A HIGH TEMPERATURE POLYMER SELECTIVE LASER SINTERING TESTBED FOR CONTROLS RESEARCH

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Abstract

High Temperature Polymers under development over the last decade show great promise for Additive Manufacturing (AM) applications in aviation, medicine, and other fields based on their high strength and high temperature qualities. Selective Laser Sintering (SLS) of these materials, derived generally from the Poly Ether Ketone Ketone class of polymers is still somewhat immature however, and certifiably repeatable SLS parts with certifiable mechanical properties remain elusive. One barrier to this is the limited number and high cost of SLS machines capable of operating at the high ~300-350C temperatures needed to build with low internal thermal stress and tight process controls. Another barrier is the lack the instrumentation in the few machines available, to develop critical feedback control and associated flexibility in the thermal management of the material from feedstock to cooled part/part-cake. This paper describes the development and initial testing of a new laboratory SLS machine with the flexibility required in deriving optimal process control for polymer SLS including these high temperature polymer powders. With such a system validated for SLS operation, we will embark on multiple control development approaches to improve part/material property performance.

Introduction

With the rapid growth of Additive Manufacturing (AM) and specifically Selective Laser Sintering (SLS) for a wide array of materials over the last few years has placed increased scrutiny on the ability of these processes to provide repeatable parts that can be certified for engineering use with predictable mechanical properties as a start point. The potential of using high temperature polymers such as Poly Ether Ketone Ketone (PEKK) and other semi-crystalline materials in this class with higher strength and temperature capabilities is likewise a primary thrust of the AM community.[1]

Though standards are still under development, it is clear that current commercial SLS machines do not contain sufficient instrumentation to understand with sufficient detail, process conditions during the build, to provide important information needed to provide quality estimation for parts as they are built and today we rely completely on the use of mechanical test specimens embedded in each build to “qualify” the build and therefor infer the quality of the included parts. The Air Force Research Lab recognizes this limitation and has initiated work with the authors at the University of Texas at Austin to design, build, and demonstrate a new design approach for SLS utilizing sever new methods to improve overall build quality and repeatability for a wide array of materials (with initial emphasis on high temperature polymers). The system is referred to as the Laser Additive Manufacturing Pilot System, or LAMPS. Design work on LAMPS began in the Spring of 2013 and construction/assembly started in the Fall of 2014.

This paper describes novel LAMPS design attributes and associated pre-build analysis and testing performed, and plans for use of this machine to assist the government and industry in refinement of SLS processing for repeatable parts, while gaining insight into thermal, and mechanical influences of SLS processing which could aid in the development of new materials with even greater processed properties and utility in both commercial and military applications.

The overall design objectives for LAMPS were:

a) Enable Laser Sintering of ASTM class tensile Specimens in high temperature Polymers of the PEEK/PEKK class.
b) Provide laser spot sizes of approximately 150 microns diameter
c) Function as a Class I laser System when in operation (safely enclose the Laser System)
d) Include the use of an inert build atmosphere
e) Accept Standard Tessellation Language input files (.stl files)
f) Include ambient temperature monitoring and control

In addition we were asked to look at making the LAMPS machine fit within a fume hood, but as the design developed, the sponsor agreed to relax this requirement for reduced risk for operating at the required temperatures with a new design approach described later. This relaxation in dimensions allowed focus to remain on maximizing operational flexibility with the thermal chamber with the assumption that once increased performance was demonstrated, a downscaling could be done in a 2nd generation design effort under the benefit of significant lessons learned and reduced cost risk. This approach clearly identified LAMPS as a laboratory testbench, filling a niche for significant advancements in SLS process monitoring and control development.

Design Principles

With the design objectives outlined in the Introduction, several guiding principles were established. These principles reinforced the role of LAMPS as a unique laboratory class instrument for advancing the state of the art in SLS, and allowing in-situ measurements to support research into the key parameters driving SLS part properties and associated repeatability.

The first of these principles was that a much more thermally stable build environment was needed. This stability is driven primarily through reducing thermally driven convective build atmospheric circulation. In conventional polymer SLS machines, thermal gradients are inherent in the heating method, which is usually associated with radiant lamp based heating of the build surface. Our approach provides heating in a more distributed manner throughout the build chamber, to raise the whole build chamber atmosphere to the desired temperature and only use minor radiant heating to fine tune build surface temperature. With a more uniform build temperature, we expect reduced temperature variation in the build surface associated with non-uniform and unpredictable circulation of cooler/heavier atmosphere from the upper chamber to the build surface during the build process. Such observed heat transfer mechanisms have been a suggested source of varying part properties in conventional SLS machines operating under identical build settings.[2]

A second, but related principle adhered with LAMPS was to reduce the electrical energy required for it's operation. We know that refinement of this principle will occur as we get actual test data for electrical consumption of various subsystems, and our primary focus is on insulating the build chamber well to preserve the thermal energy created by the heating system.

The dominance of the heater power consumption is related to the loss of heat in the typical SLS and with LAMPS we saw an opportunity (particularly given our requirement to operate at higher temperatures and our first principle of allowing the whole build chamber to reach the desired high temperature for atmospheric stability) to show a potential economic benefit with increased design consideration for insulating the hot portion of the chamber.

A third design principle was to enable multi-spectral image based sensing of the build surface throughout the build process. Although some machines have been back fitted for image analysis of the build surface, LAMPS would be designed from the beginning to give good visual access while protecting the imaging sensors from the build environment.

LAMPS was designed with a roller based powder spreader based on historical resilience of this mechanism to potential flaws in the build surface (tolerance of small amounts of part curl for instance (need a reference). In addition, our design allows for independent control of the rotation and translation of the powder spreader to enable exploration of optimal control as a function of powder properties in the future. (reference on the fluffing characteristic of counter rotation, and the use of roller for compression?)

And finally, LAMPS was designed to enable control of the complete thermal life cycle of the build material from the time it is introduced to the machine, to the time it is removed. Because some materials like PEEK are somewhat expensive (~$400/kg) and part of the purpose of LAMPS was to experiment with new custom materials that in general might be less abundant and more costly, we also took a philosophy of delaying the heating of the powder as long as possible before it's use in the build chamber, to enhance it's recyclability. This drove the design of the powder supply as described later.

Overall Machine Configuration

The resulting machine layout is shown in the Overall and Sectional Views of Figure 1 and 2 respectively. The outer stainless steel shell of the build chamber is sealed and the inner shell provides a high temperature "oven" surface for chamber operation. Strip heaters are located on both the front and back surface of the upper containment as well as on the far left side under the ports for the image sensors and the laser port (located directly over the build surface). The build plate is suspended on ceramic standoffs from the support plate and high temperature basalt fiber insulation is used throughout the outer surface (at least one layer of approximately 1" thickness is used in the initial LAMPS configuration).

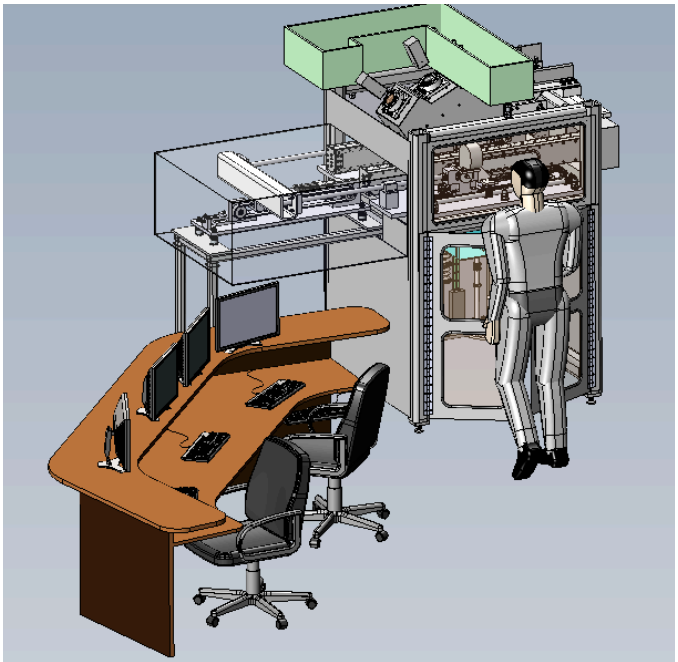

Figure 1 - LAMPS Machine Overall Layout

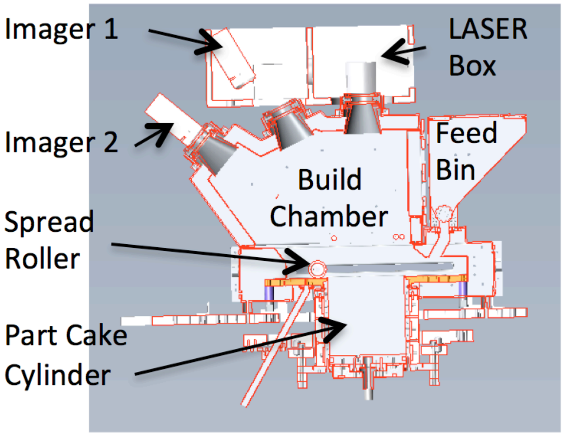

Figure 2 - LAMPS Machine Section View

The build cylinder and chamber itself are all sized for a maximum part cake volume of 22 cm cubed. This size enables the build of ASTM

The build piston is driven through an acme screw and stepper motor configuration with a step resolution of 0.0005 inches, though we expect to typically use layer thicknesses of 0.003 inches or 6 steps. The piston and build cylinder are removable from the machine after cool down to allow conveyance to a separate breakout area, this also allows for custom piston/cylinder designs to be incorporated later into LAMPS. The initial design incorporates 3 independent vertical levels of strip heater control in the cylinder and independent strip heaters in the piston to allow control of the thermal history of the part cake during the build and cool down phases of the SLS process.

Each of the 3 main ports in the upper build chamber are double layer in either quartz glass (visible wavelength camera) or ZnSe for the IR imager and IR laser being used. This dual layer reduces heat transfer out of the window, thus protecting sensitive sensors and laser scanner hardware mounted above the chamber. The ports are based on a design provided by Harvest Technologies for the introduction of atmospheric gas on the inner window material to reduce the buildup of monomer or other byproducts generated through the SLS process. It is known that such buildup reduces the effective laser power delivered to the build surface over time, and may also corrupt image data.

The powder feed bin is sized to provide enough for a full build, and is positioned above the build plate with a feed chute angled to deposit powder "in front" of the roller when it is positioned in the "home" position shown in figure 1. Powder is flash heated as it is introduced to the chute and falls to the build surface. Metering of the powder is through a rotating feed with slots designed for approximately 4 slot drops per layer. Experimentation will help refine this slot shape and reported later.

The spreader roller is driven by an external yoke, which allows the roller bearings to be located outside the build chamber environment to enhance their durability over time. A multi-layered seal mechanism has been developed to block both very high temperature build chamber gas and allow an outer seal to be implemented at lower temperature for reliable seal behavior. A high-risk element of the machine is the inner sliding high temperature tadpole seal. Our design assumes this seal is operated at low-pressure differential and also provides only a basic barrier to high temperature gas and monomer. Though preliminary feasibility testing of this seal suggests it can work, early testing will allow us to optimize the seal pressure for lifetime we hope to achieve of 10 builds without replacement.

The inert atmosphere to be used initially will be Nitrogen, but we are capable of using He or other inert gasses and may change the gasses for different phases of the build to enhance thermal control of the build surface and part cake.

Early Concept Evaluation

During the early design stage several concepts were examined experimentally and/or computationally to determine if there were insurmountable issues associated with their implementation.

The first of these related to the dispensing and rapid heating of powder through the vertical drop method. Our objective was to provide rapid temperature equalization with the build chamber using forced convection during the drop process, capitalizing on the high surface area to drop mass ratio of the fine build powder. Calculations were performed for room temperature (30C) Nylon spheres of diameter 10, 50, and 100 mm falling in a Nitrogen atmosphere at 340C with results shown in Figure 3. This preliminary analysis suggests that powders of diameters less than 100mm can be dropped from 5 cm and achieve approximately 87% of the needed temperature change before they touch the build surface. Additional heating would still occur prior to spreading both from contact with the static Nitrogen and from heating provided in the drop zone of the build plate.

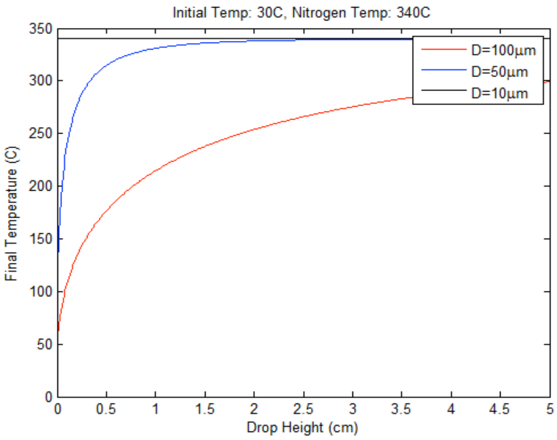

Figure 3 - Temperature gain vs powder spherical diameter and drop height.

Experiments were also conducted with Nylon powder to estimate its lateral spreading as a function of drop height. These experiments were conducted in ambient air using a test rig shown in Figure 4. Slot cross section was varied from square to rectangular in both "wide" and "tall" variations while retaining a sectional area of 0.3 cm^2 and roughly 2:1 rectangular dimension ratios in the slot. There was statistically insignificant variation in the lateral powder drift on the slot shape and height over ranges from 5 to 10 cm of interest, with only a very small portion of the powder (estimated at <2%) being spread outside the vertical drop line on each end of the slot.

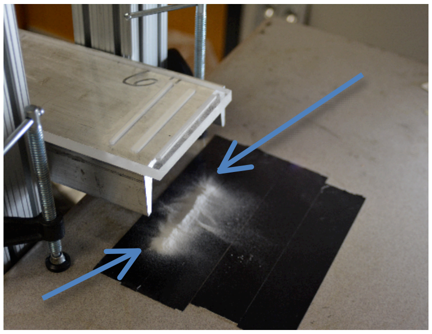

Figure 4 - Test rig for powder drop experiments (arrows indicate insignificant lateral powder drift)

Another key component examined was a tadpole seal used to provide the first barrier against the high temperature build atmosphere and any outgassed polymer, as part of our labyrinth sealing mechanism for the translating powder roller shaft system. A stainless plate, simulating the build chamber outer wall near the slot opening for the translating roller shaft, was heated to 375C and a reciprocating plate with the tadpole seal was mounted above it as shown in Figure 5. The seal was pressed against the hot plate and cycled back and forth to mimic the interface in the actual machine. Adjustment of the seal pressure over several trials indicated the need for a minimal contact to reduce wear on the seal while providing mild blockage of the highest temperature gas of the build chamber based on qualitative observation of the wear and measured friction from the seal plate as a function of cycle number. Figure 6 shows an image of the seal compression and partial fiber wear in the curved portion of the seal after prolonged exposure to 330C at the contact plate and 3000 cycles. Our final design will allow for seal compression in this curved region for increased cycle life. Note that the gas is ultimately sealed in a lower temperature seal system housed behind this seal.

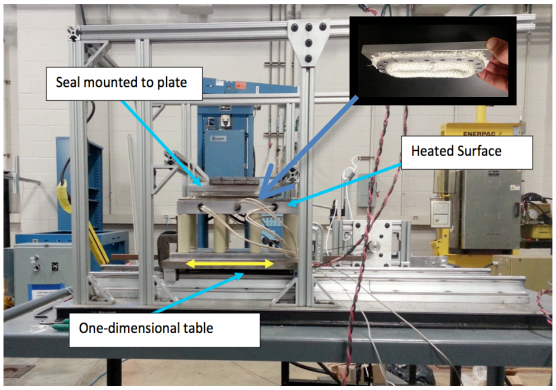

Figure 5 - High temperature reciprocating seal test rig

Figure 6 - High temperature seal after 3000 cycles at 330C

Tests were also conducted on the IR lamps to be used as local thermal control augmentation, as they are known to fail occasionally in the connector region at temperatures similar to our build environments. This design mitigates this issue by insulating the connectors and an insulated test box was used to verify that the connectors could survive when the lamp is operating at very high power in this configuration. The test setup is shown in Figure 7 along with an image of the lamp after running at a measured chamber temperature of 350C for 90 minutes.

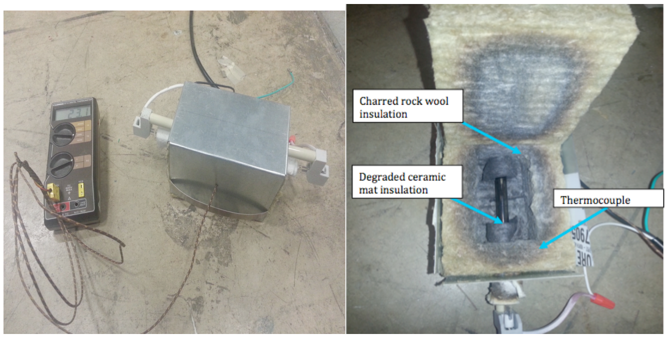

Figure 7 - Insulated lamp connector resilience Test Rig

Although we observed some minor charring of ceramic insulation where it was allowed to overlap too much with the filament area of the lamp, overall lamp operation was unaffected due to the relatively low temperature in the connector region. The rock wool used in this test will not be direct exposed to the lamp radiation in the LAMPS machine, but also validated it's resistance to significant degradation.

Planned Work

Subassembly work has been completed as of February 2014 and full assembly is awaiting delivery of several components from local fabricators. Subsystem control verification is proceeding in the interim, as is final laser integration. A view of the partially completed build is provided in Figure 8.

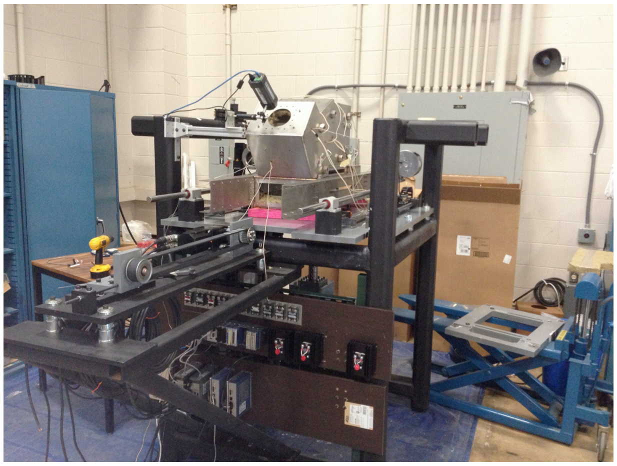

Figure 8 - Partially assembled LAMPS machine

Testing will also be conducted on the build chamber to determine final exterior insolation geometry, and the powder drop equipment to calibrate feed conditions. This activity will also enable comparison with process simulators to be used eventually in advanced control for the thermal and mechanical systems.

Once the machine is completely assembled, initial testing with Nylon 12 will be conducted to verify integrated system operation and safety. Then we will begin building tensile specimens in PEKK.

As we gain experience with high temperature build operations we will implement real-time defect/flaw detection approaches on the machine based on our extensive monitoring capacity and eventually utilize this information for candidate defect mitigation schemes currently under development.

Acknowledgments

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