some unique differences from PA2200, or Nylon 12, which is a typical material for SLS and HSS. Since the machine used for this research has been continually in development during the course of this research, a secondary goal is establishing best practices for use of the machine with Nylon 12, and developing the machine in general. Since HSS has only been attempted with Nylon 12, and given that trials with Nylon 12 have been successful, the logical next step is to attempt HSS with other thermoplastics. In theory, PMMA might be the easiest material to print, since it has the lowest melting temperature, and it has no crystallization temperature. Without a crystallization temperature, the amount of shrinkage and warping experienced by any sintered material is less severe during a sudden change in temperature is experienced. Furthermore, one only needs to worry about the glass transition temperature (T_g), where the material transitions from being hard to...
being soft and rubbery. Not only would this be a potential advantage in commercial applications, but it is also of interest for this research, since the HSS machine used is open to the environment, greatly reducing the powder’s surface temperature. PEEK can be more of a challenge, since both its $T_m$ and $T_G$ are both more than 200°C above room temperature.

The long-term goal is to be able to reliably print enough layers consecutively so that tensile test specimens can be printed, from which the desired mechanical properties could be obtained. This data could then be compared with the corresponding data for the conventional bulk material for PMMA and PEEK. Since the machine used is a proof-of-concept prototype and is open to the environment, making multiple-layer samples is extremely difficult due to a large temperature gradient. Therefore, the scope of this research project is to show that PMMA and PEEK can be sintered in a single layer in a controlled manner using black pigmented ink and an infrared lamp.

<table>
<thead>
<tr>
<th></th>
<th>Melting Temperature (°C)</th>
<th>Crystallization Temperature (°C)</th>
<th>Glass Transition Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nylon 12</td>
<td>182</td>
<td>138</td>
<td>97</td>
</tr>
<tr>
<td>PMMA</td>
<td>180</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>PEEK</td>
<td>343</td>
<td>-</td>
<td>242</td>
</tr>
</tbody>
</table>

Table 1: Thermal properties for Nylon 12, PMMA, and PEEK

2.0 Experimental Procedure

This research ran parallel with the development of the HSS prototype machine used, and since it is the first machine of its type built from scratch with common parts and materials, it is prudent to discuss in some detail the operating principles regarding the machine. Then, the Design of Experiment (D.O.E.) conducted with the Nylon 12 will be covered, along with the procedures conducted for PMMA and PEEK.
2.1 Machine Specifications and Setup

The HSS machine is a collection of systems that work together in order to achieve the sintering of a thermoplastic powder of choice. These systems, listed below, are each composed of many components, most of which are available to the common consumer.

**Powder Bed**

- A square aluminum plate, 5x5 inches, 1/4 inch thick, with heating element attached to the bottom. Plate is mounted on a set-screw, which can be turned by an attached stepper motor to allow for precise z-movement. The plate and motor are enclosed by a wooden case on all sides but is exposed on the top.
- While running the machine, extra powder is kept in a metal container in a nearby oven at a desired temperature. This extra powder is momentarily removed from the oven each time a new layer needs to be added.

**Printing/Lamp System**

- An x-y plotter with stepper motors is used to control the movement of the ink cartridge and the infrared lamp.
- The infrared lamp is attached to the x-y plotter, and the ink cartridge is attached horizontally next to the lamp. This allows for the user to quickly transition between printing ink and running the IR lamp without extra steps or having to expose the ink cartridge or electronics to IR radiation.

**Electronics**

- A power source is used to power the stepper motors and the heating element in the build bed.
Several microcontrollers are used to direct the movement of the x-y plotter’s stepper motors, the z-movement of the build bed, and the deposition of the ink. The microcontrollers communicate with each other in order to keep the system synchronized. Programming for the ink deposition and stepper motor control was taken from open-source locations online and modified to meet the needs of this machine.

Figure 2: The HSS machine as viewed from above. The infrared lamp is seen in the bottom, with the print bed directly above it. The ink cartridge is to the print bed’s left.

2.1.1 General Procedure for Printing Specimens

Now with an understanding of the machine in place, this section will cover the general procedures followed when using the machine.
When printing with Nylon 12, the following steps were followed. Note that if only one layer is being printed, the oven is not used to heat up the extra powder or the rolling rod.

1) Begin pre-heating the powder bed, with a thin layer of powder (about 0.10 inches thick) in place. Monitor the powder’s surface temperature until it reaches a temperature of 140°C. This should take about 20-30 minutes. During this time, place the small container of extra powder in an oven at a temperature of 150°C. The metal roller that is used to roll new layers of powder onto the powder bed should also be placed in the oven. Monitor the extra powder’s temperature regularly, and stir it occasionally to keep the temperature even throughout. If the powder in the oven exceeds 150°C before the build bed is finished heating, lower the oven temperature or remove the extra powder from the oven until its temperature is 140°C.

2) Once the build bed’s powder reaches 140°C, printing can begin. Zero the position of the ink cartridge by pulling to the back/left corner of the x-y plotter, then press the switch labeled “ink switch.” This will trigger the machine to print the pre-determined ink pattern in the powder.

3) Once the ink is done printing, to prepare for the sintering stroke, slide the ink cartridge out of the way, and slide the assembly backwards until the infrared lamp is just clear of the powder bed. Now, the following steps should be done, in order, in immediate succession:
   a. Turn off the heating element. Note the timing of part “e.”
   b. Press the switch labeled “infrared lamp.”
   c. Turn on the infrared lamp.
   d. Turn off the lamp immediately as the sintering stroke completes.
   e. Turn the heating element back on 15 seconds after part “a” has been performed.

4) Lower the powder bed by pressing the “z-direction” switch.

5) Remove the extra powder and rolling rod from the oven, place a small amount of powder on the powder bed, and roll it carefully onto the existing powder.
6) To print additional layers, repeat steps 2 through 7.

The steps followed for PMMA and PEEK are essentially the same, but with different operating temperatures.

### 2.2 Temperature Study of HSS Prototype Machine

It was desirous to study how the powder temperature is affected during normal operation of the machine, particularly since the powder must be kept within a certain temperature range, and because the powder experiences a large temperature gradient caused by its exposure to the surrounding environment. To conduct such a temperature study, an RTD thermocouple was attached to the aluminum plate’s top surface, a thin layer of powder (0.069 inches) was placed on the plate, and an infrared gun was used to monitor the powder’s surface temperature. Since the heat is transferred to the powder through the plate, and the powder’s top surface is exposed to room-temperature air, these locations are assumed to be the hottest and coolest areas of the powder, respectively.

![Diagram showing RTD sensor and infrared gun placement](image)

Figure 3: The RTD sensor is placed on the aluminum plate to determine the temperature at the plate-powder interface. The IR gun is aimed at the powder’s surface to obtain the temperature of the powder-air interface.

Then, the normal procedure is followed as outlined in section 2.1.1, but without the deposition of ink or the addition of more powder. To expedite the process, an auxiliary 100 Watt infrared lamp is used to add heat energy to the powder’s surface. Once the powder’s surface temperature reaches about 140°C, sintering strokes of 5 seconds are performed repeatedly, with one minute separating each sintering...
stroke. Surface temperature readings are taken immediately before and after each sintering stroke. The auxiliary lamp is turned off only while the primary IR lamp is turned on. This is repeated about ten times.

2.3 Design of Experiment with Nylon 12 (PA2200)

Two process parameters, print speed and sinter speed, were selected to be varied so their effects could be observed on the printing of Nylon 12. Print speed is defined as the ink cartridge speed as it deposits ink onto the powder. A slower print speed will increase the ink concentration on the powder. Sinter speed is defined as the speed of the IR lamp as it passes over the powder during the sintering stroke. The table below, which also visualizes the 9 samples created in this process, gives the specific speeds tested.

<table>
<thead>
<tr>
<th>Sinter Speeds (mm/s)</th>
<th>Print Speeds (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>26.6</td>
</tr>
<tr>
<td>46.5</td>
<td>Sample 1</td>
</tr>
<tr>
<td>53.2</td>
<td>Sample 4</td>
</tr>
<tr>
<td>59.8</td>
<td>Sample 7</td>
</tr>
</tbody>
</table>

Table 2: Parameters Varied in Nylon 12’s Design of Experiment (D.O.E.)

Five trials of Sample 5 were printed, while one trial was printed for all of the other combinations. The steps followed for each sample are outlined in section 2.1.1, with two layers being created. The dimensions of the samples are 2.0x0.5 inches, with a layer thickness of 200µm.

2.5 Design of Experiment for PMMA and PEEK

PMMA and PEEK had similar experimental conditions conducted to the D.O.E. for Nylon 12, but less extensive. Only one printing speed (19.9 mm/s) was considered, while the sintering speed was varied. The table below details the sintering speeds tested with these two materials. Note that these materials were printed with a bed temperature of 50°C. This is due to a new heating system that had been installed in the HSS machine that did not perform as expected, and could not reach any temperature higher than 50°C.
<table>
<thead>
<tr>
<th>Material</th>
<th>Sintering Speeds (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMMA</td>
<td>46.5  19.9  13.3  26.6</td>
</tr>
<tr>
<td>PEEK</td>
<td>26.6  3.81  4.76  4.27</td>
</tr>
</tbody>
</table>

Table 3: Sintering speeds for PMMA and PEEK experiments; Temperature was 50°C, and print speed was 19.9 mm/s.

3.0 Results and Discussion

3.1 Temperature Study

As can be seen in the graph below, it took about 1500 seconds (25 minutes) for the heating system to reach equilibrium, with a surface temperature of 140°C and a plate temperature of 162°C.

Figure 4: Graph showing the plate temperature and the powder's surface temperature over time. The "spikes" seen towards the right correspond with sintering strokes each lasting 5 seconds, separated by 1 minute each.
3.2 Experimental Results for Nylon 12

The Nylon 12’s Design of Experiment was designed to observe how sintering speed and the ink cartridge’s speed affected the print samples. The top left sample in Figure 5 experienced the slowest sinter and ink speeds. Ink can be seen pooled around the edges of the top-left sample, while none of the other samples show this phenomenon. Slower ink speeds also resulted in powder being displaced on the surface prior to sintering. This indicates that more ink is not necessarily better. The level of heat absorption is sufficient for sintering, but the displacement of powder and pooling of ink can make the process quality difficult to control. All samples with faster lamp speeds appear to have some white coloration showing through the ink, while the samples with slower lamp speeds appear more black. This is a surprise, as coloration was expected to be more related to the ink cartridge speed, since a slower ink cartridge speed corresponds with a higher concentration of ink on the sample’s surface. This may indicate that lamp speed has a stronger effect on sintering than ink cartridge speed. Overall, this D.O.E. establishes a practical range of parameters, since all samples were successfully sintered without reaching the melting temperature.

![Image of samples](image-url)

Figure 5: Pictures of all 9 samples after sintering (Desired sample size = 50.8 mm by 12.7 mm)
3.4 PMMA and PEEK Experiments

Right before the PMMA and PEEK samples were printed, a new heating system had been installed on the HSS prototype machine. While the previous heating system could bring the plate temperature up to 160°C, the new heating system could only reach about 50°C. This meant that neither the PMMA nor PEEK powder could be held near their melting temperatures during printing, even though PMMA has a lower melting temperature than Nylon 12. As such, the PMMA samples and especially the PEEK samples were expected to experience severe warping and shrinkage immediately after being sintered.

Surprisingly, the PMMA samples encountered no warping or shrinkage visible to the naked eye. This may be due to the molecular structure of PMMA compared to Nylon 12, as PMMA is more of an amorphous material with Nylon 12 being semi-crystalline. When a semi-crystalline polymer is heated to near-melting temperature, the crystalline structures unravel, increasing the volume of the material. Cooling the material necessarily reverses the effect, re-crystallizing the polymer chains and reducing the overall volume. Another quality of the PMMA is how weak and brittle it is. Simple handling the samples and trying to dust off excess powder caked around the sintered area would result in a broken sample. It is possible that little to no actual sintering occurred with the given sintering times. If this is the case, it is likely due to not increasing the sinter time enough to compensate for great the difference between the powder’s melting temperature and its actual temperature in the experiment. A lack of complete sintering could also explain the lack of shrinkage and warping, since in order for such deformation to occur, the powder would have to be sufficiently heated in the first place to where the molecular structure of the powder becomes significantly more voluminous.

Figure 6 shows the PMMA print samples in descending order, and Figure 7 shows the relationship between sintering times and the weighted mass of each sample post-sintering. The mass of the samples appears to be inversely proportional to their sintering speeds. This matches expectations, since a slower
sintering speed results in a longer sinter time, which then results in more heat energy transferred to the powder. This essentially deepens the powder’s heat-affected-zone, which subsequently increases the layer thickness. Due to their fragile nature, the white powder caked around the edges and bottom of the samples was not removed. Additionally, sample 1 is not included in the mass measurement, since much of its mass was lost due to breakage. Sample 1, which is seen already broken into two smaller pieces, appears to be minimally sintered.

The PEEK samples prove to be much stronger and more flexible than the PMMA samples. Not only could the excess powder be removed quite aggressively from the sample, but one could pull on both ends of any of the samples, or bend them 180° around a tight radius, and they would not break or tear. This
strength and flexibility lends itself to the excellent mechanical properties of PEEK, and shows promise that structurally critical components made from PEEK could be printed using HSS. Visually, cracks can be seen in the ink pattern of samples 1 and 2, indicating that the surface of the samples cooled much more quickly than the sintered powder directly beneath the surface.

Unlike the PMMA samples, the PEEK samples experienced significant shrinkage and warping, as seen in figure 8. All of the samples curled upwards, indicating much more rapid cooling on the top of the samples than on the bottom. Like PMMA, PEEK is an amorphous polymer, and might not be expected to experience much deformation. The jump in temperature due to sintering, however, is much greater with the PEEK samples than with the PMMA, which may lead to higher thermal stresses immediately after sintering. As such, it is reasonable to assume that deformation due to temperature change would be insignificant if the PEEK powder were kept much closer to its melting temperature during operation.

The sintering speeds required to sinter the PEEK samples is about 20% that of the PMMA’s sintering speeds. This is not believed to be due to any difference in material properties, but rather is due to the large difference each powder’s melting temperature. Both the PMMA and PEEK were tested with a bed temperature of 50°C, but while PMMA’s melting temperature is only 110°C higher at 160°C, PEEK’s melting temperature is about 290°C higher than the bed temperature, at 343°C. This difference is about 260% of PMMA’s temperature difference, which, given the same material properties, would mean the PEEK’s sintering speed would need to be about 38% as fast as the PMMA’s sintering speed. In addition to the need for more heat energy to reach sintering temperatures, it is reasonable to assume that the powder’s exposure to the environment results in substantially greater heat loss, which must also be overcome in order to achieve sintering. Unlike the PMMA samples, the PEEK samples don’t appear to show any correlation between sample mass and sintering speed.
In Figure 9, the PEEK sample mass appears to have no correlation with sintering speed. This may be due to a lack of consistency in powder removal from the samples. Additionally, it is possible that the high temperature gradient resulted in thermal behavior that varied from one sample to the next. Finally, it is possible that the powder in some of the samples might not have been given enough time to heat up to 50°C, thereby reducing the amount of sintering that occurs with similar sintering speeds. This matches the course of events, as the first sample’s powder was given several minutes to reach temperature, while subsequent powder was not given as much time. This is unlikely, since the surface powder of the temperature was always recorded to be within two degrees of 50°C, and such an occurrence would indicate inaccuracy of the IR gun used.

Figure 8: PEEK samples in descending order. A defect due to an ink-printing error is seen on the top left corner of sample 1. The two top samples, which experienced the slowest sinter speed, show signs of shrinkage with white cracks in the ink pattern.

Figure 9: PEEK samples, showing little relation between mass in grams and sinter speed in mm/sec.
3.5 Future Work

This research has established a feasible range of operational parameters for Nylon 12 (PA2200) with this particular HSS prototype machine, and has shown that HSS can be performed with alternative materials such as PMMA and PEEK. The next step would be to create specimens that could have their mechanical properties evaluated and compared to conventionally produced specimens of the same material. These larger samples could then also be examined under optical or electron microscope to evaluate porosity and other internal properties. In order to match mechanical performance with print quality, test specimens could be printed with an extra segment that could then be cut off and examined under a microscope, as illustrated in Figure 10.

With some practice and procedure refinement, it might be possible to print test specimens from PMMA or PA2200 with the machine used for this research. PEEK specimens are entirely unrealistic with the open build bed, since it would have to be held at a temperature about 300°C higher than room temperature. A new HSS machine is currently being planned at WSU Vancouver, and is planned to include automation of all steps, as well as an enclosure to allow for better temperature control.

![Figure 10: A single printed specimen can be cut into a tensile specimen and a microscope specimen.](image)

![Figure 11: The next iteration of HSS machine planned at WSU Vancouver.](image)
4.0 Conclusion

Additive manufacturing, or 3D printing, gives users options that are either unavailable or much more expensive with conventional manufacturing methods. Complex geometries can be created, customization is inexpensive, and material waste is low. Of the many 3D printing methods available in the market, Selective Laser Sintering (SLS) is a popular choice for creating components intended for use in a final product. HSS is a method similar to SLS, but instead of using a laser to sinter the powder, carbon black ink and an infrared lamp are used.

Since only semi-crystalline Nylon 12 has been tested with HSS, the amorphous thermoplastics PMMA and PEEK were chosen to be tested with this new 3D printing method. Nylon 12 was also tested with varied sintering speeds and ink printing speeds to determine ideal parameters for printing.

Results show that more ink is not necessarily better. If the ink concentration is too high on the powder’s surface, the ink can pool, powder can be displaced, and the pattern can be made uneven. This can make controlling layer thickness and print quality difficult.

Before the PMMA and PEEK powder was tested, a new heating system was installed on the HSS machine, which proved to perform poorly, as it only heated the powder bed up to 50°C. This made printing any multi-layer samples impossible due to the near-instant cooling and subsequent shrinkage experienced by any sintered powder. Single layer samples, however, were produced successfully by lengthening the sintering time to account for the lower temperature. PEEK especially needed to have increased sintering time, since its melting temperature is 343°C, but it is suspected that its sintering time would be similar to that of PA2200 if a powder temperature above 300°C could be maintained.

The PMMA samples experienced no shrinkage, but were extremely brittle and weak. The PEEK samples experienced shrinkage and warping in the form of bowing upward as they cooled to room temperature.
The PEEK samples were also much more tough and resilient than the PMMA samples, as the samples could be pulled on from both ends, twisted, and bent up to 180°, and still return to their original shape.

The mass of the PMMA samples are inversely proportional to the sintering speed, while the PEEK samples don’t seem to show any correlation between mass and sintering speed. This may be due to inconsistency in powder removal, poor temperature control, or varied powder temperature prior to sintering.

The results show that PMMA and PEEK are viable candidates for HSS. Future work should involve creating specimens that can have mechanical properties matched against the same materials made through conventional means. This will require an enclosed system with more automation, which is currently being designed and built at WSU Vancouver.
References


