Additive Manufacturing 22 (2018) 606–617

Contents lists available at ScienceDirect

Additive Manufacturing

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

Full Length Article

Voids and tensile properties in extrusion-based additive manufacturing of moisture-cured silicone elastomer

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ARTICLE INFO

Keywords:
Silicone additive manufacturing
Extrusion-based
Soft materials
Tensile testing

ABSTRACT

The tensile strength and strain properties as well as failure modes in silicone dumbbell specimens fabricated by extrusion-based additive manufacturing are investigated. Effects of process parameters, specifically the infill direction (0°, ± 45°, and 90° relative to the tensile direction) and adjacent line spacing on the void formation and ultimate tensile strength are studied and compared to the baseline of stamped silicone specimens. The additive manufactured specimens with ± 45° and 90° infill direction and either the minimal or small void extrusion configuration had the strongest ultimate tensile strength (average ranged from 1.44 to 1.51 MPa). This strength is close to that of the sheet stamped specimens which have an average ultimate tensile strength of 1.63 MPa. As the void size became larger and more elongated in shape, the average ultimate tensile strength significantly reduced to 1.15 and 0.90 MPa for specimens with ± 45° and 90° infill direction, respectively. Counterintuitively, specimens with 0° infill direction were consistently the worst performing due to the tangency voids and poor edge surface finish resulting from the toolpath. We show that, to maximize ultimate tensile strength of silicone parts made by extrusion-based additive manufacturing, it is important to select process parameters which minimize the elongated voids, infill tangency voids, and surface edges. If these conditions can be achieved, the infill direction does not play a significant role in tensile strength of the tensile specimen.

1. Introduction

Additive manufacturing (AM) can fabricate a wide range of soft, flexible custom parts for applications in soft robotics, wearables, assistive and rehabilitation devices, seals, actuators, cushioning, energy absorption, and others [1–6]. As summarized in Table 1, five major AM processes, the selective laser sintering [7], photopolymer jetting [8,9], stereolithography based on digital light projection [1,10–12], extrusion-based fused deposition modeling of thermoplastic elastomers (TPE) [4,13], and direct extrusion of silicone [3,14] have been studied for AM of soft parts.

Each soft material in AM comes with certain limitations (Table 1). For example, most of the current commercially available soft materials for AM [7–12] have low elongation at break (110–270%). The thermoplastic polyurethane [4,13] with higher elongation at break (660%) is limited by high hardness (85 Shore A). The elastomer created by blending commercially available materials [1] can achieve a high elongation at break (1100%) but is still limited by high hardness (65 Shore A). This elastomer material blend can also be adjusted to lower the hardness, but the elongation at break quickly deteriorates. Additionally, the maximum operating temperatures of the above materials are typically low (< 60 °C).

Conversely, many silicone elastomers, denoted as silicone hereafter, are readily available and suitable for direct extrusion-based AM (the main requirement being that the material does not self-level or wet-out before curing). This can reduce the cost and barrier to entry while enabling a wide range of material properties such as high elongation at break, high tensile strength, extreme use temperatures, high fatigue life, and hardness ranging from 3 to 90 Shore A and beyond [3,14,15]. Unfortunately, there are many challenges to overcome in direct extrusion of silicone for AM of soft 3D parts. One important challenge is understanding how voids generated during the AM process impact the tensile strength and strain of the resultant part.

In the direct extrusion AM process, uncured silicone is extruded through a moving nozzle line-by-line, building up multiple layers to fabricate a 3D part [2,3,14,18]. When two silicone lines are in contact with each other, inter-layer cross-linking can occur and chemically bond adjacent lines together. Because of this, the inter-layer bonding strength in AM of silicone can be close to the original silicone material. However, it can be difficult to completely fill the 3D geometry without

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https://doi.org/10.1016/j.addma.2018.06.010
Received 28 June 2017; Received in revised form 4 June 2018; Accepted 12 June 2018

Nomenclature

C	Distancebetween two adjacent silicone lines
Cedge	Distancebetween two adjacent silicone lines at edge
Di	Innerdiameter (ID) of nozzle tip
Q	Volumetric flow rate
T	Layer height
V	Nozzle speed in the layer

Table 1
Summary of soft materials for AM. Some values for Shore A hardness, denoted with *, were approximated from the elastic modulus using Gent's correlation [16,17].

AM Process	Material	Tensile Strength [MPa]	Elongation at Break [%]	Shore A Hardness	Maximum Use Temperature [°C]	Remarks
Selective Laser Sintering	DuraForm Flex [7]	1.8	110	45 – 75	–	Low elongation
Photopolymer Jetting	TangoBlackPlus [8]	0.8 – 1.5	170 – 220	26 – 28	–	Low elongation
	Agilus30 [9]	2.4 – 3.1	220 – 270	30 – 35	–	Low elongation
Stereolithography:	SUV Elastomer [1]	0.9	500	34*	–	Properties depend on formulation.
Digital light projection		7.5	1100	65*	–	Tensile strength and elongation at break reduce with hardness.
	Spot-E resin (Spot-A Materials) [10,11]	2.26 ± 0.71	65 – 140	65	–	Low elongation High hardness ~9 cycle fatigue life
	Carbon Elastomeric Polyurethane 40 [12]	6 ± 1	190 ± 10	68	–	Low elongation High hardness
Extrusion-based: Fused deposition Modeling	NinjaFlex Thermoplastic Polyurethane [4,13]	4	660	85	60	Yield at 65% strain High hardness
Extrusion-based:	Silicone [2,3,14,18]	5 – 11	100 – 1100	3 – 90	−110 – 300	Available in many grades (e.g. food, medical, etc.).
Direct (this study)	Dow Corning 737 Silicone (this study) [19]	1.2 – 1.8	600 – 710	33	−65 – 177	> 100,000 cycle fatigue life [3]

internal voids (or internal gaps within the part) which can lead to stress concentration under loading.

Voids are challenging to minimize in parts produced by extrusion-based AM of silicone and can be a key factor impacting the part strength and durability. There are two regions for void generation in extrusion-based AM: "between layers" and "within layers". For between layers, Plott et al. [3] studied the effects of compression in extrusion-based AM of silicone to avoid or reduce the void formation. The cross-sectional view of the vertical stack of extruded silicone lines showed that "voidless" AM of silicone was feasible. Compression of silicone during extrusion-based layer deposition also caused the deformation which affected the part mesostructure [3]. The other source of void generation, within the layer, is caused by geometrical situations (e.g. the sharp corner) where a given line width cannot fill 100% of the area within a layer. Tensile testing of dumbbell (or dog-bone) shaped specimens is a standard way of quantifying the effects of AM process parameters on void formation and tensile strength and strain.

A plurality of tensile test studies have been performed for extrusion-based fused deposition modeling (FDM) of acrylonitrile butadiene styrene (ABS) material [20–25]. These studies showed that the build direction, material flowrate, distance between adjacent lines, layer orientation, and layer thickness all affect the strength of the FDM parts. Another study utilized computed tomography (CT) to reveal that voids of various sizes exist inside a FDM part [26]. It is evident that parts produced by FDM had a lower tensile strength than an injection molded part of the same shape and material due to the void formation and other factors [24].

In this study, the ASTM D412 Type C dumbbell tensile specimen [27] is selected as the standard shape for extrusion-based silicone AM to fabricate tensile specimens and investigate the void formation effect on tensile strength and strain. A variety of AM toolpaths and process parameters were used to fabricate these specimens with voids of varying dimensions and locations. Tensile specimens of the same dumbbell shape were also stamped out of a solid sheet of the cured silicone material and evaluated as the baseline results for comparison. Prior to the tensile tests, optical examination was used to quantify voids, or internal gaps, within the specimens to determine the effects of void geometry and orientation on tensile strength and strain. After the tensile tests, the broken surfaces were imaged for failure mode analysis. Breaking these specimens in tension allows for the quantification of tensile strength and strain, observation of the fracture surface, and correlation of voids and AM process parameters on the failure mode and tensile test results.

The silicone material, extrusion-based AM methods, and tensile test setup are introduced in the next section. The pre-tensile test inspection

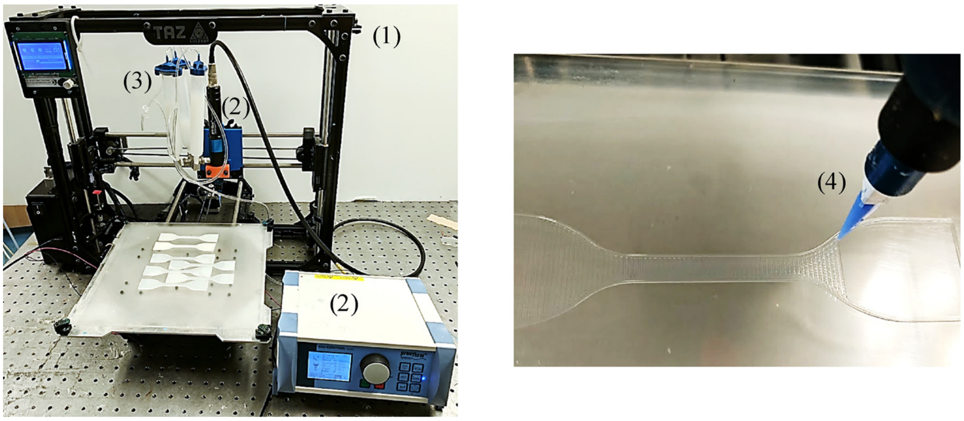

Fig. 1. Experimental setup for extrusion-based silicone AM including: (1) motion control platform, (2) progressive cavity pump and controller, (3) pressurized syringe barrels, and (4) tapered nozzle.