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Feed-forward laser control in selective laser sintering for improved part consistency

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Abstract

Selective Laser Sintering (SLS) is one of the most common industrial additive manufacturing techniques for functional polymer components. As is typical with other additive manufacturing processes, the components built using SLS exhibit a large range of properties when compared with those built using traditional manufacturing techniques. This increased range is likely caused by inadequate control throughout the building process and is the subject of significant amounts of research. Using a custom research machine developed at the University of Texas at Austin, researchers have identified processing temperature as having a significant impact on the final part quality. The data collected by this machine illuminates a strong correlation between temperature the polymer achieves during the sintering process and resulting mechanical strength. The typical low level of control over this variable leads to significant part-to-part variations.

This paper will discuss how build position plays a role in mechanical strength due to inadequate control over the preheating system, causing detrimental thermal gradients. It will then detail a feed-forward laser control technique that uses dynamic surrogate modelling to decrease the thermal variation among components. Results will be presented showing that the control technique discussed is capable of decreasing post-sintering temperature standard deviation by up to 57% when compared with baseline testing. Destructive testing of flexure specimens show that this improvement in thermal uniformity also reduces the ultimate flexural strength standard deviation by up to 40%. These improvements allow for increased confidence in SLS parts and may increase the volume of structurally critical components capable of being built using SLS.

Selective Laser Sintering, Laser Control, Process Control, Mechanical Properties, Consistency

1. Selective Laser Sintering

Selective Laser Sintering (SLS) is a powder-based additive manufacturing process that uses a high-powered laser to fuse polymer materials into complex 3D geometries. Components are built in a layer-wise fashion directly from CAD geometry by spreading thin layers of polymer powder onto the build surface and controlling the laser to sinter cross-sections of the 3D components. SLS is one of the most common additive manufacturing techniques for creating functional plastic components [1].

1.1. SLS Materials

One of the keys to success in SLS is selecting an appropriate material that exhibits the required thermal characteristics. Typically, semi-crystalline materials that exhibit a large temperature disparity between their melting and recrystallization temperatures are used. During the building process, the entire powder bed is heated above the recrystallization temperature, near the melting temperature of the material being processed. By maintaining all material between these two temperatures, solid-state powder can coexist with material that was melted by the laser. This allows for a slow and controlled cooling process to take place after building has been completed, minimizing thermal distortion. This enables free-floating components to be built without the use of support structures. Nylon is the most common SLS material, making up 90-95% [2] [3] of the SLS market, and is the material used for testing throughout this paper.

1.2. Thermal Control

Controlling the temperatures achieved during the build process is critical, as differences of just a few degrees can be the difference between premature failure and excellent mechanical properties. The powder preheat systems in many commercial SLS machines are not capable of producing a highly uniform temperature across the powder surface. Typical temperature ranges across the powder surface can be between 5-15 °C [4]. In general, machines with more heaters or those that employ directional heaters, such as quartz lamps, produce smaller temperature ranges. While the temperature profile created on the powder surface is not entirely static, hot- and cold-spot patterns do emerge. These temperature patterns can influence the ultimate strength of components, creating positional-dependent mechanical properties.

Previous efforts to improve control over the sintering temperatures have focused on decreasing temperature gradients caused by the powder preheat system. While this improves the outcome, the current preheat systems are not capable of completely eliminating these gradients. A more direct approach is to modulate the laser power to achieve desired temperatures.

Real-time laser control has been implemented in other manufacturing industries [5] [6] and has been demonstrated in metal additive manufacturing [7] [8]. Due to the unique thermal characteristics of polymers, however, those approaches are not directly applicable. It was decided that a more appropriate approach for SLS was to develop a feed-forward approach that modulates laser power based on thermal measurements of the pre-sintered powder.

2. Feed-Forward Active Laser Control

Implementing a functional feed-forward controller requires knowledge of how the system will react to an input. One way to accomplish this is through physics modelling of the build environment. This approach, however, requires precise knowledge of thermal characteristics of the system and typically requires long solution times that are not suitable for an in-situ control method. Instead, the approach taken in this paper was to use surrogate modelling using empirical results to form a relationship between achieved temperature increase and delivered laser energy. Since SLS is a highly dynamic process with variables that change throughout the length of a build, the surrogate model is dynamically updated after each layer to improve its prediction capabilities and ensure it remains accurate to the current machine parameters.

2.1. Thermal measurements

During the build process, thermal measurements are taken with a FLIR A6701sc Mid-Wave Infrared (MWIR) camera. This camera produces 640x512 pixels images at a rate of 60 Hz. In order to simplify the computation and reduce the amount of storage used for the thermal data, the information for each layer is reduced to two significant images. The first image is referred to as the "pre-sintering temperature" as it depicts the temperature on the powder surface prior to using the laser. The second image is a composite that contains the maximum value each pixel on the MWIR camera recorded during the building of that layer and is referred to as the "post-sintering temperature". Subtracting the pre-sintering temperature from the post-sintering temperature also produces a useful metric of how much temperature increase was caused by the laser.

The first step in processing these images is to apply a registration and perspective transformation to bring the images from the camera coordinate system to the CAD coordinate system. This allows for probing temperature values at specific geometric coordinates. Next, a mask is created from the laser scan path that indicates where the laser was commanded to heat during this layer. Applying this mask to the registered MWIR images produces an image that displays temperature values in CAD coordinate space everywhere the laser was fired. Examples of these images can be found in Figure 1.

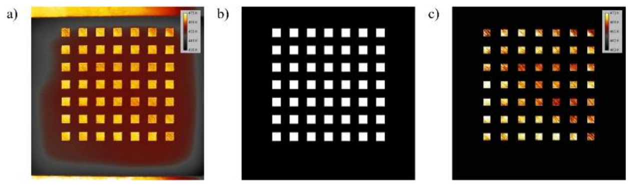

Figure 1. Images depicting (a) the post-sintering temperature of a layer, (b) a binary mask created from the laser scan file, and (c) the post-sintering temperature with the sintering mask applied.

2.2. Sintering Model

Dynamic surrogate modelling is used throughout the build process to specify laser power. Due to position-dependent differences in laser transmission, a global model that relates expected temperature increase to delivered laser power is not sufficient. Instead, the build surface is discretized into 1 mm x 1 mm areas, with each area receiving its own thermal model. The proposed laser control technique can be split into two phases that are operated in sequence on each layer: update thermal models, and execute sintering.

After each layer is built, the thermal data collected during lasing is used to update the thermal models. The MWIR images are reduced to the significant images and undergo coordinate transformation into CAD space, as described in section 2.1. The temperature increase value is extracted for each of the model areas that were sintered, as indicated by the laser scan mask. This value is paired with the commanded laser power used within that area and linear regression is used to determine the relationship between temperature increase and laser power. The regression weights new measurements more highly, while decrementing the weight for all previous measurements every time a new data point is added. This allows the model to receive a lower penalty when deviating from older information that may no longer accurately represent the system.

Once a new layer of powder is spread, the laser control system enters the execute sintering phase. This begins by taking the pre-sintering temperature measurement and transforming it into CAD coordinate space. This is compared with the desired post-sintering temperatures to yield an image containing desired temperature increase values in CAD space. The laser scan mask for the upcoming layer is used to identify which areas on this image are to be sintered. For each of these areas, the corresponding thermal model is solved to find the predicted optimal laser power. After each model area is solved, the optimal laser power information is used to create a parametric power surface that will be used during lasing. More information on how this power surface is used is given below in section 2.3.

2.3. Laser Controller

At the time of writing, there are no commercial laser control systems that allow for equation-based, intra-vector power modulation. As such, a custom solution was developed and is referred to as the Position-Based Laser Power (PBLP) controller. The experimental testbed used for this paper utilized a Cambridge Technology EC1000 laser controller. The EC1000 receives commands from the host computer, such as power and vector coordinates, then sends the appropriate signals to the laser and galvanometer controller to sync up their execution. Creating a custom controller to completely replace the EC1000 would be a large and expensive task. Instead, the PBLP controller is used in conjunction with the commercial controller by sitting between the EC1000 and the laser. This setup can be seen in Figure 2.

The PBLP controller receives real-time position feedback from the galvanometers as well as the parametric power surface derived in section 2.2. It also receives the original laser signal sent by the EC1000 and uses this as a trigger. When that signal is high, the PBLP controller continuously samples the galvanometer position, solves the power surface at that location, and outputs the correct power signal to the laser. This setup allows the EC1000 to maintain control over all delays and galvanometer movements while the PBLP enables further control over the laser output.

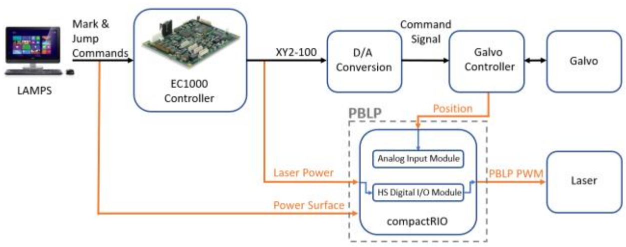

Figure 2. Signal diagram for the Position-Based Laser Power controller

3. Results

The proposed laser power controller was evaluated by building two sets of components, each set containing baseline components using a fixed laser power and test components using the laser power controller. The first set consisted of approximately 100 flexure specimens and the second set consisted of approximately 100 miniature I-beams. Half of each set was built using the laser power controller while the other half received a nominal, fixed laser power and served as the baseline for comparison. Both sets were evaluated for post-sintering temperature uniformity while the flexure specimens also allowed for destructive flexural strength testing.

The improvement in temperature uniformity for the flexure specimens was determined by calculating the standard deviation of post-sintering temperatures for all components built using the laser power controller and comparing it with the same measurement of all baseline specimens. Doing so revealed an improvement in post-sintering standard deviation of 57%. This improvement in temperature uniformity resulted in a 45% reduction in standard deviation of ultimate flexural strength. These results can be seen visually in Figure 3.

Temperature uniformity improvement for the miniature I-beam specimens was also calculated by comparing the test results to the baseline components. In this case, the laser control method presented in this paper resulted in a 45% reduction in standard deviation of post-sintering temperature. Since there is no appropriate testing standard for these 3D components, thermal uniformity was the only metric considered; however, based on the flexure specimens' results, it is expected that the large improvement in I-beam temperature uniformity will also result in a large improvement in strength uniformity.

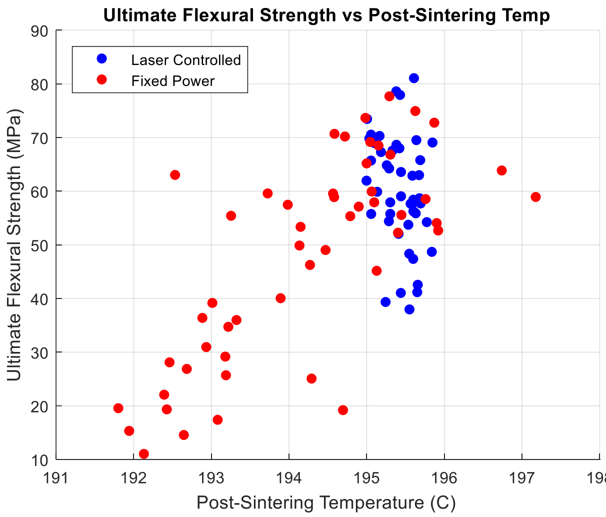

Figure 3. Ultimate flexural strength vs average post-sintering temperature

4. Conclusion

This paper presented a novel laser control technique for improving component consistency in Selective Laser Sintering. A dynamic surrogate model-based controller was developed that predicts optimal laser powers based on real-time thermal measurements. The models are updated during run-time using thermal data collected in the machine to improve their prediction capabilities. The efficacy of the laser power controller was evaluated by comparing the results it produced with those found when using a fixed laser power. It was found that the laser power controller improved temperature uniformity by up to 57%, resulting in an improvement in strength uniformity of 45%.

This improvement in strength uniformity helps overcome some of the uncertainty surrounding the performance of additively manufactured components. Improving confidence and consistency in the SLS process may lead to more widespread adoption, especially among structurally critical components.

A few avenues of future work have been identified that may further increase the impact of the work presented here. One avenue is to test the controller on additional materials. All results presented here used nylon 12, but there is no restriction on the laser power controller that requires this. The controller may show improved performance among a wide range of additive materials, especially among materials that are more difficult to process using traditional techniques. Another avenue of research would be to improve the method of deciding on the optimal post-sintering temperature. In this work, the desired temperature was found experimentally by analysing temperatures of previously built components. A more sophisticated approach to deciding this temperature value may improve performance and could reveal that a uniform post-sintering temperature may not be optimal. For example, different features, sintering dimensions, or build conditions may influence the optimal post-sintering temperatures.

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