Journal of Manufacturing Processes 24 (2016) 179–185

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Technical Paper

An in-process laser localized pre-deposition heating approach to inter-layer bond strengthening in extrusion based polymer additive manufacturing

Abinesh Kurapatti Ravi, Anagh Deshpande, Keng H. Hsu*

Ira A. Fulton Schools of Engineering, Arizona State University, United States

ARTICLE INFO

Article history:
Received 15 October 2015
Received in revised form 4 May 2016
Accepted 22 August 2016
Available online 21 September 2016

Keywords:
3D printing
Additive Manufacturing
Fused Deposition Modeling
Inter-layer bond
Inter-layer strength

ABSTRACT

Material extrusion-based 3D printing processes have shown importance in the overall development of the field of additive manufacturing and displayed tremendous potential to becoming a cross-cutting tool for research, engineering, developmental work in a wide array of disciplines. In the context of the Fused Deposition Modeling (FDM, one form of Materials extrusion-based 3D printing), one of the main process issues lies in the property anisotropy of parts built using this method, even with process optimization. To address this issue, we report a near-IR laser-based pre-deposition heating method to locally heat up the region of an existing layer near the nozzle before an extrudate comes in contact with the heated region. This in-process approach raises the inter-layer interface temperature to above the critical temperature to increase the interpenetrating diffusion, and therefore the inter-layer bond strength. A 50% increase in the inter-layer bond strength in parts built with this approach is demonstrated. The in-process pre-deposition local heating approach reported here represents an effective means to increase the inter-layer bond strength, and property isotropy of FDM parts. Further, this approach is capable of real-time monitoring and controlling of temperatures at the inter-layer and inter-filament interfaces across the entire volume of a built part, allowing control of the physics of the FDM process to achieve desired mechanical properties.

Published by Elsevier Ltd on behalf of The Society of Manufacturing Engineers.

1. Introduction

Current AM processing capability limitations prevent many applications from being economically viable at production volumes and often require extensive secondary post processing to achieve the same characteristics as conventionally manufactured parts. In the context of the Fused Deposition Modeling, FDM, technology, property anisotropy of the built component is the main barrier to typical engineering applications. The FDM technology represents a capable, flexible, and cost effective-option in the additive manufacturing industry. However, for FDM to evolve into a true manufacturing tool, and be widely adopted into production of engineering products, the material property, geometry, dimension tolerance and accuracy, surface finish, process rates, part size and resolution limits, as well as the predictability and uniformity of all of these characteristics need to reach high levels of standard.

While over the past two decades, the FDM technology has seen breakthrough in many areas of development, there are still technological gaps that need to be bridged to bring the FDM technology to the next level of adoption as a manufacturing tool. An example is the low part strength in the build direction of FDM parts. Though the material and process capabilities of this technology have evolved over the years and are now at a point where end-user products can be directly produced, a main property anisotropy issue is still present in FDM parts with optimized build process parameters: the part strength in the direction normal to the build layers is only 10% to 65% of that in the directions along the filaments with low predictability. This issue places significant design constraints in the growing number of unique engineering applications of FDM-fabricated parts where dynamic loads or multi-direction static loads are present.

So far the FDM process has seen research efforts in mainly five areas: part quality improvement, process improvement, new materials development, materials properties, and applications. Among them, three key areas are relevant to the work presented here: (1) material properties, (2) process improvement, and (3) part quality improvement. In material properties, significant work has been focused in the areas of materials testing, and the use of design of experiments to optimize known process parameters for given part properties. While in process improvement work has been done to

* Corresponding author.
E-mail address: keng.h.hsu@gmail.com (K.H. Hsu).

http://dx.doi.org/10.1016/j.jmapro.2016.08.007
1526-6125/Published by Elsevier Ltd on behalf of The Society of Manufacturing Engineers.

improve support generation process, and to establish numerical simulations of the FDM process, research and development work in FDM part quality improvement has seen progress in accuracy, surface finish, build orientation of parts, and in extension, repeatability. Here we will provide a review of works most relevant to our proposed effort.

In the context of FDM part mechanical behavior, significant amount of work has been put in by various groups that focused on the investigation of effects of FDM process parameters including extruder temperature, raster angle, layer thickness, air gaps in between layers and FDM roads, as well as road widths on the tensile and flexural strengths, elastic behaviors, and residual stresses [1–19]. The conclusions from these studies all point in the same direction: each parameter in the FDM process has different effects on different properties of a part, and that an optimal set of parameters for one property can result in worsening of other properties. An example is that when a minimal dimensional deviation and surface roughness are desired, lower extruder temperatures or active cooling should be used. However, lowering the extruder temperature or the use of active cooling reduces the overall part strength due to less inter-filament and inter-layer bond strength [5].

With the technology evolving for the past few decades mainly under Stratasys, the optimization of process parameters for "best possible" combinations of part dimensional accuracy, surface roughness, and strength is mainly determined in the factory. From end-user's perspective, there isn't much that needs to/can be done to improve part qualities. With the original patent expiring in 2009, many low-cost FDM-based 3D printing solution surfaced and have become an important part of the Additive Manufacturing revolution taking place in the design community. Irrespective of the level of the FDM machine, for part strength isotropy, the "as-built" tensile strengths of parts in the inter-filament/-layer directions fall in the range of 10–65% of that in the direction along the filaments [20]. For the part strength along the directions on a slice/layer, though it also depends on the inter-filament bond strength, it can be remedied by alternating raster angles of adjacent layers (tool path planning) such that in any given direction along the layers the filament-direction strength can contribute to the overall strength of that layer. Here we introduce a "strength isotropy factor" to describe the ratio of the tensile strength of FDM parts in the normal-to-layer direction to the strength in the directions along-the-filament. By this definition, the strength isotropy values would range from 0 to 1 with 0 being the case where there is no strength in the normal-to-layer direction, and 1 being the case where the strengths are the same in both along the layer and across-layer directions. Current FDM parts have a strength isotropy factor ranging from 0.1 to 0.65 with 0.65 being the case with optimized process parameters and a heated build envelope. Almost all work existing in the literature studying part strength properties takes the viewpoint of process parameters and build orientation and their optimization, but only a handful of studies examine the physics of the inter-layer bonding process taking place during FDM and its relation to process inputs.

In a handful of studies, the effect of various process parameters on the bond formation between a "hot" polymer filament and a "cold" existing polymer surface has been investigated. The findings of these studies all indicated that the critical factors that determine the extent of the bond strength between a filament to its adjacent ones lie in the temperatures of the nozzle and the build environment, as well as the heat transfer processes in the vicinity of the bond site [21,22]. Of the two temperatures, the build environment temperature has a more significant effect on the bond strength. While it suggests that one could simply increase the build envelope temperature to increase the inter-filament bond strength, the ramification of doing so is that the part dimensional and structural accuracy and tolerances goes way down as the build envelope temperature increases beyond a certain point. One team devised a way of heating the entire part surface with hot air during a build process [23]. Though the effect of using hot air was inconclusive due mainly to the approach, the observations very much were in agreement with earlier studies that a critical interface temperature needs to be reached and maintained for a given amount of the time for the bond formation between the filament and the existing surface to go through its three stages of formation: wetting, diffusion, and randomization, much like the reptation model introduced by De Gennes [24] and later adopted by Wool et al. [25].

In this work an in-process laser local pre-deposition heating method is reported wherein a near-IR laser supplies thermal energy to a focused spot located on the surface of an existing layer in front of the leading side of the extrusion nozzle as it travels. The principle of this process is shown in Fig. 1. As the polymer extrudate comes in contact with the laser-heated region of the surface of the existing layer, the wetting, diffusion, and randomization stages needed to form a strong intermolecular-penetrated bond takes place to a larger extent as compared to deposition processes without local pre-heating. In the results reported here a 50% increase in inter-layer bond strength has been observed. Unlike the current build envelop heating method where the highest temperature used is around half of most polymer's T_g to prevent dimensional and geometrical issues, the laser-based local pre-heating demonstrated in this report is capable of heating extremely locally at only the actual bond site-to above its T_g without a negative impact on the part dimension and geometry.

2. Experimental

The experimental FDM platform was built upon a commercial open source desktop 3D printer (lulzbot mini). 2.89 mm diameter ABS filament and a 0.5 mm nozzle were used for all samples built. A filament liquefier temperature of 230 °C, and a built platform temperature of 110 °C were used for all prints. Open source pre-process programs "Slic3r" and "Printrun" were used to perform slicing of stl file, generation of g-codes, and machine interface and control.

The localized laser heating was accomplished through a custom laser and optics system adapted into the open source 3D printing platform. Shown in Fig. 2 is a schematic of integrated system. An 802 nm solid-state laser at a maximum intensity of 2 Watt was used as the laser source for optical heating. In this study, black-color ABS filaments were used. Carbon black was used as the color pigment in the material. As shown in Fig. 2, the laser beam first passes a Glan polarizer-rotating polarizer beam attenuator to allow optical intensity control and modulation of laser pre-deposition heating of the polymer surface along the deposition path. The beam is then directed by two Au-coated mirrors and a focusing lens (20 mm diameter, NIR coated Achromatic lens, 100 mm focal length, and an NA of 0.13) to allow the beam to be projected onto a spot 1 mm away from one side of the extruder nozzle.

Test coupons in the dog-bone geometry with the dimensions as shown in Fig. 3 were built using an identical set of raster, layering, and fill parameters for variables of nozzle travel speed and laser intensity. These raster, layering, and fill parameters are tabulated in Table 1. 3-Point bending tests were used to determine the bending load required to fracture the samples the bending load-beam deflection relations were also collected.

In order to allow the in-process laser local preheating to take effect during the build process, the built orientation and raster patterns were set such that the build direction are along the length direction of the test samples. In addition, the width direction of the samples was in-line with the nozzle-laser spot orientation. As a result, in each layer of the test sample during their build one of the long edges would see pre-deposition heating, and the other edge