Closing the material loop in additive manufacturing: A literature review on waste recycling

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Abstract. Additive manufacturing (also referred to as 3D printing) technologies have found applications in a wide range of industries such as aerospace and automobile, due to their superior manufacturing capability and design freedom enabled by the layer-wise fabrication method. Over the past decade, the adoption of additive manufacturing has evolved from rapid prototyping and tooling to rapid manufacturing of end-use products, which, on the other hand, introduced new challenges for reducing the environmental impacts and enhancing resource sustainability of additive manufacturing from a lifecycle perspective. In current literature, some research efforts have been conducted on waste recycling aiming to close to material loop and relieve the environmental consequences caused by both pre- and post-consumer wastes generated from additive manufacturing. This article provides an overview of the state-of-the-art on additive manufacturing waste recycling and identifies critical gaps for future research in this field.

Keywords: Additive manufacturing; Recycling; Closed-loop material flow; Environmental impact; Resource sustainability.

1. Introduction
Additive manufacturing (AM), or 3-dimensional (3D) printing, refers to processes that fabricate products from 3D model usually layer-by-layer, and it is fundamentally different from traditional formative and subtractive manufacturing. Based on different processes, AM can be categorized into seven groups [6], i.e., binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization. In recent years, owing to technological advancements in AM processes and materials, the global AM market has been rapidly increasing. According to surveys conducted by the Wohlers Associates, in 2017, the AM industry consisting of all AM products and services worldwide, grew 21% from 2016 and reached to USD 7.34 billion [55]. The global AM market is expected to grow to USD 36.61 billion by 2027 from USD 8.44 billion in 2018, at a compound annual growth rate (CAGR) of 17.7% [32].

Compared to traditional manufacturing, AM can provide shortened product development cycle, additional design freedom, and increased manufacturing complexity. Additionally, enhanced environmental sustainability has been touted as one of the main advantages of AM with respect to high material efficiency, low scrap rate, and reduced or even eliminated need for tooling, cutting fluids and lubricants. Furthermore, AM can revolutionize the current supply chain structures by offering localized
and/or regional strategies for production, transportation, as well as end-of-life (EOL) options. An example of AM supply chain is illustrated in Figure 1. In current literature, most research efforts are focused on developing new AM feedstock materials [26][33][46], improving printing technologies [28][30], and evaluating production performance and quality [11][13][29][57].

![Figure 1. An example of additive manufacturing supply chain.](image)

Comprehensive reviews exist for the state-of-the-art of AM in terms of design and modelling methodologies [9][56], production processes [8][23][45][58], feedstock materials [17][27][34][54], different applications [53][59], and environmental sustainability [1][2][35][39]. In this article, we aim to provide an overview on AM waste recycling and identify critical knowledge gaps in facilitating the closed-loop material flows in AM. The current literature on AM waste recycling is reviewed based on different feedstock materials, i.e., metal powder recycling as shown in Section 2 and plastic wastes recycling as shown in Section 3. In addition, conclusions and future research topics are discussed in Section 4 aiming to provide useful insights on AM waste recycling and facilitate multidisciplinary collaboration in the field.

2. The state-of-the-art on AM metal powder recycling

The current literature on waste recycling of metal powders used in AM is summarized in Table 1. Most studies reviewed in this section are focused on evaluating the performance of recycled powders (micro-level performance in terms of porosity, particle size distribution, etc.) and printed parts using recycled powders (macro-level performance in terms of mechanical properties and surface quality). Meanwhile, the lifecycle environmental sustainability of recycling metal powders is also investigated. In addition to the literature shown in Table 1, research efforts have also been dedicated to improving the performance of recycled powders. As an example, thermal post-processing is adopted to enhance the recyclability of AlSi10Mg powders in SLM [31].

| Category                     | Citation                                      | Material                  | AM   | Main findings                                      |
|------------------------------|-----------------------------------------------|---------------------------|------|----------------------------------------------------|
| Recycling performance evaluation | (Strondl, Lyckfeldt, Brodin, & Ackelid, 2015) | Ti-6Al-4V, Ni alloy       | EBM, SLM | Differences in particle size and flow ability      |
|                              | (Slotwinski et al., 2014)                     | Stainless steel & cobalt-chrome | DMLS | Increased powder size distribution                 |
|                              | (Asgari, Baxter, Hosseinkhani, & Mohammadi, 2017) | AlSi10Mg_200C              | DMLS | Comparable powder characteristics, microstructure and mechanical behaviour |
|                              | (Ardila et al., 2014)                        | IN718                      | SLM  | No significant change in powder and test part properties |
|                              | (Popov, Katz-Demyanetz, Garkun, & Bamberger, 2018) | Ti-6Al-4V                 | EBM  | Recycling causes various defects                   |
The following observations can be made from the current literature.

- Sieving is used as the sole recycling method in most metal powder recycling studies. New methods are required in order to further improve the quality of recycled powders.

- The comparison results on micro-level powder characteristics between virgin powders and recycled powders are not consistent for different materials and/or AM processes. As an example, no significant changes are observed in powders for IN718 in [4] while increased porosity is detected in [40].

- The macro-level properties of parts fabricated using recycled materials need to be further expanded to include the profiles and roughness of printed surfaces.

- Most existing studies indicate no significant change in mechanical properties within a certain range of recycling cycles.

- Almost all studies adopt empirical approaches, and therefore their results are only applicable to certain experimental conditions.

### 3. The state-of-the-art on AM plastic waste recycling

The current literature on waste recycling of plastic feedstock used in AM is summarized in Table 2. Two types of plastics are usually used in AM and investigated by the literature, i.e., thermosetting resin and thermoplastic polymers like ABS, HDPE and PLA. The current literature on recycling plastic wastes in AM is mainly focused on three aspects, 1) proposing recyclable materials to be used in AM; 2) recycling performance evaluation; and 3) sustainability evaluation, as categorized in Table 2.

### Table 2. A summary of current literature on plastic recycling in AM.

| Category                        | Citation                                                                 | Material               | AM     | Recycling            | Main findings                                                                 |
|---------------------------------|--------------------------------------------------------------------------|------------------------|--------|---------------------|-------------------------------------------------------------------------------|
| Proposing recyclable material   | (Plummer, Vasquez, Majewski, & Hopkinson, 2012)                         | Thermoplastic PUR powder | LS     | Sieving             | No significant degradation in properties                                       |
|                                 | (Shi et al., 2017)                                                      | Thermosetting epoxy ink | DIW    | Chemical dissolution| Good printability                                                             |
|                                 | (Boparai, Singh, Fabbrocino, & Fraternali, 2016; Stoo & Pickering, 2017, 2018; Tian et al., 2017) | Composites             | FDM    | Fiber treatment     | Enhanced mechanical properties & thermal stability                            |
| Recycling performance evaluation | (Baechler, DeVuono, & Pearce, 2013)                                      | PLA                    | FDM    | Mechanical (RecycleBot) | Technical evaluation (quality, time & energy consumption)                      |
The following observations can be made from the current literature.

- Most studies on thermoplastic polymer recycling are focused on PLA. Acrylonitrile butadiene styrene (ABS) needs to be studied as well.
- Almost all studies adopt empirical approaches, and therefore their results are only applicable to certain experimental conditions.
- The material properties of recycled plastics have not yet been comprehensively characterized, which is the root cause for potential decrease in print quality and mechanical properties.
- The sustainability of recycling needs to be further evaluated from both process-level and lifecycle perspective. For example, the cost-effectiveness of recycling wasted materials is currently unknown, and whether incorporating recycling into the AM lifecycle is environmentally sustainable has not yet been assessed.

### 4. Conclusions and Future Research Directions

In this article, the state-of-the-art on AM waste recycling is reviewed for both metal and plastic feedstock materials. To further advance the understandings of the recycling process, some future research directions are identified as follows.

- The relationships between waste material properties (for both metal powders or plastic scraps), recycling process design and planning, and achieved print performance using recycled materials, need to be characterized. This interrelation will enable a prior prediction on recycling performance and greatly aid the better control and optimization on the recycling process.
- The energy and material flow in the recycling process needs to be characterized and incorporated into a comprehensive life cycle assessment as inventory data, to evaluate the environmental sustainability of AM waste recycling.
- Different supply chain designs considering AM waste recycling need to be compared and evaluated jointly considering cost and carbon footprint.

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**Acknowledgements**

This research is supported by the Research Experience for Undergraduates (REU) program, College of Engineering, University of Texas at Arlington (UTA). This research is also supported by the National Science Foundation under Grant No. 1605472. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.