Scripta Materialia xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Scripta Materialia

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

Viewpoint Set

Role of anisotropic properties on topology optimization of additive manufactured load bearing structures

Pu Zhang [a,b,1], Jikai Liu [a,c,1], Albert C. To [a,*]

[a] Department of Mechanical Engineering and Materials Science, University of Pittsburgh, Pittsburgh, PA 15261, United States
[b] School of Mathematics, University of Manchester, Manchester, United Kingdom
[c] Department of Mechanical Engineering, University of Alberta, Edmonton, Canada

ARTICLE INFO

Article history:
Received 23 July 2016
Received in revised form 13 September 2016
Accepted 18 October 2016
Available online xxxx

Keywords:
Additive manufacturing
Anisotropy
Topology optimization

ABSTRACT

Additive manufacturing technology provides a revolutional way of producing engineering structures regardless of their geometric complexity. Hence, topology optimization technique is rapidly becoming a promising tool to design additive manufactured structures to reduce weight and achieve optimal performance simultaneously. However, a common feature of additive manufactured materials is their anisotropy arising from the design and manufacturing process. Therefore, this viewpoint paper aims at presenting an overview of the anisotropy of additive manufactured materials and providing some insights into the role of anisotropy in topology optimization of additive manufactured load-bearing structures.

1. Introduction

Additive manufacturing (AM) technology is now able to manufacture engineering components with plenty choices of materials and processing methods [1], while meeting the standards in load bearing applications. AM enables the fabrication of parts with complicated geometry that are impractical to be manufactured using conventional subtractive manufacturing methods. Since complex geometry can be easily realized by AM, topology optimization technique [2] has become a powerful tool to generate optimal design for AM parts. For example, researchers have achieved unprecedented success in integrating AM technology with conventional topology optimization techniques to design and manufacture engineering parts with reduced weight and optimal performance. However, it is well-known that mechanical properties of the materials fabricated by AM are quite different from those of traditional molded or wrought counterparts. A ubiquitous feature is that almost all of the AM as-built materials exhibit some anisotropy in different mechanical properties due to the layer-by-layer manufacturing technique employed in AM. Thus, this letter aims at briefly reviewing the anisotropy of AM materials and providing insights into the influence of material anisotropy on the topology optimization of AM load-bearing structures. Some perspectives on future research trends and challenges will be provided as well.

* Corresponding author.
E-mail address: albertto@pitt.edu (A.C. To).
[1] PZ and JL contribute equally to this work.

2. Anisotropy of AM materials

2.1. Overview

A common and well-known feature of AM materials is their material anisotropy. The material anisotropy can be roughly classified into two categories: Process-induced anisotropy and intrinsic anisotropy. Some typical causes of material anisotropy are illustrated in Fig. 1. The process-induced anisotropy is caused by the layer-by-layer manufacturing feature of the AM process [1], which results in anisotropic microstructures. In contrast, the intrinsic anisotropy arises from the materials or structural design process, such as multilayered composites or anisotropic lattice materials [3]. In general, process-induced anisotropy is not preferred while the latter is beneficial. Almost all AM materials including metals, alloys, plastics, composites, and ceramics exhibit certain extent of anisotropy.

2.2. Metals and alloys

Ti and Ni based superalloys play a central role in the AM industry for metals and alloys [4]. The material anisotropy of AM Ti-6Al-4V has been studied extensively for both the powder bed fusion (PBF) and direct energy deposition (DED) processes [5–7]. The microstructure of Ti-6Al-4V, typically a lamellar structure with columnar grains, is anisotropic [8] due to layer-wise processing and directional grain growth. The mechanical behaviors along the horizontal and building directions can be quite different [8–10] and are dependent on processing parameters, microstructure evolution, impurities and defects, etc. Detailed research on the anisotropic elastic, yielding, and fatigue behaviors can be found in

http://dx.doi.org/10.1016/j.scriptamat.2016.10.021

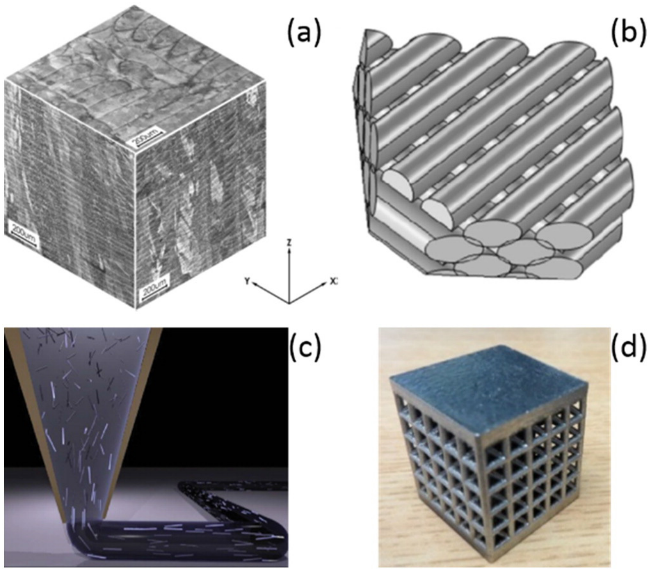

Fig. 1. Some origins of material anisotropy in AM materials. (a) The lamellar structure of Inconel 718 [14]. (b) The orthogonal filaments in the FDM process [24]. (c) Short fiber alignment during the extrusion process of a composite [3]. (d) An AM lattice structure (Inconel 718) with designed cubic structure.

the literature [8–12]. In addition, the material anisotropy can be reduced by proper post heat treatment [8,9], that is accompanied by reduced strength, enhanced ductility, and higher fatigue resistance.

Ni alloys including In718 (see Fig. 1(a)), In625, and In939 have been manufactured by AM and characterized by a few researchers [13–15]. Both microstructure anisotropy and material property anisotropy are observed for Ni alloys. Interestingly, the material properties are usually the highest along the inclined direction (45°) [13,14], implying the preferred growth direction for the columnar grains. Therefore, the material anisotropy will depend on the anisotropic grain structure and also the preferred growth direction of the crystal.

2.3. Plastics, composites, and lattice materials

The widely adopted AM techniques for plastics include selective laser sintering (SLS), stereolithography (SLA), ink-jetting, PolyJet, and fused deposition modeling (FDM). The material anisotropy of AM plastics is much more significant than that of metals and alloys. Generally, the elastic modulus, yield strength, ductility, and fracture strength are strongly dependent on the building direction. The SLA, ink-jetting, and PolyJet techniques all adopt UV crosslinked polymers. The material anisotropy depends on the monomers/oligomers being used, UV light intensity, exposure time, layer thickness, et al. Generally, the plastics manufactured by these three processes exhibit lower moduli and tensile strength along the building direction [16,17], but there are also a few

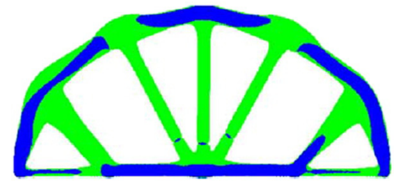

Fig. 3. Optimal geometry for a two-material topology design [44].

exceptions. The FDM products [18] show strong material anisotropy (see Fig. 1(b)), not only because of the layer-wise manufacturing feature, but also due to the use of filaments as its feedstock material.

Composites can usually be manufactured via SLA and FDM processes by mixing particles/fibers into the feedstock polymers [3,19] or employing multiple material printing technology [20,21]. The material anisotropy of the AM composites depends on two factors: The layer-wise processing feature and the inclusion phase distribution (see Fig. 1(c)). However, there is little work done to characterize the material anisotropy of AM composites.

Meanwhile, it is quite convenient to employ AM to fabricate lattice materials/structures designed with certain geometry but with exceptional mechanical/physical performance and lightweight characteristics [3,22]. These lattice materials produced by AM exhibit two levels of anisotropy [17,23], e.g., at the macroscale and microscale (see Fig. 1(d)).

3. Topology optimization of AM structures: Current status

Topology optimization has been recognized as a powerful technique for designing AM load-bearing structures [25] because the optimal structures could be manufactured by AM easily even for highly complex geometries (see Fig. 2). The standard methods, including homogenization [26], SIMP (Solid Isotropic Material Penalization) [2], level set [27,28] have been widely adopted for AM-oriented topology optimization. Several AM-related aspects have been targeted or addressed, including multi-material structures [29], the manufacturability issue [30], and the minimum component size issue [31], etc. Nevertheless, as pointed out in [31,32], a lack of feasible solutions is still the situation for many problems. Specifically, we focus on the issues of topology optimization in the presence of material anisotropy of AM materials.

3.1. Topology optimization subject to material anisotropy

Topology optimization in the presence of material anisotropy is a long-standing research topic, which primarily concerns with the concurrent topology and material orientation optimization. Several approaches have been developed and are compared below.

A theoretical approach is to distribute the material orientation along the principal stress direction, which is named stress-based method [33,34]. This approach was proven effective for shear "weak" and some shear "strong" orthotropic materials. In addition, similar rules have

Fig. 2. Load-bearing structural components that are fabricated by additive manufacturing. (a) An automotive control arm printed by the binder jetting process in 420 stainless steel (courtesy of Jeff Shepler (ExOne)), (b) An accelerometer bracket printed by the electron beam method (EBM) in titanium alloy (courtesy of Keith Roberts (AMRDEC) and Devlin Hayduke (Materials Sciences Corporation)), and (c) A lattice structured pillow bracket fabricated by the selective laser melting process in titanium alloy.

Please cite this article as: P. Zhang, et al., Role of anisotropic properties on topology optimization of additive manufactured load bearing structures, Scripta Materialia (2016), http://dx.doi.org/10.1016/j.scriptamat.2016.10.021