3D Printed Electronics for Printed Circuit Structures

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Abstract

Printed electronics is a familiar term that is taking on more meaning as the technology matures. Flexible electronics is sometimes referred to as a subset of this and the printing approach is one of the enabling factors for roll to roll processes. Printed electronics is improving in performance and has many applications that compete directly with printed circuit boards. The advantage of roll to roll is the speed of manufacturing, the large areas possible, and a reduction in costs. As this technology continues to mature, it is also merging with the high profile 3D printing. 3D printing is becoming more than just a rapid prototyping tool and more than just printing small plastic toys. Companies are embracing 3D printing as a manufacturing approach to fabricate complex parts that cannot be done using traditional manufacturing techniques. The combination of 3D printing and printed electronics has the potential to make novel products and more specifically making objects electrically functional. Electrically functional objects have the advantage of competing with printed circuit boards. Printed circuit structures will be a new approach to electronic packaging. It is the desire of many companies to reduce assembly processes, decrease the size of the electronics, and do this at a reduced cost. This is challenging, but the potential of printing the structure and the electronics as a single monolithic unit has many advantages. This will reduce the human touch in assembly, as the electronics and the object are printed. This will increase the ruggedness of the product, as it is a monolithic device. This will eliminate wires, solder, and connectors, making the device smaller. This has the potential to be the future of printed circuit boards and microelectronic packaging. This paper will show working demonstrations of printed circuit structures, the obstacles, and the potential future of 3D printed electronics.

Introduction

While 3D printing, as stereolithography (SLA), has been around since the early 1980s, it is has evolved considerably into many forms. For the purposes of this paper, fused filament deposition (FFD) also known as fused deposition modeling (FDM) will be considered. Only recently has FDM printing been joined by electronic printing to create 3D printed electronics. With this evolution in 3D printing, Printed Circuit Structures (PCS) can possess distinct advantages over Printed Circuit Boards (PCB). Many components that are present on a PCB can be integrated into a PCS. It has been shown that PCSs can contain fully embedded circuity such as antennas [1][2], lumped components [3], and even connectors [4]. Instead of creating a PCB to attach to an object, it would be possible to print the object with the circuitry as an integrated part of it. This printing method is made possible using a Direct Digital Manufacturing (DDM) machine which combines the use of multiple tool heads including a micro-dispensing pump, a heated extrusion head, a pick-and-place head, and a micro-milling, drilling, and polishing head. While PCBs require the use of many machines and require masking, PCSs can be completely automated as total fabrication is done in-situ on a single machine [5][6]. Although PCSs do have advantages, there are still several obstacles to overcome, namely speed of fabrication and strength of final parts.

Fabrication Speeds

FDM style 3D printing is notorious for being slow. This is mainly due to the low volumetric extrusion rates of conventional desktop 3D printers. There are many factors that determine extrusion rate. Some of these include nozzle diameter, nozzle temperature, bed temperature, X-Y movement speed, material, and even the extrusion motor. While all of these have an effect on the total amount of filament being extruded, the nozzle diameter is the main determiner of extrusion rate. Layer height, extrusion widths, and print speeds are all based on the nozzle diameter, therefore this is the facet of the printing process that stands to generate the most benefits from improving. The standard printing nozzle has a 0.4mm inside diameter. This allows for print speeds of up to 80-100 mm/s, depending on machine and desired print quality. Nozzle size can be increased, however, while this can shorten the overall print time, a decrease in quality will be seen. These decreases in quality can be things such as a rougher surface finish, rounded corners, and incorrect dimensions. Larger diameter nozzles are also limited when printing small objects as the small features can be problematic. While the quality-related downsides of selecting a large diameter nozzle are not attractive, they can be dealt with. A method of printing called “Spaghetti” printing was developed to greatly increase extrusion rates and decrease print times. This process involves printing filament out of a specially designed 1.75mm nozzle and then utilizing a milling head to give a high-quality surface finish where required as well as bringing the print into dimension. A speed experiment was set up comparing the printing speed of an ASTM D638 Type V tensile specimen printed using a 0.4mm nozzle and the “Spaghetti” printing approach. Two types of tensile specimens were printed; one with a 0° infill and one with a 90° infill from the horizontal. These samples were printed with no perimeters as this would throw off tensile testing.

Both of these sample types are 1.0 mm thick and were printed with a nozzle temperature of 235° C and a bed temperature of 50° C. The perimeters seen in **Figure 1** and **Figure 2** are used to show dimensions.

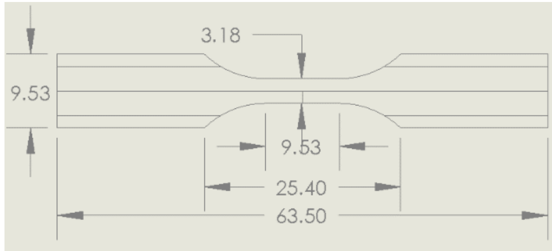

Figure 1: ASTM D638 Type V Tensile Specimen 0° Infill

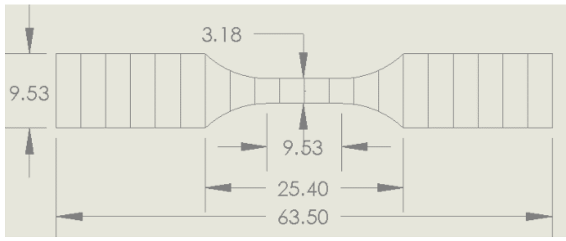

Figure 2: ASTM D638 Type V Tensile Specimen 90° Infill

When printed with the 0.4 mm nozzle, each tensile specimen completed printing in 4 minutes and 24 seconds. When done with the Spaghetti method, each tensile specimen averaged 1 minute and 58 seconds total time with the actual 3D printing portion only taking 32 seconds. This experiment was repeated 25 times. Not only did the "Spaghetti" method complete the object more than twice as fast, the final surface finish from milling was far superior to that of the conventionally printed specimen.


Figure 3: Spaghetti Printed Tensile Specimen Before and After Milling

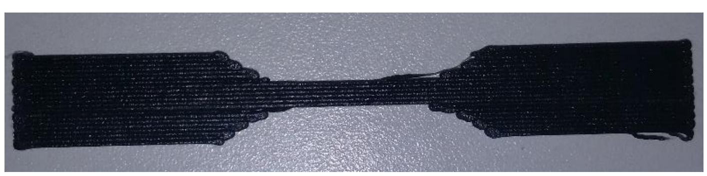
Figure 4: 0° Printed Tensile Specimen Using 0.4mm Nozzle

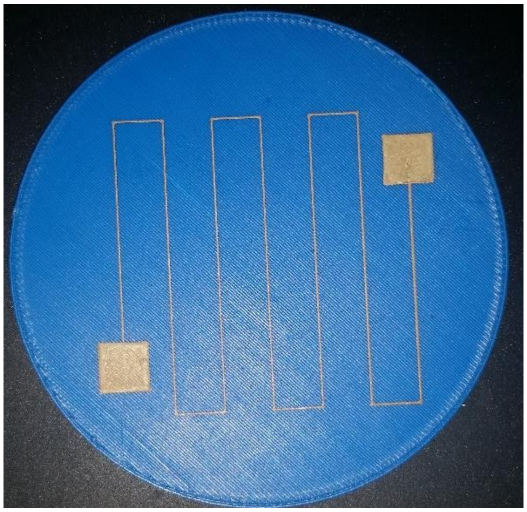

Figure 5: Micro-Dispensed Conductive Paste on 3D Printed Substrate

This benefits PCS greatly as printing the electronics portions requires a smooth surface for conductive material to be dispensed. Normally, for a conductive print to be successful, the FDM substrate layer needs to be printed with a nozzle as small as 100 microns to provide a smooth surface for the conductive material to be printed accurately and true to design. Although surface mapping is available, which enables contour printing, a smooth surface is preferred. This also provides an ideal surface when printing multiple thermoplastics onto one another.

Figure 6: Steps of a Printed USB Device

The smooth surface enabled the level placement of a USB chip using pick-and-place. Then conductive paste was dispensed to extend the pads of the USB from the chip. Next, a polycarbonate shell was printed around the perimeter of the circular portion to form a cup for an epoxy to be dispensed. Once cured, the epoxy was milled smooth. This is a small demonstration of multi-material, multi-process in-situ PCS fabrication.

Strength of Printed Parts

Printable fused filaments range from somewhat durable materials such as acrylonitrile butadiene styrene (ABS) to flexible thermoplastic elastomers (TPE) and even FST-rated ULTEM. These materials have their own strengths and weaknesses. Whether it is the high impact strength of ABS or the chemical and temperature stability of ULTEM, choosing the right material for a particular application can determine whether or not it is successful. However, FDM printed parts fall well short of the strengths of other fabrication methods such as injection molding [7]. This is due to the fact that the strength of 3D printed parts rely on layer-to-layer surface adhesion, adhesion of side-by-side printed lines, and print direction as well as the mechanical properties of the material itself. Another aspect of 3D printing that decreases overall strength of printed parts compared to bulk material properties is the presence of voids that are introduced into the part during the printing process.

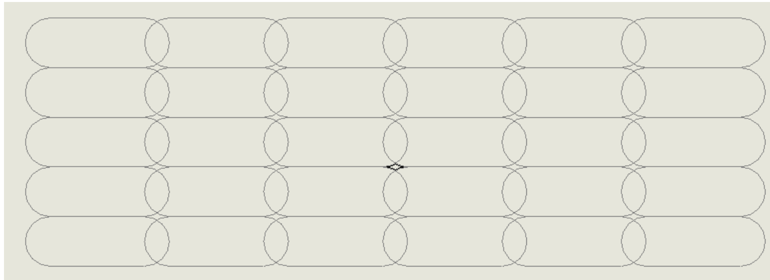

Figure 7: Cross Section View of Printed Layers with a 0.4mm Nozzle

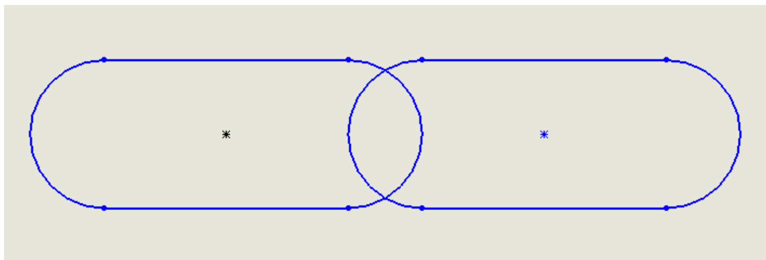

Figure 8: Cross Section View of "Spaghetti" Printed Layers

In both of these examples (**Figure 7** and **Figure 8**), voids can be observed wherever there is an overlap of side-by-side lines. This is due to the fact that the edges of printed lines are rounded. To combat voids, an overlap factor can be input into the generation of the print path of the object. This will squeeze the lines closer together, minimizing voids, to an extent. When a high overlap factor is specified, the material being squeezed together must go somewhere and thus it is displaced upwards. This will create a rough surface finish if on the top layer and could throw off overall height dimensions if allowed to compound throughout the print. When printed with the 0.4mm nozzle, many, albeit smaller, voids are introduced into the object. While the few voids that are present with the Spaghetti printed layer are larger, the total void area of the parts printed with the 0.4mm nozzle is greater. These voids contribute to the ~10% difference in ultimate tensile strength for the printed specimens (**Figure 9**).

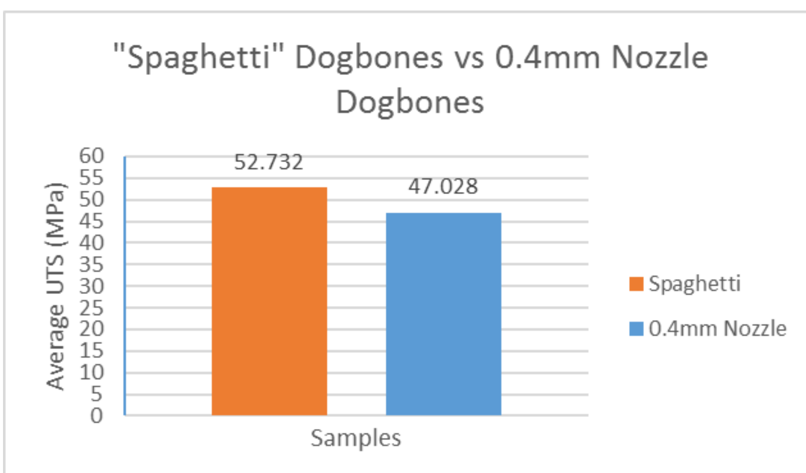

Figure 9: UTS Comparison of "Spaghetti" and 0.4mm Nozzle Tensile Specimens

The print direction plays a major role in the strength of printed parts [7][8]. It is common practice when printing structural parts to have layers printed in the direction of force that the final part will experience. To exemplify why printing in the direction of force is important, tensile specimens were printed in the direction of force (0° specimens) and perpendicular to the direction of force (90° specimens). The 0° specimens failed at an average of 47.028 MPa UTS while the 90° specimens failed at a much lower force of 13.572 MPa, a ~72% loss of strength. The difference in observed UTS is drastic and shows the effect that print direction has on strength. This difference is again due to the fact that since the direction of force is perpendicular to the 90° specimen's print direction, the adhesion between lines is the only thing providing resistance rather than the material itself.

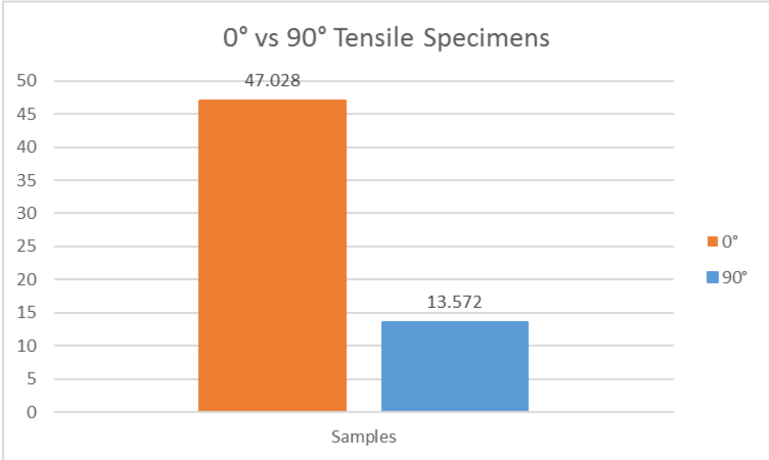

Figure 10: UTS of 0° and 90° Tensile Specimens

Ideally, there would be strength in every direction as there can be multiple directions of force in certain applications. It is common in 3D printing to not print 0° or 90° infills, but rather to print 45° as this would provide strength in multiple directions [7][8]. However, this is a compromise as this decreases the overall tensile strength when compared to printing solely in the direction of force. Furthermore, if the direction of force is in the Z-direction, the same problem arises because layer adhesion is the predominant factor in determining how much force a part can be subjected to before failure. Since layer and side-by-side line adhesion are aspects of 3D printing, there needs to be a way to increase the force they can sustain. To do this, a "reflow" experiment was performed. The approach was to use a temperature-controlled laser to heat and essentially "reflow" the already-printed plastic. A 30W laser was mounted on the machine and was placed just above the 90° tensile part. Using a non-contact thermometer, the temperature of the plastic part was elevated and held to 120° C while the laser traveled across the surface of the specimen. The laser completed three passes over the middle section of the part, reflowing the plastic and increasing the adhesion between layers.

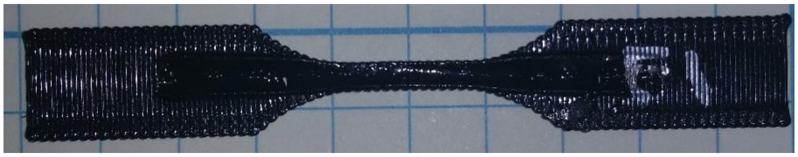
Figure 11: Laser "Reflowed" Tensile Part

Tensile testing these "reflowed" samples yielded an average 21.574 MPa UTS compared to the untreated samples' average 13.572 MPa UTS, a 58% increase.

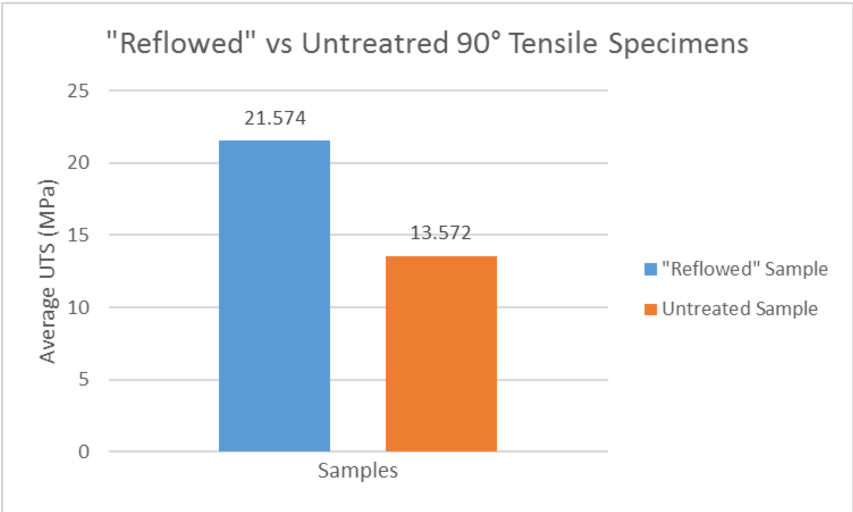

Figure 12: Average UTS of "Reflowed" and Untreated 90° Tensile Parts

While the strength increase is much improved, it is still below the UTS of parts with infill printed in the direction of force. This is important because it can enable the printing of stronger parts that exhibit force in multiple directions. While this was performed to essentially increase side-by-side line adhesion, it could also be applied to layer adhesion. By placing the laser in front of the printing head, the previous layer of deposited material would be reheated while simultaneously being printed on top of, creating a more solid part. This will increase layer adhesion with the added benefit of possibly removing voids, resulting in a stronger overall part; this is for future work.

Conclusion

PCBs today are optimized and ubiquitous. They can be mass produced, created relatively quickly, and are a proven, reliable product. They do have their limitations, though. They are process intensive, one-offs are not necessarily economical, and they produce a lot of waste, which creates extra expense to manufacture in the U.S. Printed circuit structures are the evolution of the PCB and 3D printing industries. They have several distinct advantages over PCB in that they greatly reduce process steps, one-offs and customization are easy because of the DDM process, and since they are primarily additive, there is very little waste. However, there are still some obstacles present. PCS as it is today would struggle with large volumes because the speeds are not yet there. Strength of fabricated parts is another obstacle in the way of PCS. 3D printed parts are not as strong as bulk properties, so consideration must be taken into the design of the PCS. Using the methods described in this paper, these two issues were addressed and improvements have been made. A more than 2x speed increase was realized through the use of “Spaghetti” printing which also yielded a stronger, smoother part. Another method of increasing strength utilized a laser to reflow already printed plastic creating better line-by-line and layer adhesion. Combining these methods, stronger, more durable printed circuit structures can be fabricated much faster.

References

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TECHNOLOGY'S TURNING POINT

TURN ELECTRONICS MANUFACTURING INSPIRATION INTO INNOVATION

Printed Circuit Structures

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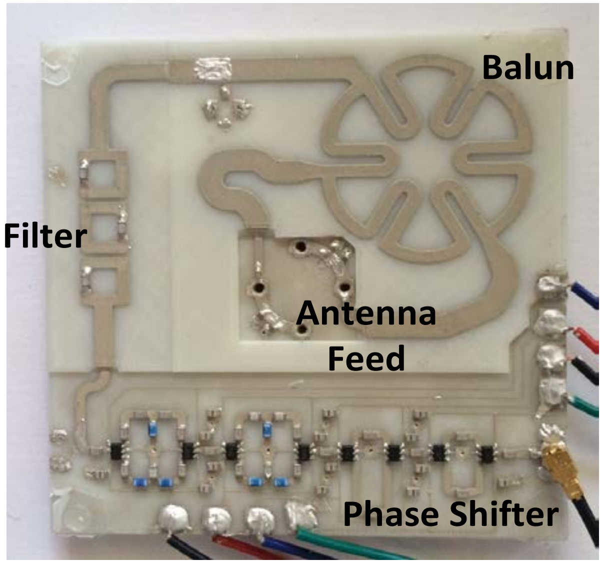
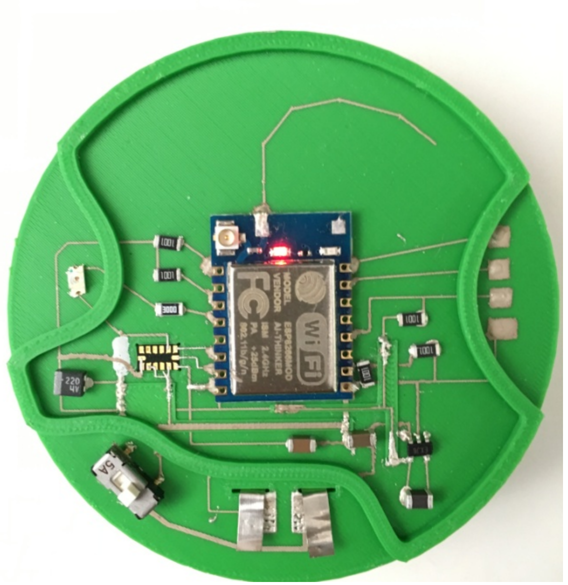
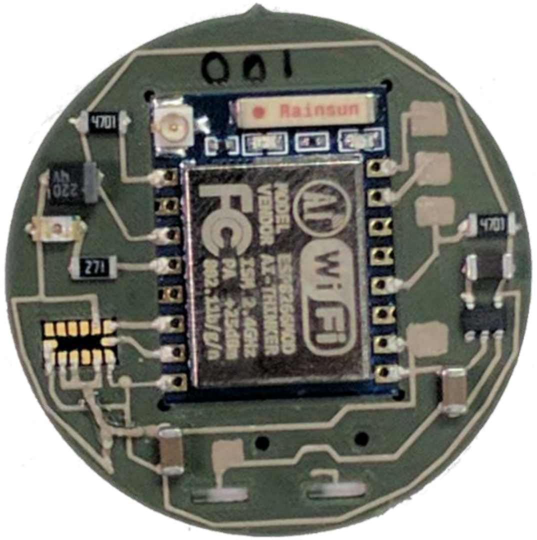
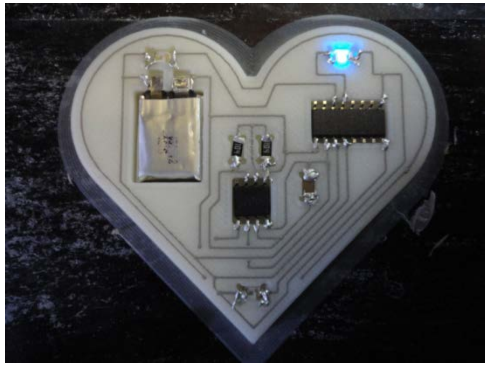
What is PCS

- Printed Circuit Structures (PCS)
  - *Take PCB to the 3rd dimension*
  - *Combine 3D Printing and Electronic Printing*
  - *Any shape, customizable, personalized*

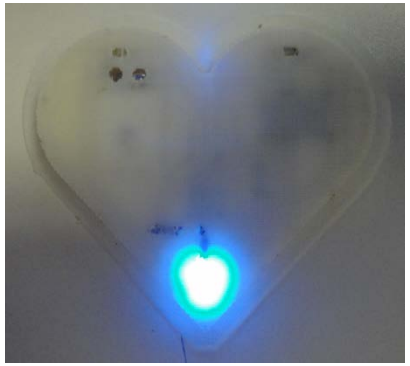




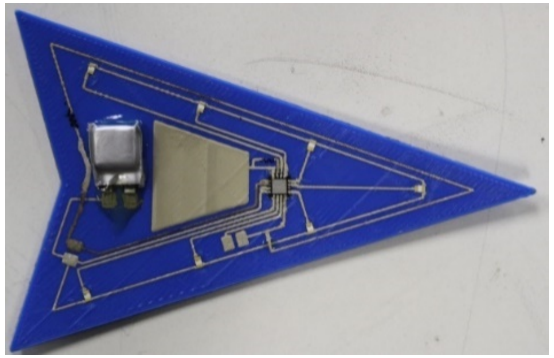




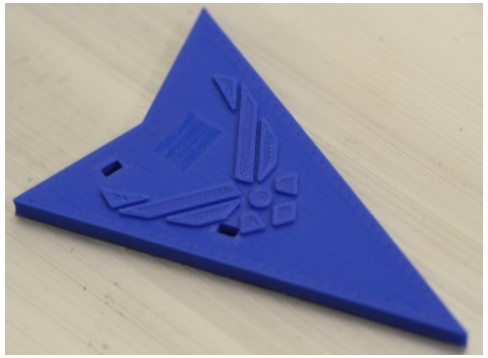
Timing circuit heart



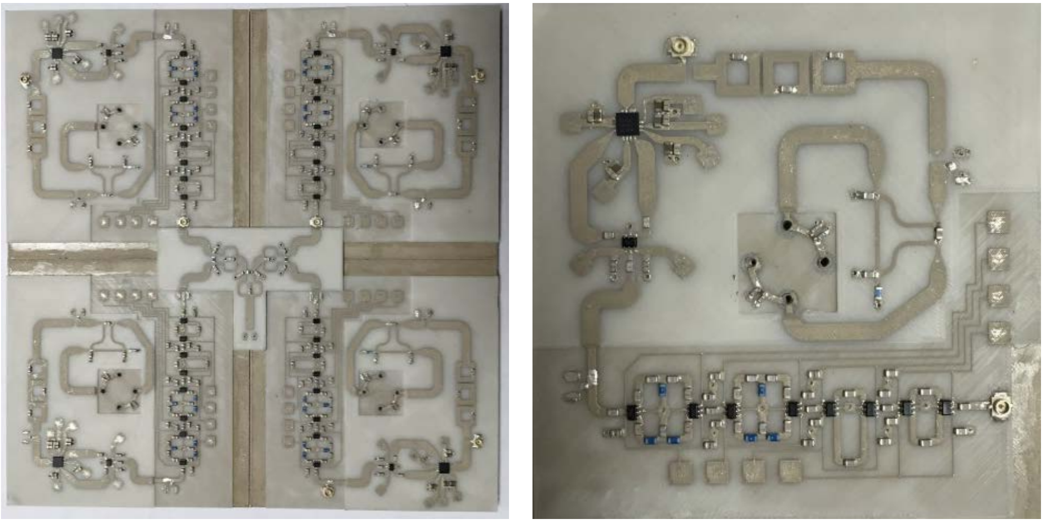
Embedded timing circuit heart



Micro-controller



Embedded micro-controller



4 Element Phased Array Antenna

Progression of Embedded USB Device

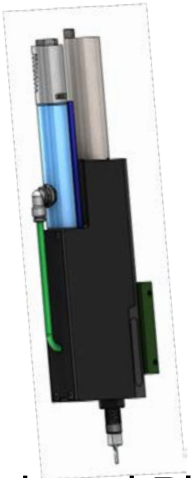
PCS – How it is done

- Micro-dispensing Head
- 3D-Printing Head
- Milling Head
- Pick and Place Head
- Direct Digital

Dispense

3D-Print

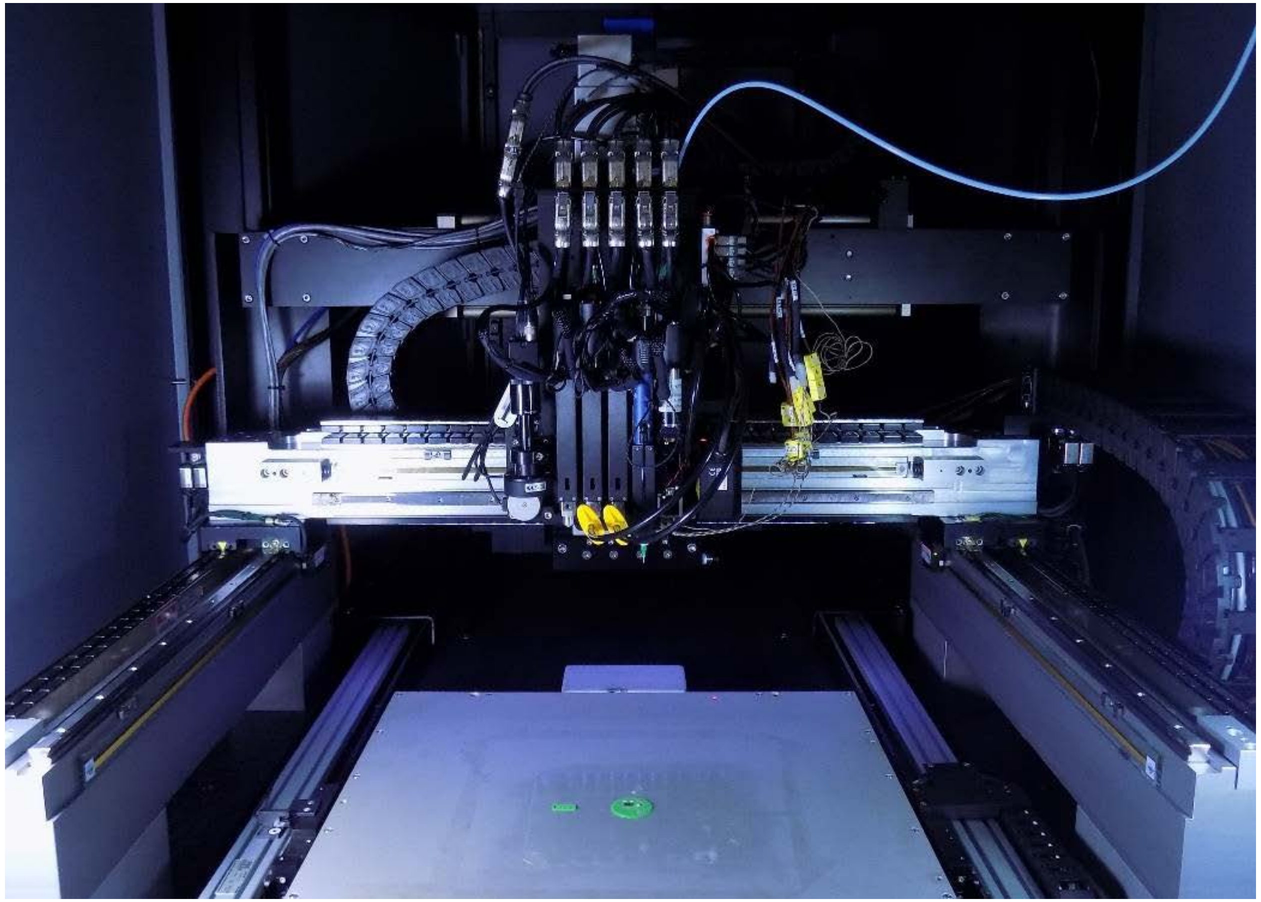
Mill



Pick and Place

Gantry Configuration

- Tool plate allows multiple heads
- Everything In-Situ
  - Printing
  - Dispensing
  - Milling
  - Pick and Place
  - Curing



Electronic Printing

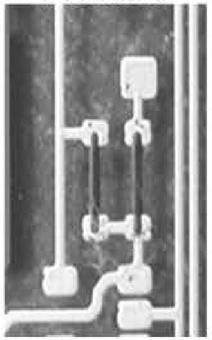
- Material choice
  - *Conductives*
  - *Dielectrics*
  - *Epoxies*
  - *Adhesives*
  - *Solders*

- Conformal printing
- High-resolution
  - *25µm to 3mm+*

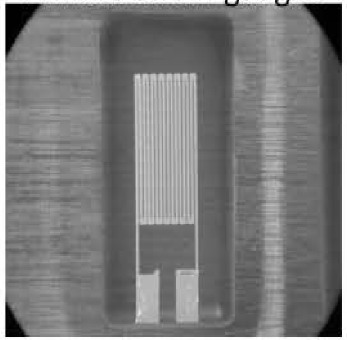
Antenna on UAV

Interconnects on bare die

Resistors

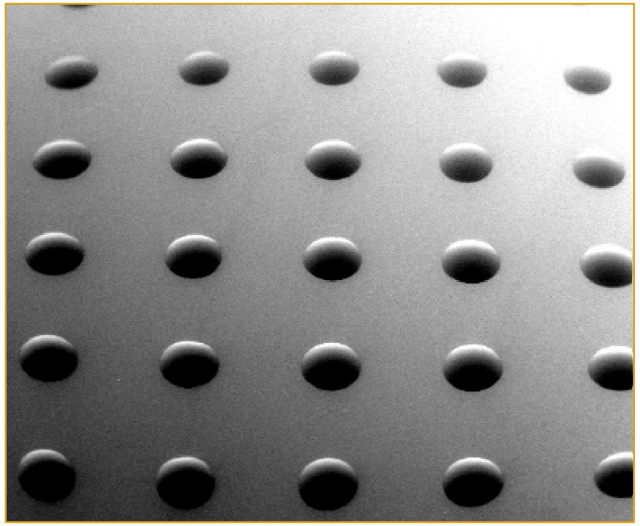


Printed strain gauges

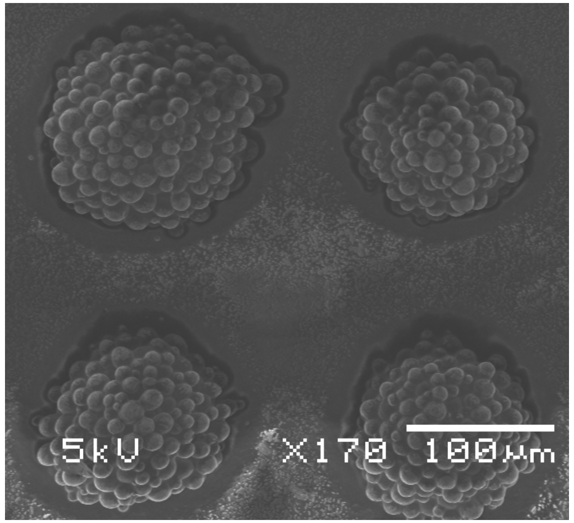


Lattices

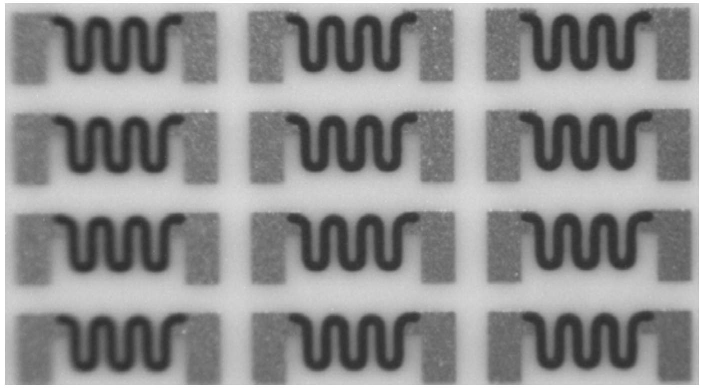
RF strip guides



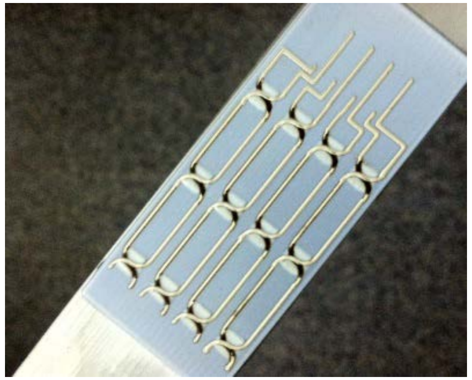
75µm Adhesive Dots



100µm Solder Dots



Resistives



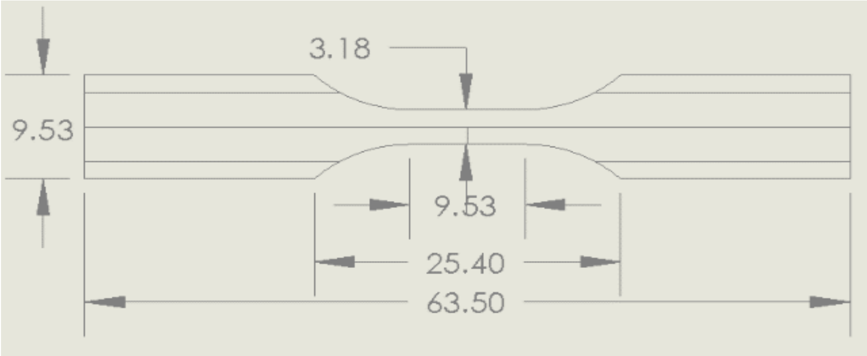
Ceramic and Conductive Multi-Layer

3D Printing

- Fused Filament Deposition (FFD)
  - *Extruding thermoplastic*
- Up to 400° C
  - *Enables higher temperature filaments – Polyetheretherketon (PEEK) and Poleyetherimide (PEI)*
- Interchangeable nozzles
  - *12.5µm to 1.75mm*

Direct Digital Manufacturing

- G-Code
  - *3D Print object*
  - *Dispense*
  - *Mill*
  - *Pick and Place*
- Customization
- Personalization



Advantages

- In-situ fabrication
  - *Reduced labor costs*
  - *Reduced time*
  - *Reduced process steps*
- Embedded Electronics
  - *Rugged, increases durability*
- Weight Reduction
- More efficient use of space, no wires, connectors

Limitations

- 3D printing (FDM) is notoriously slow
  - *Higher the resolution, more time it takes*
- Printed parts cannot match the strengths of injection molding
- Material selection

Improvements

Spaghetti Printing

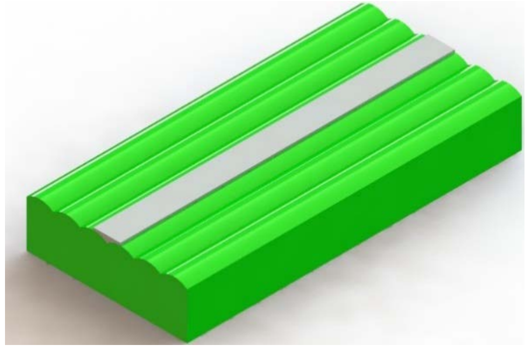
- *1.75mm Nozzle - Speed*
- *“Smart” slicing of objects*
- *Mill*
- *Laser Reflow*

Milling

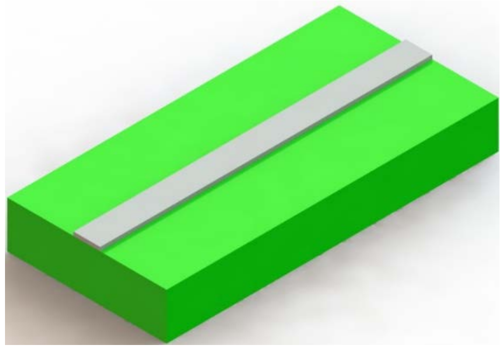
- Improved surface finish
  - Better suited for electronic printing onto surface
  - More suitable for RF purposes
  - Better adhesion of materials printed onto surface
  - Better dimensional accuracy

Side View: Printed Surface

Side View: Printed and Milled Surface



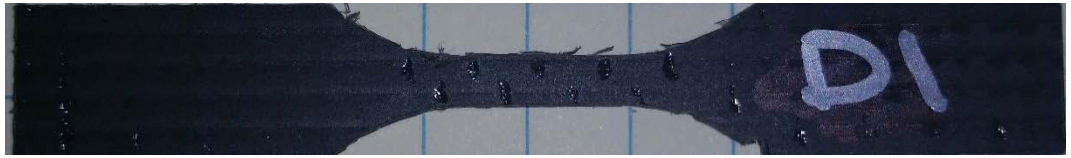
Iso View: Printed Surface



Iso View: Printed and Milled Surface

Milling

- Printed larger and milled to dimension
  - Smooth surface finish
  - Better dimensional accuracy
  - Sharp features
  - 0° and 90° print directions

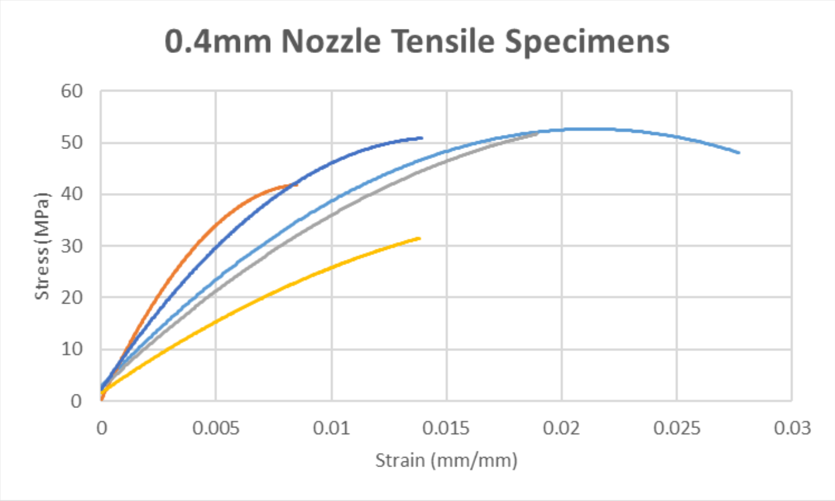


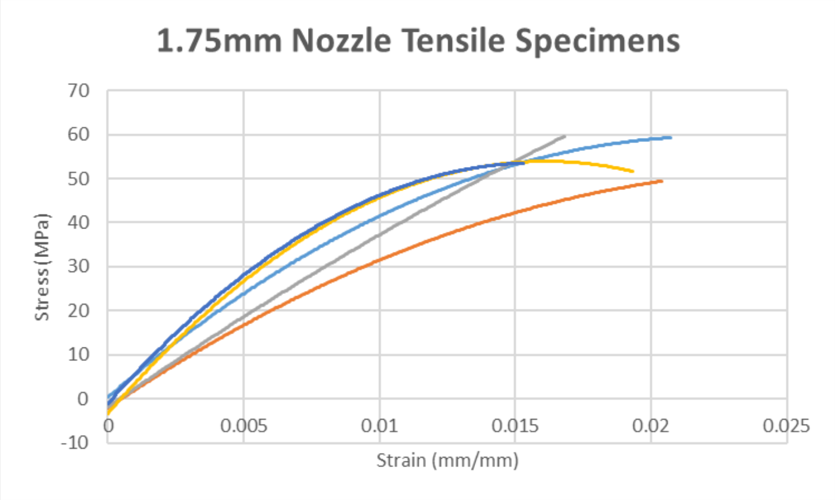
0° Printed and Milled Tensile Specimen

90° Printed and Milled Tensile Specimen

Nozzle Choice

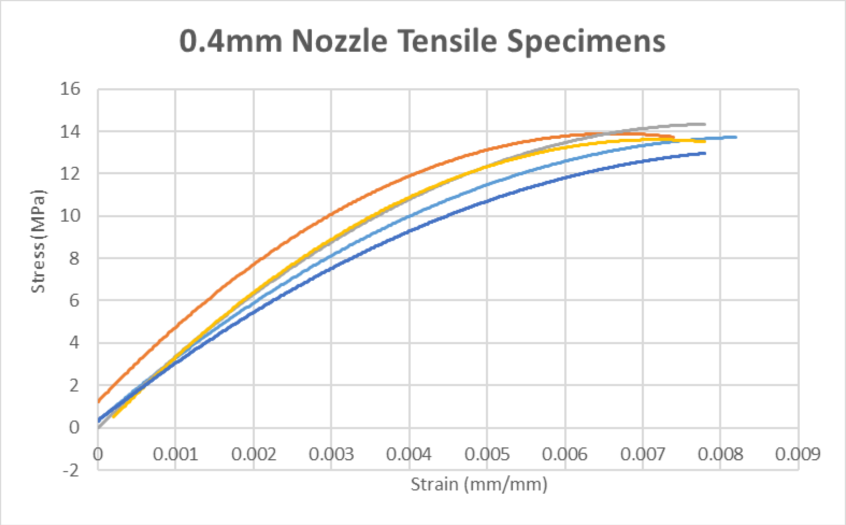
- Strength
  - *Printed in direction of force*
  - *0.4mm nozzle vs 1.75mm nozzle*
    - UTS – 47.028 MPa and 52.732 MPa respectively
    - 12% Increase in UTS

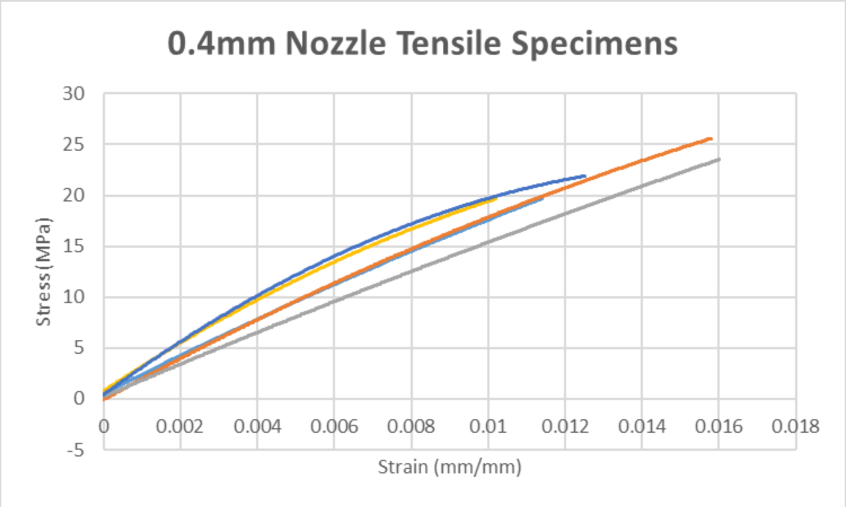




Laser Reflow

- Strength
  - *Printed perpendicular to direction of force*
  - *0.4mm nozzle*
  - *30W Laser used to "reflow" plastic*
    - 58% Increase in UTS
  - *Improved strength in multiple directions*

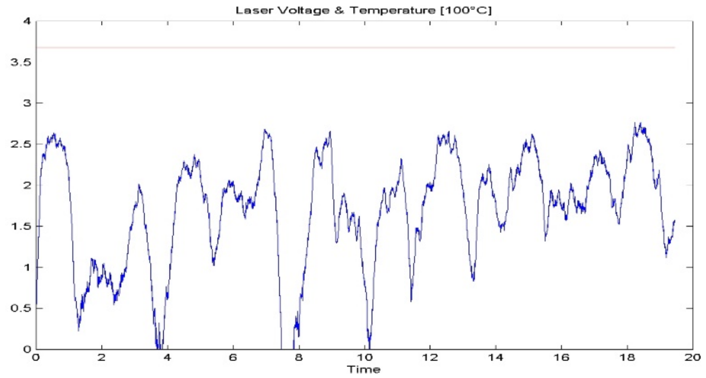


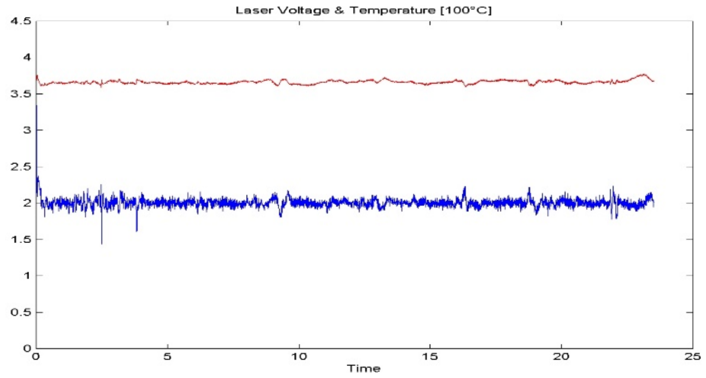


Laser Reflow

- 30W Laser attached to gantry
- Driven over area of interest
- Real-time feedback
  - *Held at 100° C*
- Improved interlayer adhesion

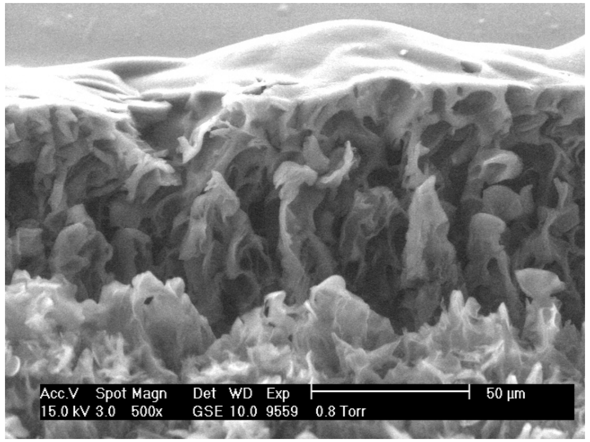
90° Tensile Specimen after Laser Reflow



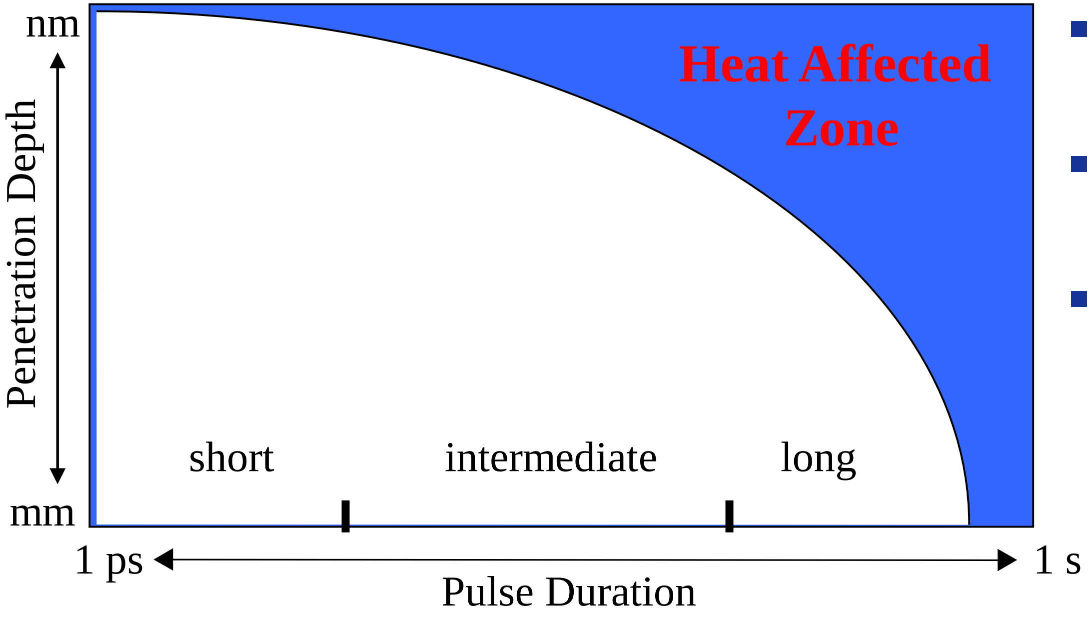


Non-feedback Control vs Feedback Control

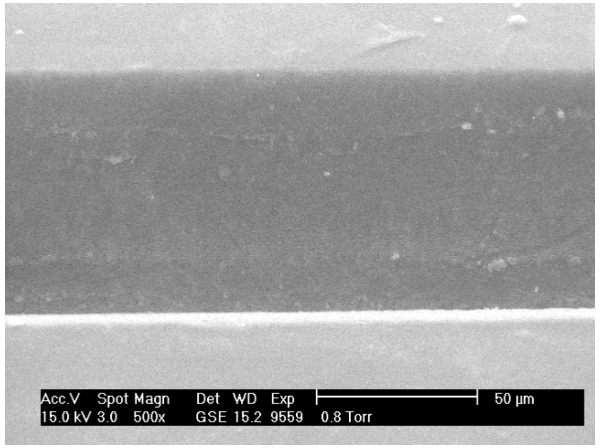
Pulse width effectively controls the rate at which energy/ heat is transferred to the target material.



ΔT = Absorbed Energy - Thermal Loss { Thermal diffusivity, Thermal conductivity, Vaporization



- Short Pulses - (< 1 µs)
  - *limited thermal loss*
  - *penetration < 500nm*
- Intermediate Pulses (1µs to 1ms)
  - *greater thermal loss*
  - *penetration (um to mm)*
- Long Pulses (1ms to CW)
  - *greater thermal loss*
  - *penetration (> 500 µm)*



Conclusion: Need tunable pulse widths over microsecond region.

<u>Intermediate pulse widths</u>

Conclusions

- "Spaghetti" Printing:
  - *Speed – 9x speed increase, optimizing,10-100 times faster*
  - *Strength - ~12% increase*
  - *Laser reflow - ~58% increase in strength*
- Direct Digital Manufacturing
  - *Customizable*
  - *Personalized*

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