Scripta Materialia xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Scripta Materialia

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

Viewpoint article

Non-beam-based metal additive manufacturing enabled by additive friction stir deposition

Hang Z. Yu [a,*], Mackenzie E. Jones [a], George W. Brady [a], R. Joey Griffiths [a], David Garcia [a], Hunter A. Rauch [a], Chase D. Cox [b], Nanci Hardwick [b]

[a] *Department of Materials Science and Engineering, Virginia Tech, 445 Old Turner Street, Blacksburg, VA 24061, USA*
[b] *Aeroprobe Corporation, 200 Technology Drive, Christiansburg, VA 24073, USA*

ARTICLE INFO

Article history:
Received 8 February 2018
Received in revised form 13 March 2018
Accepted 16 March 2018
Available online xxxx

Keywords:
Metal additive manufacturing
Thermomechanical processing
Friction stir welding
Dynamic recrystallization
Equiaxed microstructure

ABSTRACT

Beam-based processes are popularly used for metal additive manufacturing, but there are significant gaps between their capabilities and the demand from industry and society. Examples include solidification issues, anisotropic mechanical properties, and restrictions on powder attributes. Non-beam-based additive processes are promising to bridge these gaps. In this viewpoint article, we introduce and discuss additive friction stir deposition, which is a fast, scalable, solid-state process that results in refined microstructures and has flexible options for feed materials. With comparisons to other additive processes, we discuss its benefits and limitations along with the pathways to widespread implementation of metal additive manufacturing.

1. Introduction

Among the seven types of additive manufacturing (AM) technologies classified by the American Society for Testing and Materials (ASTM) [1], the beam-based technologies, i.e. powder bed fusion and directed energy deposition, represent the main approaches for fabricating metals and alloys today. These are high-temperature and high-energy processes, in which a laser or electron beam is applied to selectively melt powders that are either pre-deposited to form a powder bed or delivered by powder feed nozzles [2–9]. The interactions of the high-energy beam and powders cause a series of complicated physical processes, including powder melting, dynamic melt flow, and rapid solidification [3,10]. Because the microstructure of the raw powders is destroyed during melting, the microstructure of the as-manufactured part is mainly determined by the rapid solidification process, with a cooling rate around 10^3–10^7 K/s [4]. The last few years have borne witness to exciting advances in the research of beam-based technologies, including microstructure manipulation and quality control [2–18].

Even with these advances, significant gaps still exist between what the high-cost, high-energy, beam-based AM technologies offer and what society and industry need. First, beam-based metal AM processes are energy inefficient and incapable of reliably fabricating non-weldable alloys, such as 2xxx or 7xxx Al alloys [19,20]. In addition, most structural applications require isotropic mechanical properties; because of epitaxial solidification, however, beam-based AM processes generally lead to highly orientated, columnar grains with anisotropic mechanical properties [13,21]. Moreover, future critical applications will necessitate the use of high performance alloys with specific compositions, such as twinning induced plasticity steels and quenching and partitioning steels [22–25]. To fabricate these alloys with beam-based AM processes, high-quality powders with the desired composition, shape, and size distribution are required [26–28]. Making suitable powders is already time-consuming and expensive, let alone the subsequent efforts needed to determine the processing conditions for optimal part quality. These factors severely limit the viability of beam-based technologies for manufacturing large-scale, high-quality parts with consistent composition and isotropic properties.

The above limitations stem from the nature of beam-based processes: melting of high-quality powders followed by rapid solidification. Are there alternative metal AM approaches that avoid these limitations? Scientists and engineers have developed several non-beam-based, solid-state additive processes [29–33], and some are promising for widespread use. The metal AM research community is starting to acknowledge these alternative processes. For example, the MS&T 2017 conference featured a symposium titled ‘Non-beam-based additive manufacturing approaches for metallic parts’ [34].

In this viewpoint article, we introduce and discuss *additive friction stir deposition*, which is an emerging low-temperature and low-cost additive process that consistently produces a ‘wrought microstructure’ (i.e. result of thermomechanical processes) rather than a ‘cast microstructure’ (i.e. result of solidification). It enables fast, scalable

---

* Corresponding author.
E-mail address: hangyu@vt.edu. (H.Z. Yu).

https://doi.org/10.1016/j.scriptamat.2018.03.025
1359-6462/© 2018 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.

Please cite this article as: H.Z. Yu, et al., Non-beam-based metal additive manufacturing enabled by additive friction stir deposition, Scripta Materialia (2018), https://doi.org/10.1016/j.scriptamat.2018.03.025

manufacturing for a broad range of engineering alloys and composites [33,35,36]. While most solid-state additive processes are based on sheet lamination [30,37], this process enables near-net shaping via *site-specific deposition.* The size of the site in this context is dependent on the in-plane resolution of the process. As a new technology that recently entered the public eye, however, its research is still in an elementary state with many fundamental aspects not fully understood. This viewpoint article aims to provide an overview of the status of additive friction stir deposition, to discuss its benefits and limitations through comparisons to other AM processes, and to stimulate discussions on the pathways to widespread implementation of metal AM.

2. Basic physical processes

2.1. Process description

Additive friction stir deposition enables solid-state additive manufacturing of metals and metal matrix composites [35,36]. The central component of the system is a hollow shoulder, through which the feed material in the form of either a solid rod or powder is delivered [38]. The shoulder rapidly rotates and generates heat through dynamic contact friction at the shoulder-material interface and material-substrate interface (Fig. 1 (a)) [32,33]. Heated and softened, the filler material is fed through the tool and bonds with the substrate through plastic deformation at the interface. The transverse motion of the shoulder results in deposition of a single track of material, typically several hundreds of microns thick. The first layer is formed by the tool traveling across the surface of the substrate; by selectively adding subsequent layers upon the initial one, 3D parts are made.

The first commercialized technology of this type was developed and patented by Aeroprobe Corporation, which has a proprietary version of the process [36]. To highlight its deposition nature and distinguish it from other friction stir processes, we refer to the process as additive friction stir deposition throughout the paper.

2.2. Underlying materials science

Additive friction stir deposition is a thermomechanical process. Important processing parameters include the shoulder rotation frequency Ω, shoulder normal force P, filler material feed rate R, layer height h, and transverse speed V_{Tra} [35,38]. These parameters control the heat flow and material flow processes, which are fully coupled. For the deposited material, the heat generation, dissipation, and transfer mechanisms are similar to the stirred material in friction stir welding or processing. In both cases, heat is generated by dynamic contact friction between material and tool, dissipated by severe plastic deformation of the material, and transferred inside the material by thermal conduction and thermal convection via material flow. The governing equation of heat transfer is expected to be similar for the two cases [39]:

$$\frac{\partial}{\partial t}\rho C_P T + \nabla\cdot\rho\vec{u}(C_P T) + \nabla\cdot\kappa\nabla T = \dot{q}. \tag{1}$$

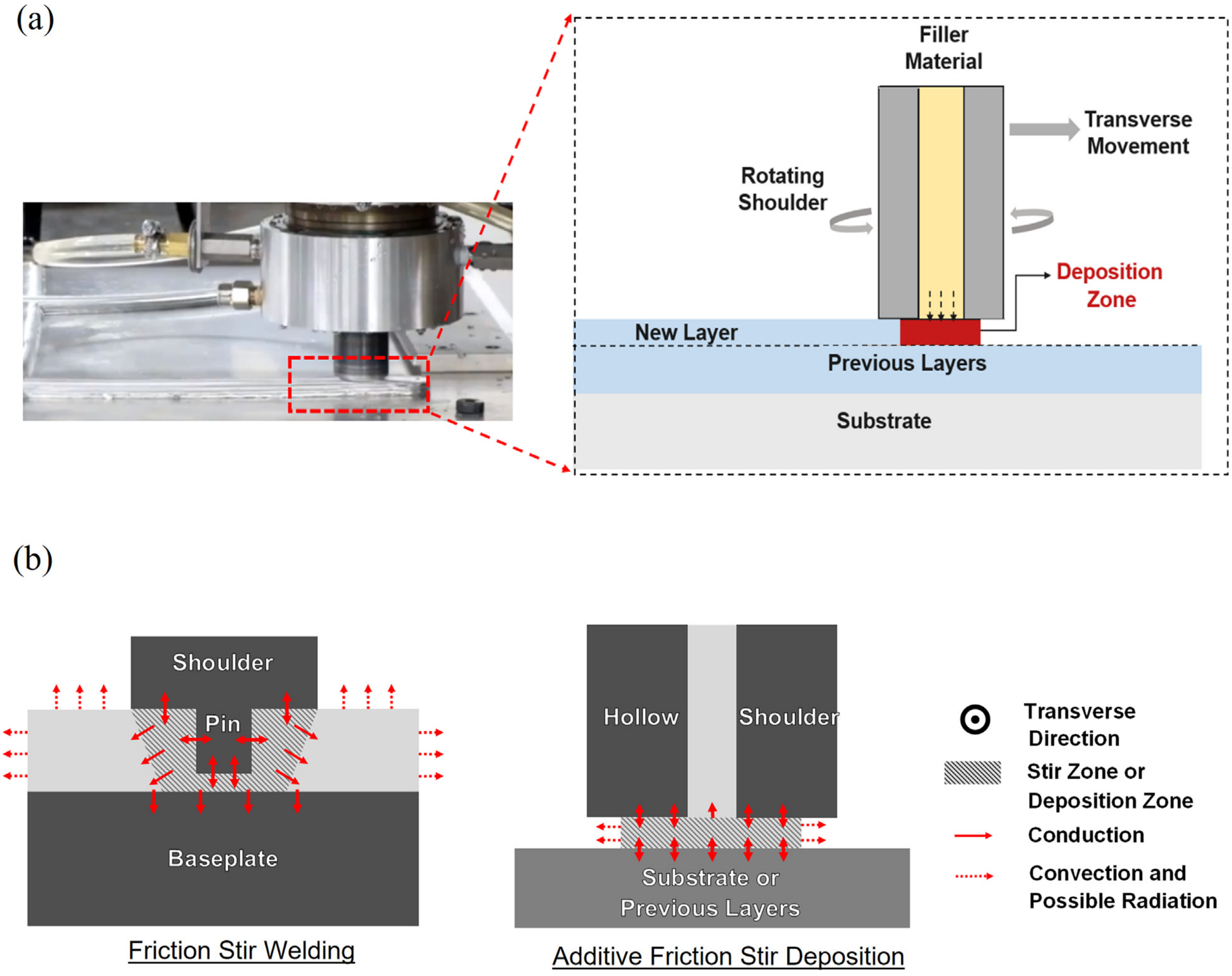

Fig. 1. (a) An image of the rotating shoulder during additive friction stir deposition and a schematic to highlight the basic physical processes in the deposition region. (b) Boundary conditions of heat flow: a comparison between the stirred material in friction stir welding and the deposited material in additive friction stir deposition.

Please cite this article as: H.Z. Yu, et al., Non-beam-based metal additive manufacturing enabled by additive friction stir deposition, Scripta Materialia (2018), https://doi.org/10.1016/j.scriptamat.2018.03.025