Additive Manufacturing 19 (2018) 29–38

Contents lists available at ScienceDirect

Additive Manufacturing

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

Full Length Article

Process-structure-property effects on ABS bond strength in fused filament fabrication

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ARTICLE INFO

Article history:
Received 1 March 2017
Received in revised form 25 October 2017
Accepted 3 November 2017
Available online 4 November 2017

Keywords:
Fused filament fabrication
IR camera
Road-to-road bond strength
Mesostructure

ABSTRACT

Interlayer bonds pose regions of weakness in structures produced via melt extrusion based polymer additive manufacturing. Bond strength was assessed both between layers and within layers as a function of print parameters by performing tensile tests on ABS coupons printed in two orientations. Print parameters considered were extruder temperature, print speed, and layer height. An IR camera was used to track thermal history of interlayer bond lines during the printing process. Contact length between roads was measured from mesostructure optical micrographs. Print speed was found to have a large impact on tensile strength with high speeds generally yielding lower strength. A plateau in tensile strength of 22 MPa was observed for a normalized contact length greater than 0.6 independent of print orientation.

1. Introduction

Additive manufacturing is an emerging manufacturing technique in which objects are fabricated in a layer-wise manner. Material extrusion (ME), also known as fused filament fabrication (FFF), is an additive manufacturing strategy whereby polymer filament is fed through a heated liquefier, is extruded through a nozzle, and is deposited on a build surface or previously printed layers where it quickly cools. Structural integrity of AM parts is derived from bonding between adjacent and stacked extruded roads. Bonding forms via a polymer coalescence mechanism and is a function of thermal history at road interfaces. The cooling profile at road interfaces defines a time window over which molecular diffusion and randomization of the polymer chains at the interface can occur and is limited at the low end by the polymer glass transition temperature at which polymer dynamics drop by an order of magnitude. Additionally, the quality of the bond depends on the neck growth which is formed between the adjoining rasters. Increasing interfacial contact area between road interfaces offers greater potential for strong bond formation as long as thermal conditions drive polymer coalescence. Analysis that combines thermal history at road interfaces with printed part mesostructure is critical as it relates to measured mechanical properties and elucidates relationships between the ME process, printed structure, and structural performance. In this work, tensile strength of bonds between adjacent roads and between layers in printed parts is measured while considering two factors: cooling profiles at layer interfaces and road-to-road contact. These factors are varied by manipulating print parameters in accordance with a design of experiment. Tensile strength results are analyzed as a function of road-to-road contact normalized by the road dimensions.

Print parameters available for user control have a large impact on the mechanical performance of printed parts. While available parameters depend on the slicing software used and machine limitations, some common parameters include: layer height, infill orientation, infill density, and extruder temperature (T_E). Several studies have utilized a design of experiment (DoE) approach to analyze the effects of print parameters on mechanical properties of parts printed with acrylonitrile-butadiene-styrene (ABS) thermoplastic polymer. Tensile properties have been measured in response to build orientation, infill angle, road width, air gap between adjacent roads [1], extruder temperature, polymer colorants [2], unidirectional infill angle [3,4] and angle-ply laminates [5–8]. Flexure properties [9,10] and compression properties [11] have also been studied with respect to similar print parameters. Other properties that have been considered include dimensional accuracy [12,13] and elastic flexibility [14]. In general, these studies found infill angle and air gap to have the largest influence on mechanical properties with infills aligned along the loading direction and small air gaps resulting in higher performance. Smaller layer heights were also found to slightly improve mechanical performance in most cases. Extruder temperature was generally not observed to have a large impact on mechanical performance. All of these studies varied print parameters and measured changes

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https://doi.org/10.1016/j.addma.2017.11.002
2214-8604/

to some performance metric. However, underlying relationships between print parameters and resulting mesostructure of printed parts and their impact on mechanical performance have not been explored in detail.

In the ME process, extruded roads of material partially coalesce with adjacent and underlying roads. Road-to-road coalescence is the mechanism that drives bond formation between roads. Formation of strong bonds is critical to the structural performance of printed parts. Bond formation involves neck growth, molecular diffusion between road interfaces, and polymer chain entanglement which are strong functions of temperature [15]. Polymer coalescence has been studied in literature [16–22] and is typically expressed as a function of the material properties surface tension and viscosity. For the ME process, the thermal history at road interfaces influences the dynamics of molecular diffusion and entanglement and defines the processing window over which physical bonds can form. Thermal history of printed roads in the ME process have been analyzed using thermocouples [9], fiber Bragg gratings [23], and IR cameras [24–28], but little work has been done to couple to printed part mechanical properties.

In this work, a DoE was applied to select print parameters to observe the effects on extrudate cooling profiles, road-to-road contact lengths, and transverse tensile strength. To reduce the number of parameters in the DoE to a tractable amount, the four most significant parameters were varied: extruder temperature, print speed, layer height, and build orientation. Extruder temperature and print speed were selected as means of varying thermal history while layer height was selected to manipulate mesostructure. Build orientation was probed by fabricating tensile specimens in two orientations shown in Fig. 1a with infill patterns arranged perpendicular to the loading direction such that either road-to-road bonds (Fig. 1b) or interlayer bonds (Fig. 1c) carried applied load. Other print parameters not included in this DoE, such as nozzle size, feeder system, infill pattern, and build plate temperature, are expected to have minor effects on thermal history of interlayer bonds and mechanical performance. Nozzle size is expected to affect the number of roads in a layer and thus may impact road-to-road contact length and interlayer strength to a small degree. Changing feeder systems is expected to have a negligible effect on mechanical performance provided the target volumetric flow rate out of the extrusion nozzle is satisfied. Infill pattern of specimens printed in the XY orientation as shown in Fig. 1a will have a large effect on mechanical properties. However, in the ZX orientation, infill pattern will affect the number of roads in a layer, but the effect on interlayer bond strength is expected to be minor. Cooling of interlayer bonds was followed with an IR camera during the printing process. Printed mesostructures were analyzed by optical microscopy and normalized contact lengths were measured. Tensile specimens were printed in the build orientation described because road-to-road and interlayer bonding are identified as performance limiting. Therefore, tensile specimens were loaded to assess the performance limiting strengths. A tensile test was seen as the most direct way of probing road-to-road and interlayer bond strength and was therefore selected over other test methods, such as bending, which introduce other modes such as compression and shear. Measured tensile strengths were examined relative to normalized contact lengths.

2. Experimental procedures

2.1. Definitions of mesostructure parameters

Specimens were printed in two orientations to measure road-to-road and interlayer bond strengths. Bond strength between adjacent roads within the same layer aligned in the axial direction can be assessed with tensile coupons printed flat (XY orientation). Vertically printed (ZX orientation) tensile coupons have bonds between layers oriented in the axial direction (Fig. 1a). Mesostructures are described by measured parameters shown in Fig. 1b and 1c where L_{cx} and L_{cz} are the contact lengths over which tensile load is applied, h_x is the height or thickness of a road in the XY orientation and h_z is the road width in the ZX orientation, and W_{sx} and W_{sz} are referred to as road spacing. W_{sx} and W_{sz} are taken as the distance between adjacent contact lengths such that W_{sx} and W_{sz} reduce to h_x and h_z if there is no additional space between adjacent roads.

Table 1
Print parameters and levels from which a full-factorial DoE was created.

Factor	Low level	High level
Extruder temperature (°C)	230	270
Print Speed (mm/s)	10	50
Layer height (mm)	0.1	0.3
Orientation	XY	ZX

2.2. Printing procedure and design of experiment

Tensile strength of unidirectional ME coupons printed in the XY and ZX orientations was measured for dog bone shaped coupons. Specimens were 64 mm long, 10 mm wide in the grip section, with a gage section 5 mm wide and 28 mm long, and 2 mm thick. Coupons were fabricated from Makerbot ABS filament using an nScrypt 3Dn-500 system with an nFD pump. While the molecular weight of the filament was not measured, common values for number average molecular weight of polymer filaments used for ME are 100–200 kDa [29,30]. It is recognized that molecular weight plays a vital role in road-to-road diffusion and bond formation [31,32]. The nScrypt 3Dn-500 system utilizes a 3-axis Aerotech gantry with support for four tools. One such tool is the nFD pump which features a worm gear mechanism to advance standard 1.75 mm diameter polymer filament into a heated section comprised of a ceramic nozzle through which the polymer is extruded and a metal nozzle holder. The nozzle holder houses a cartridge heater and thermocouples connected to controllers for closed loop feedback temperature control. The gantry system is outfitted with a heated build plate measuring 330 mm square and capable of heating to 200 °C. Polyimide tape was placed over the build plate to provide a surface for adhesion to ABS and the plate temperature set points were 110 °C and 120 °C for XY and ZX oriented coupons respectively. An increased build plate temperature was required for ZX coupons to ensure adhesion between the coupons and the polyimide substrate. At a set point of 110 °C, the measured temperature at the center of the build plate was 106 °C. At a set point of 120 °C, the measured temperature at the front edge of the build plate was 113 °C. Temperature variation across the entire build plate was within 10 °C. Slic3r was used to generate G-code machine control code based on user-selected print parameters.

A full-factorial DoE procedure was used to measure tensile strength as a function of the selected print parameters in Table 1. These print parameters were selected for their expected influence over road cooling time and adjacent road contact area. Large contact area and slow cooling are expected to promote diffusion of polymer across adjacent road boundaries thereby improving road-to-road tensile strength. The DoE was conducted with four parameters each with two levels to form an experimental matrix with sixteen unique parameter combinations. These parameter combinations were applied to each print orientation. Three replicates were printed for each combination. For XY oriented coupons, three replicates sharing the same print parameters were printed non-sequentially (one layer for each before printing the next layer)