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Low cost irregular feed stock for laser powder bed fusion

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ABSTRACT

Spherical powders are almost exclusively deployed for metal laser powder bed fusion (LPBF) additive manufacturing (AM). In this work, low-cost irregular powder feedstock is studied for its potential in three key areas to meet minimum AM process requirements, namely: (1) hopper flow, (2) layer spreading, and (3) de-powdering. Irregular water-atomized Iron powder was used as the study population, while spherical plasma-atomized Inconel 625 powder was used as the control. Powder flow characteristics were obtained using a FT4 Powder Rheometer (Freeman Technology). Layer spreading was evaluated indirectly via powder bed density measurements. Measurements were quantified by using printed artifacts for captive powder and evaluated using isopropanol infiltration and three-dimensional computed tomography (CT) imaging (Zeiss Xradia 520 Versa). Powder clearing from fine channels was quantified through vision-based measurements of printed artifacts (Dino-Lite DinoCapture 2.0). The results from this work demonstrated that: (1) A larger opening and steeper hopper angle are necessary to maintain a mass flow regime with the irregular powder. (2) Powder bed density is similarly consistent across the bed indicating adequate spreadability. (3) Water-atomized Iron powder has better de-powdering characteristics in the smallest cleared 0.6 mm diameter features, likely due to its 15% lower bed density.

1. Introduction

Additive manufacturing (AM) has had an impact in nearly every sector of our economy, with a disruptive effect on supply chains [1]. For metal laser powder bed fusion (LPBF) AM, there is a need for access to low-cost metal powders. Pure Iron has previously been used as a low-cost feedstock material for LPBF [2–9]. With the exception of the work of Zhang and Coddet [8], all reports for this material in the open literature use irregular powder feed stock such as water atomized powder [2–6,9] or hydrogen reduced sponge Iron [7]. This successful body of work calls into question the need for highly spherical powder, leading to the hypothesis that feedstock costs may be greatly reduced for some alloys through use of a less expensive atomization technology. Anticipating industry interest in deployment of low cost alloys, the authors have identified three key areas where irregular feedstock may pose a challenge for LPBF, namely: (1) hopper flow, (2) layer spreading, and (3) de-powdering. These areas will be described in more detail and the performance of low-cost water-atomized iron is evaluated for these aspects.

1.1. Hopper flow considerations

While the majority of powder bed systems use a piston powder feed bed system, a significant number of systems use some form of hopper powder delivery mechanism. The market share for piston-based systems is approximately 64% (EOS, Concept Laser, 3D Systems), while the market share for hopper-based systems is approximately 34% (Arcam, Renishaw, Realizer) [10]. The advantages of hopper feed powder delivery systems are the potential for automated powder recycling and reduced operator exposure associated with powder bed management. The disadvantage is the dependence on gravity to introduce powder flow, unlike the positive displacement associated with piston designs. Poor powder flow may also lead to non-uniform spreading onto the build bed, which may lead to part defects.

Particle shape has been shown to significantly affect the flow pattern, discharge rate, and clogging probability in hopper systems [11,12]. For spherical and ellipsoidal granular materials, it was found that flow patterns are organized, with a good flow irrespective of the wedge angle of the hopper and displaying a parabola flow pattern shape [11]. The irregular-shaped powders have an unsteady flow with a flow zone characterized by straight lines; however, these powders display shorter residence times than spherical or ellipsoid granules [11]. Hopper flows are classified into three primary regimes: mass flow, funnel flow, and mixed flow [13]. Under the ideal mass flow regime, powder flow is orderly and predictable and a *first in, first out* condition

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prevails, minimizing segregation by having all the stored particles in motion during discharge [13]. In funnel flow, select particles are in motion, forming a channel above the discharge outlet [13]. In funnel flow, several failure modes can result, namely: (1) segregation due to stagnant regions, (2) powder starvation due formation of a stable arch, or (3) erratic flow leading to inconsistent powder feed [13]. Mixed flow is a combination of both methods, with transition phases between mass and funnel flow depending on various factors such as shear forces between particles and between the wall and particles, particle interlocking, gravity effects, and hopper inclination. Overall, the type of hopper flow regime is predictable in a hopper system configuration with a given powder, based on experimental rheological analysis of the powder and knowledge of the limiting hopper system geometry. For irregular-shaped powders, it is important to understand the limiting factors associated with the hopper flow. Rheological analysts of the water-atomized Iron powder was deployed to evaluate hopper flow.

1.2. Layer spreading and powder bed density considerations

The most significant effects of poor layer spreading are expected to be spatially inconsistent powder bed density and powder segregation [14,15], leading to variations in part quality (porosity, geometry, microstructure) due to inconsistent laser interaction with the powder bed [14,16]. Part geometry effects can be evaluated based on the assumption that the powder bed thickness in a given region is sufficient to melt down into a solid layer of the desired layer thickness (Fig. 1a). The powder layer is notably thicker than the final solidified layer thickness [14,17] and inconsistencies in powder bed density are expected to result in geometric distortions proportional to the layer thickness multiplied by the difference in bed density (Fig. 1b). In addition, the significance of powder density variations due to spreading on laser-powder interaction can be evaluated via an internal reflection model proposed by [16] that accounts for particle size, layer thickness, and relative density.

Two factors have been discussed in literature in the context of non-uniform powder density distributions across the build bed, namely powder starvation due to excessively low flowability and low powder bed relative density; both factors resulting in poor part qualities. Powder starvation effects are not specifically highlighted in the available literature for the Iron material [2–7,9] and is easily avoided via selection of an appropriate layer thickness for the particle size distribution [14]. In general, with conventional spherical powders, part densities of 99%+ are routinely produced despite the powder bed relative density being between 40% (predicted [14]) and 60% (measured [15]). For irregular powders, the density is expected to be closer to the lower 40% range [18]. Limited experimental information is available in the open literature on powder bed density measurements [19]. To the authors' knowledge, none is available for irregular powders. This is in part due to challenges in sampling the undisturbed powder bed. The approach used in this paper extends the work of Jacob et al. [15] with powder capture artifacts, by examining the suitability of powder capture cups and the practicality of evaluating cup volume via X-ray computed tomography (CT). The powder bed density measurements for water-atomized Iron powder at various locations across the build bed were considered in this work. This knowledge will enable a better understanding of the layer re-coating performance and allow for better tailoring of LPBF process parameters for optimized recipe development.

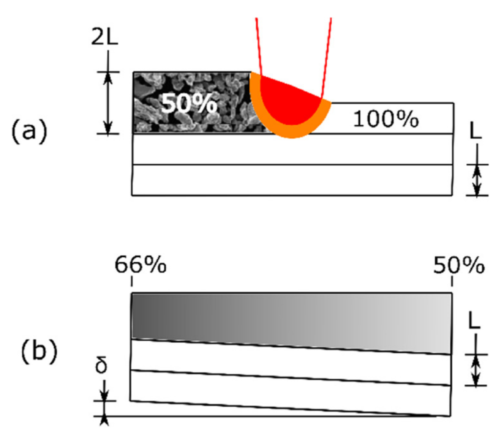

Fig. 1. Geometric effects of powder bed density: (a) uniform density layer re-coating; (b) variable density layer re-coating.

1.3. De-powdering considerations

Most artifacts for AM aim at evaluating part quality, such as dimensional accuracy, mechanical properties, or process feasibility for a minimum feature size. Rebaioli and Fassi [20] present an extensive and recent review on AM test artifacts, where the authors discuss the artifact designs and the associated part qualities of interest. While some of these artifacts include holes or channels, no significant comments are made about testing for powder clearing, powder removal or de-powdering. Letenneur et al. [9] studied the same material used in this paper with LPBF, and reported successfully printing a horizontal channel of width 0.2 mm. However, the authors do not comment on the channel depth or how well the powder cleared out of the channel. De-powdering thus remains to be understood for this material and has been explored in this work.

Overall, when deploying irregular powder particles in the production of metal components using LPBF, it is important to understand three important aspects. Firstly, the relationship between the powder and the powder delivery mechanisms to ensure that powder is dispensed with a steady and uninterrupted flow, specifically if a hopper system is used. Secondly, it is necessary to have an understanding of the achievable powder bed density to avoid powder starvation and low part density. Lastly, it is important to experimentally validate the minimum achievable feature size due to de-powdering considerations. In this work, these three aspects are considered for water-atomized Iron powder. The performance of this powder is compared against spherical plasma-atomized Inconel 625 powders with a similar powder size distribution.

2. Materials and methods

2.1. Powder characterization

Water-atomized pure Iron powder (passing 325 mesh, < 44 μm) was supplied by RioTinto Metal Powders. The chemical composition is identical to that used by [9]. Plasma-atomized Inconel 625 (Renishaw plc) was used as a control.

Powder size distribution and sphericity distribution with respect to particle size were characterized by using a Retsch Camsizer X2 with XJet module. Six replicates were run, with a sample size of 2 g, dispersion pressure of 20 kPa, active velocity adaptation, and a nominal covered area of 0.2%. The Camsizer uses an image-based approach to characterize the powder. Sphericity is described in Eq. (1), where A is the area covered by a particle projection and P is its perimeter. For an ideal sphere, the value of sphericity is 1.

$$sphericity = \frac{4\pi A}{P^2} \tag{1}$$

A number of characteristics of particle size are available; two are used in this paper. Maximum Feret diameter (X_{Fe_max}) is defined as the maximum distance between two tangents to the particle surface placed perpendicular to the measuring direction. X_{c_min}, is defined as the shortest chord length of the set of maximum chord lengths with respect to rotation angle around the particle centroid. Maximum Feret diameter and x_{c_min} respectively characterize the largest gap a particle is able to