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Feedstock powder processing research needs for additive manufacturing development

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ABSTRACT

Additive manufacturing (AM) promises to redesign traditional manufacturing by enabling the ultimate in agility for rapid component design changes in commercial products and for fabricating complex integrated parts. By significantly increasing quality and yield of metallic alloy powders, the pace for design, development, and deployment of the most promising AM approaches can be greatly accelerated, resulting in rapid commercialization of these advanced manufacturing methods. By successful completion of a critical suite of processing research tasks that are intended to greatly enhance gas atomized powder quality and the precision and efficiency of powder production, researchers can help promote continued rapid growth of AM. Other powder-based or spray-based advanced manufacturing methods could also benefit from these research outcomes, promoting the next wave of sustainable manufacturing technologies for conventional and advanced materials.

1. Introduction

Additive manufacturing (AM) is an extremely active area of materials and manufacturing sciences research due to its promise to change the manufacturing game. AM can permit ultimate agility/customization for rapid component and system design changes in commercial products, as well as enabling component part consolidation and "impossible" composite materials or structures. For polymers and polymer-based composites with widely available low-cost feedstocks, the highly flexible AM platform is being quickly expanded and is now widely deployed with great success for both small and large-scale part builds. For example, big area additive manufacturing (BAAM) with polymers has been demonstrated for large structures, including cars and buildings. While the technical barriers for polymeric materials have been mostly overcome, additive manufacturing of metallic alloys remains challenging.

To be clear, this exploration of the status and prospects for improvement of metallic AM feedstock powders is targeted at two specific types of AM technologies, out of 7 types, that are being most widely developed for fabricating complex shapes of metals and alloys, namely powder bed fusion (PBF) and directed energy deposition (DED) [1]. A spherical powder shape is preferred for feedstock powders in all of these AM technologies to enhance flowability, layer spreading, and loose powder packing, particularly in powder bed types. DED processes are more tolerant of fragmented powder shapes, as long as the powder feeder employed can maintain a constant powder feed rate. Further, specific PBF processes include Selective Laser Sintering (SLS), Direct Laser Metal Sintering (DLMS), and Electron Beam Melting (EBM), all of which involve highly localized melting (typically) of powders and re-solidification of the "micro-weld" fusion zone. In fact, depending on the depth of penetration of the heat source and the scan pattern and speed, most volumetric regions of the AM build can experience multiple melting and re-solidification cycles during the AM process. Specific DED processes include Laser Engineered Net Shaping (LENS), Direct Metal Deposition (DM3D), Laser Deposition Technology (LDT), and Electron Beam Additive Manufacturing (EBAM). These "blown powder" methods utilize single or multiple powder feeders and either a laser (most commonly) or an e-beam as a highly localized heat source for melting a portion (typically 20–30%) of the injected powders to build up a free-form object [2].

A growing consensus within the AM community is that sufficient understanding of AM process fundamentals and process control is lacking to produce the desired microstructures and properties needed for robust metallic parts, particularly for operating in extreme environments or high stress and fatigue conditions [3–7]. There have been observations of degraded mechanical behavior in AM built test specimens that can be traced back to

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several types of microstructural defects that develop during the AM process. These processing/microstructure challenges that limit the properties of AM builds include reducing/eliminating residual stresses [3,5,7] and controlling as-built microstructure texture [8]. In some existing alloys designed for cast and wrought parts, AM processing results in cracking or other microstructure deficiencies due to inability to suppress unwanted inclusions/precipitates during processing [2,4] and poor composition control from evaporation of some alloy components [5,6,9]. To overcome these challenges, it is desirable to develop a wider range of build parameters, e.g., solidification temperature gradient control and an increased pallet of alloy designs that are specific to AM processing. To accelerate verification of new alloy designs, the experimental alloys should be readily available in affordable small batches of high quality powder feedstocks for build trials.

While some defects that occur during a build are build parameter or alloy design related and can be minimized/healed by post-processing, e.g., hot isostatic pressing (HIP) and/or annealing, many defects related to porosity have their origin in the "quality" attributes of initial powder feedstock and cannot be healed by these methods. Limits on fatigue strength and fracture toughness due to voids in the build are probably the most important type of microstructural defect that must be avoided for wide acceptance of critical parts made by AM [3,5,9,10]. Thus, it is typically total void volume, void size distribution, and void shape that are characterized in detailed studies of AM build samples in an attempt to recognize an optimum "minimum void" condition [9]. Powder quality related defects include internal porosity of large size (pore dia. >10–90% of powder dia.) from trapped atomization gas [11] that is most prevalent in coarser size powders (dia. >70 μm), which are usually used for EBM/PBF and for LENS/DED, to some extent. It also should be noted that pores of very small size (pore dia. $\ll$5% of powder dia.) from trapped interdendritic solidification ("micro") porosity are related to alloy "mushy" zone (liquid + solid) range. These also are more apparent in coarser powders due to slower solidification rate [12], but do not typically present a problem in build microstructures. Another type of problematic larger porosity in AM builds can result from powder that has attached "satellites" or projections [13] that prevent smooth flowability and impede uniform powder packing during spreading of successive powder layers. Surface impurities (e.g., adsorbed water vapor) also can promote powder agglomeration-induced spreadability deficiencies and porosity of larger size [14] in an AM build. These large pores may contain trapped hydrogen from decomposition of physisorbed water molecules or of chemi-sorbed hydroxides [15] during AM processing. Although this may be as-produced powder quality issue [15], it is typically due to inadequate atmosphere control during powder storage or handling [14].

It is important to describe the probable origin of two as-produced powder quality deficiencies (leading to larger, problematic build porosity) to add background about the challenges that are presented in this paper to the powder making community. To trace back the source of trapped atomization gas porosity defects, it is necessary to examine the droplet formation mechanisms that are active, particularly during gas atomization (GA). As described previously [11,13,16,17] in any GA process there are many types of liquid breakup mechanisms occurring at any one time that can be ranked according to the energetics of the atomization gas interactions with the molten metal. Melt break-up into droplets also occurs in a dynamic sequence with droplet cooling and solidification. Break-up also can occur during a dramatic melt viscosity increase [11,16,18], especially in early solidification stages of mushy alloy fragments or droplets. When one of the most energetic mechanisms, "bag" break-up (see Fig. 1), is stimulated at high gas velocities, a melt fragment (or large droplet) becomes shaped into a bag-like sheet that spreads in a direction normal to the gas flow. The bag sheds small droplets from its periphery and may shatter into fine droplets. Alternatively, if the viscosity rises sufficiently, the sheet collapses on itself to form a large drop (hollow sphere) with a trapped pocket of atomization gas inside. Thus, it can be reasoned that to suppress the generation of hollow spheres, one should reduce the energetics of the breakup process to avoid operation of bag break-up, but this is difficult to achieve without precise control of the atomization process.

Identification of the source of attached "satellites" or projections on GA powders that prevent smooth flowability and packing appears to be complex, with at least two separate causes that have been proposed. One widely cited source [13] attributes satellite attachment to the (unavoidable) "rendezvous" of fine powders with coarser powders during their flight downstream in the spray of an atomizer. It was proposed that the fines would cool and solidify before larger droplets in the droplet size distribution of the atomized spray and would accelerate faster in this high velocity gas flow, eventually impinging/welding onto the larger (fully or partially) molten droplets. The other explanation considers spray chamber designs typical for industrial production of metal powders and offers alternative design options that can reduce satelliting. This alternative satellite attachment mechanism [19] relates to entrainment of "clouds" of fine solidified powders into the exterior of the atomization spray "cone," where they weld themselves onto

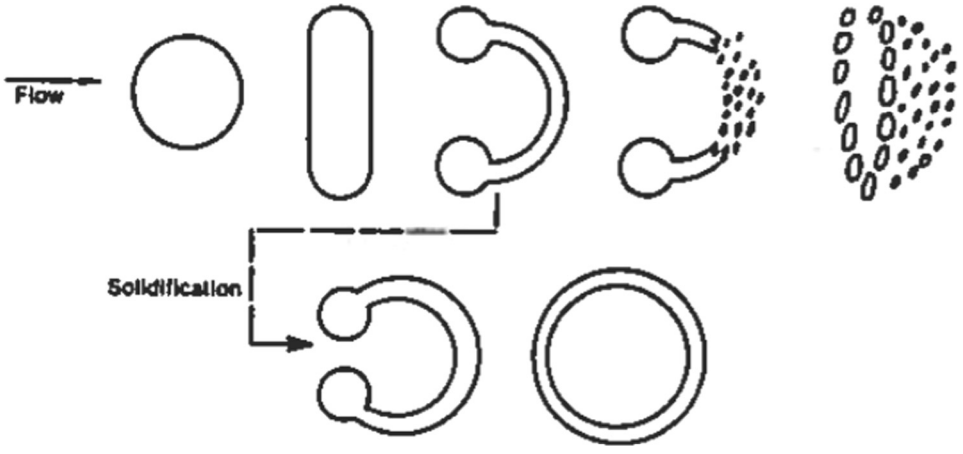

Fig. 1. Schematic is shown of two options for the bag break-up mechanism of liquid droplet formation at high gas velocities (12 < We < 50). During solidification the bag may either shatter or, with sufficient viscosity rise, may close in on itself, entrapping an atomization gas bubble. [Adapted from [11].]

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