In-process laser heating-a cost-efficient way to improve mechanical and geometrical properties for fused filament fabrication

P. Han*, S. Zhang**, and K. Hsu***

* Fulton Schools of Engineering, Arizona State University, Pu.Han@asu.edu
**Speed School of Engineering, University of Louisville, Sihan.Zhang@louisville.edu
*** Fulton Schools of Engineering, Arizona State University, Keng.H.Hsu@asu.edu

ABSTRACT

In-process laser heating technique delivers a cost-efficient way to improve mechanical and geometrical properties to nearly isotropic and extremely smooth, respectively. The technique involves the incorperation of a solid-state laser into a commercial off-the-shel 3D printer, mechanical system to allow controll-able laser allumination on desired surfaces, and a gcode postprocesser to proper control of the mechanical system. This process uses laser for local heating, to enhance mass transfer between boundaries or to enhance surface reflow to smooth surface irregularity, to improve mechanical and geometrical properties. Only less than 3 W of laser power (CO2 laser) was used for high temperature material like PEEK and Ultem; less than 1 W (808nm laser) was found to be sufficient for achieving optimal properties for PLA. This technique has the potential for after-market integration into most commercial FFF 3D printers to achieved nearly isotropic and smooth 3D printed objects with various thermoplastic polymers.

Keywords: laser assisted process, fused filament fabrication, laser heating, interface healing, surface healing.

1 INTRODUCTION

Fused filament fabrication (FFF) is the most preferred additive manufacturing technique for the fabrication of thermoplastic polymer parts. Compared to most conventional fabrication methods, such as injection molding and blow molding, which require an expensive mold to build a simple part, FFF is capable of building complex-structured three-dimensional (3D) object directly with a digital 3D model [1]. Therefore, FFF outperforms conventional methods by its flexibility and cost-effectiveness. However, the building process of FFF is extrusion-based, that objects are built track by track, layer by layer, which result in weak mechanical strength between tracks and layers, and rough side surface finish [2].

Numerous approaches have been performed to improve the mechanical and geometrical properties by optimizing printing parameters or using post-process techniques. However, the improvement on the properties with manipulating printing parameters failed to fully resolve the problem [3,4]; post-process techniques, that performed remarkable mechanical properties by annealing, deforms small structure features [5,6]. Post-process techniques for geometrical properties either only works for flat surface with laser post-remelting [7,8] or removes small features with chemical etching [9–11]. Therefore, despite various efforts to resolve the problem, the challenge persists.

To address the problems related to weak mechanical strength and rough surface finish in FFF built parts, an in-process laser heating technology was developed.

2 EXPERIMENTAL

2.1 In-Process Laser Heating

The in-process laser heating technique utilizes laser power to enhance mass transfer or surface reflow by local heating, therefore improving mechanical and geometrical properties. To manage the local heated region, the implementation of the laser process consists of an orbiting system that allows the laser diode to orbit surround the nozzle (Figure 1). Depends on the heated region, this technique can be used for inter-layer interface healing, inter-track (track: deposited track-shape material (Figure 1 marked in blue)) interface healing, and surface reflow.

Two laser heating system were designed and implemented on two commercial 3D printers. A “Type A Machine” 3D printer that is capable of printing low temperature polymers such as PLA, ABS and Nylon was used for the in-process orbiting laser heating apparatus with an 808nm diode laser (1 W). The second 3D printing system that does not consist of the orbiting feature was implemented on a “Funmat HT” 3D printer with CO_2 laser for high temperature polymer materials, such as Ultem and PEEK [12].

2.2 Mechanism of the Technique

Due to the deposition process of FFF, polymer chains are stretched and disentangled as extruded out from the nozzle [13,14]. Therefore, increases the difficulty for mass transfer to occur across interfaces by increasing the radius of gyration of polymer chains. This technique reduces the radius of gyration (Rg) by allowing polymer chains to release the residual stress through thermal relaxation, and therefore increases thermal reptation (mass transfer) that enhanced by smaller Rg and higher temperature [15,16]. Hence, the micro-structure of polymer chains in the fabricated object is capable of reaching the equilibrium state (fully entangled without residual stress). As a result, the mechanical properties are improved.

2.3 Sample Preparation

Tensile strength sample groups were fabricated using the high temperature laser heating apparatus with 3DXtech Ultem and PEEK filaments. The print temperatures for Ultem and PEEK samples are 360 °C and 380 °C for nozzle, 160 °C and 150 °C for build plate, 90 °C for ambient, respectively. Both materials were printed at 10 mm/s into a 1mm wide single wall rectangular box (100 mm long and 20 mm high) with 0.2 mm layer height (0.3 mm layer height for PEEK with carbon fiber infill). The walls were milled into tensile bars for tensile test.

Surface finish sample groups were fabricated using the low temperature orbiting laser apparatus with Makergear black PLA filament. Samples were printed at 195 °C nozzle temperature, 60 °C build plate temperature and 10mm/s print speed. The layer height is 0.2 mm and the extrusion width is 1 mm.

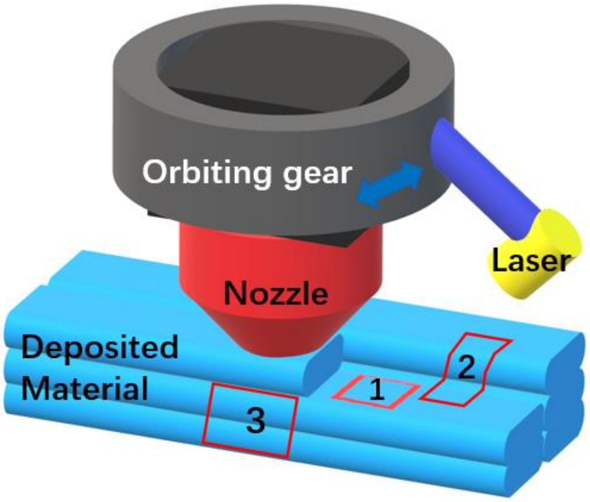

Figure 1. Schematic diagram of the in-process laser heating apparatus. Regions: 1. Inter-layer interface, 2. Inter-track interface, 3. Side surface.

3 RESULTS

The effect of laser pre-heating (Figure 1 position 1) on mechanical strength of PEEK and Ultem was investigated (Figure 2). With the usage of 1.6 W of laser output power, the tensile strength of Ultem along build direction increased remarkablly from 30 MPa to 82 MPa, which reached 82.8% percent of that along track direction (considered as isotropic value). Similarly, the tensile strength of PEEK along build direction increased from 17.8 MPa to 80.4 MPa with 2.13 W of laser. An improvement was found on the tensile strength along track direction, which demonstrates the potential of this process on contributing to inner material healing (polymer chain relaxation). The ductility of the printed sample along track direction improved from 50 % to 178% with the application of laser heating. The infill of carbon fiber in PEEK induced voids to the material, while the carbon fiber at inter-layer interface may behave as a barrier for mass-transfer (polymer reptation) during deposition, therefore result in weaker tensile strength. With the inter-layer interface laser pre-heating, the tensile strength increased by more than 500%.

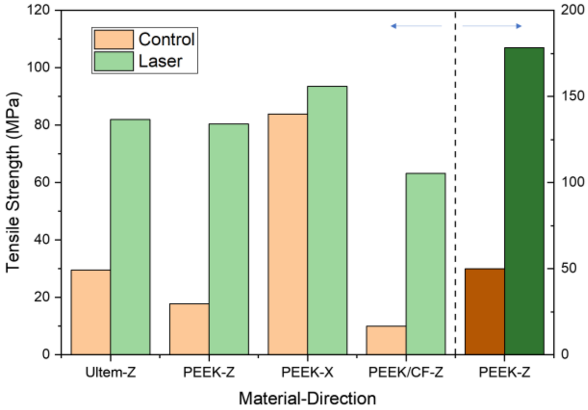

Figure 2. Comparison of mechanical properties between control and laser samples. Left Y-axis applies for left 8 bars, Right Y-Axis applies for right 2 bars. (Directions: Z: build direction, X: track direction)

Surface morphology of the sample's side surface were characterized using profilometry. A 1.4 mm length along build direction were plotted for both control and laser-assisted surface finish samples (Figure 3). The laser treatment was at 0.7 W of laser output power with the printing speed at 2.5 mm/s. The average height along the length was used as 0 in the plot. With the utilization of the orbiting laser process, the wavy shape feature on the surface was smoothed. Hence, this process has shown potential to reduce surface roughness in FFF built part.

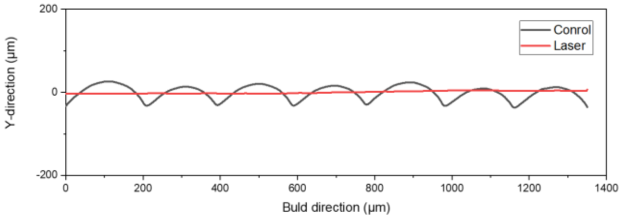

Figure 3. Photograph of samples for geometrical property.

4 BENEFITS AND POTENTIAL APPLICATIONS

This technique is capable of improving the mechanical strength of FFF printed part to nearly reach that for bulk material. From the observation on PEEK, the tensile strength along build direction increased to almost the same value of that tested along track direction. It further increased the tensile strength along track direction. Therefore, with the utilization of this technique, part fabricated using could be nearly isotropic and reach above 80% tensile strength of bulk material along its weakest direction. Moreover, the ductility of the PEEK also improved by 250%.

The geometrical property is advanced with the usage of this technique. This improvement has the potential to broaden the application of FFF printed object to fields that requires smooth surface or seal feature.

This technique can be built into a compatible package for most commercial 3D printers. It can be designed for different build volume, and it works for most thermoplastic filament. The implementation on “Type A Machine” contains one laser diode, one stepper motor and one customized bracket with gears for orbiting. Compared to post-process techniques that requires an oven for annealing [5] and laser[8] or chemical for surface smoothing[9], this technique can be done in-process during printing. Only less than 3 W (output power) was used to reach the optimal mechanical strength of Ultem and PEEK, and less than 1 W (output power) for surface finish. In addition, it has been found that with the utilization of laser, the temperature of heated bulid plate can be reduced to further save energy (with the increase of print height, the effect of heated bed reduces, while laser remains the same).

5 CONCLUSIONS

This work performed a novel technique - in-process orbiting laser heating - that can be implemented on commercial FFF 3D printers to improve mechanical and geometrical properties of fabricated objects. The improvement on mechanical and geometrical properties to nearly isotropic and extremely smooth, presents the possibility to fully replace traditional method for fabrication of decent quality thermoplastic objects. Energy consumption from heated build plate can be reduced with the usage of this technique.

REFERENCES

[1] S.C. Daminabo, S. Goel, S.A. Grammatikos, H.Y. Nezhad, V.K. Thakur, Fused deposition modeling-based additive manufacturing (3D printing): techniques for polymer material systems, Materials Today Chemistry. 16 (2020) 100248.

[2] A. Tofangchi, P. Han, J. Izquierdo, A. Iyengar, K. Hsu, Effect of Ultrasonic Vibration on Interlayer Adhesion in Fused Filament Fabrication 3D Printed ABS, Polymers (Basel). 11 (2019) 315.

[3] J. Gockel, L. Sheridan, B. Koerper, B. Whip, The influence of additive manufacturing processing parameters on surface roughness and fatigue life, International Journal of Fatigue. 124 (2019) 380–388.

[4] G. Ćwikła, C. Grabowik, K. Kalinowski, I. Paprocka, P. Ociepka, The influence of printing parameters on selected mechanical properties of FDM/FFF 3D-printed parts, in: IOP Conf. Ser. Mater. Sci. Eng, 2017.

[5] K. Coasey, K.R. Hart, E. Wetzel, D. Edwards, M.E. Mackay, Nonisothermal welding in fused filament fabrication, Additive Manufacturing. 33 (2020) 101140.

[6] K.R. Hart, R.M. Dunn, J.M. Sietins, C.M.H. Mock, M.E. Mackay, E.D. Wetzel, Increased fracture toughness of additively manufactured amorphous thermoplastics via thermal annealing, Polymer (Guildf). 144 (2018) 192–204.

[7] Y. Chai, R.W. Li, D.M. Perriman, S. Chen, Q.-H. Qin, P.N. Smith, Laser polishing of thermoplastics fabricated using fused deposition modelling., International Journal of Advanced Manufacturing Technology. 96 (2018).

[8] F. Lambiase, S. Genna, C. Leone, Laser finishing of 3D printed parts produced by material extrusion, Optics and Lasers in Engineering. 124 (2020) 105801.

[9] L.M. Galantucci, F. Lavecchia, G. Percoco, Quantitative analysis of a chemical treatment to reduce roughness of parts fabricated using fused deposition modeling, CIRP Annals. 59 (2010) 247–250.

[10] L.M. Galantucci, F. Lavecchia, G. Percoco, Experimental study aiming to enhance the surface finish of fused deposition modeled parts, CIRP Annals. 58 (2009) 189–192.

[11] F. Lavecchia, M.G. Guerra, L.M. Galantucci, Chemical vapor treatment to improve surface finish of 3D printed polylactic acid (PLA) parts realized by fused filament fabrication, Progress in Additive Manufacturing. (2021) 1–11.

[12] P. Han, A. Tofangchi, A. Deshpande, S. Zhang, K. Hsu, An approach to improve interface healing in FFF-3D printed Ultem 1010 using laser pre-deposition heating, Procedia Manufacturing. 34 (2019) 672–677.

[13] F. Snijkers, R. Pasquino, P.D. Olmsted, D. Vlassopoulos, Perspectives on the viscoelasticity and flow behavior of entangled linear and branched polymers, Journal of Physics: Condensed Matter. 27 (2015) 473002.

[14] C. McIlroy, P.D. Olmsted, Deformation of an amorphous polymer during the fused-filament-fabrication method for additive manufacturing, Journal of Rheology. 61 (2017) 379–397.

[15] P. Han, S. Zhang, A. Tofangchi, K. Hsu, Relaxation of residual stress in fused filament fabrication part with in-process laser heating, Procedia Manufacturing. 53 (2021) 466–471.

[16] P. Han, A. Tofangchi, S. Zhang, A. Desphande, K. Hsu, Effect of in-process laser interface heating on strength isotropy of extrusion-based additively manufactured PEEK, Procedia Manufacturing. 48 (2020) 737–742.