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2014

Hascoet, J. Y., Marya, S., Marya, M., & Singh, V. (2014). “Materials Science” Challenges in the Additive Manufacturing of Industrial Parts. Proceedings of the 1st International Conference on Progress in Additive Manufacturing (Pro-AM 2014), 133-138.

https://hdl.handle.net/10356/84277

https://doi.org/10.3850/978-981-09-0446-3_037

“MATERIALS SCIENCE” CHALLENGES IN THE ADDITIVE MANUFACTURING OF INDUSTRIAL PARTS

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ABSTRACT: Additive Manufacturing (AM), somewhat like fusion welding, brings into play: (1) complex and interacting physical phenomena such as heat and mass transfer, phase changes (including melting, solidification, allotropic transformations and diffusion phenomena such as epitaxial growth, grain growth), (2) a number of process variables associated to the moving heat source (e.g., its power, power distribution, relative speed, size, all affecting energy density), its paths (e.g., linear, circular, oscillatory), and added metal feed rate via powder, wire, or ribbon, all controlling deposit dimensions, aspect-ratios, and properties, including defects. The effect of successive thermal cycles, as induced by the heat source moving away from an already deposited metal further adds to the overall challenge of fabricating parts with industry-compliant physical, mechanical, and electrochemical properties and proper dimensional controls. This paper discusses fundamental aspects of AM from a metallurgical standpoint.

INTRODUCTION

Subtractive manufacturing, wherein most commonly a solid material stock is progressively machined has been the dominant manufacturing route for industrial parts. Early signs from subtractive to additive manufacturing came in 1987 with the advent of the first rapid prototyping machine by 3D Systems in the US. From subtractive to additive, manufacturing was made possible through several new technologies involving computer hardware, software and controls of either electron or laser beams. Additive manufacturing is a step forward from rapid prototyping as its main goal is to directly manufacture fully functional parts from digital models, in contrast to rapid prototyping that aimed at non-functional parts. Additive manufacturing is also a farsighted approach to flexible cell manufacturing applied to parts that are often selected for their difficult-to-make shapes, including intricate passageways. Additive manufacturing may be seen as a “factory in a box” since it also allows for the concurrent making of multiple parts with no or limited human intervention. Figure 1 depicts the basic schematics of the additive manufacturing process. From industrial perspectives, part repeatability, reliability, quality and procurement (supply) are always of great considerations, and a main concern in AM is in the manufacturing process itself, including post operations such as hot-isotatic pressing (HIPing), heat treatments, machining (including grinding, honing or polishing), all aimed at “going around” inherent deficiencies in today’s AM processes. Foreseen advantages of AM are cost competitiveness, particularly for small orders of complex and customized parts as well as lead-time reduction; however, AM first needs to be investigated from process and metallurgical standpoints while for the time beings and in

Proc. of the Intl. Conf. on Progress in Additive Manufacturing
Edited by Chua Chee Kai, Yeong Wai Yee, Tan Ming Jen and Liu Erjia

ISBN: 978-981-09-0446-3 :: doi:10.3850/978-981-09-0446-3_037

anticipation for more demanding applications AM parts will require thorough first-article-qualifications, thereby disadvantageously lengthening time-to- markets.

Additive manufacturing is the layer-by-layer construction of a part with tracks built on the CAD/CAM data). For metallic parts, AM relies on some heat source (e.g., electron beam, laser beam) for the full or partial melting of the feedstock. The feedstock is generally supplied either as stationary powder bed or continuous powder feed. As alternative to electron beam or laser, arc technologies like GTAW (TIG), GMAW (MIG) or Plasma can offer interesting possibilities in terms of investment and running costs. Feedstock materials may range from powders, wires to ribbons. Additive manufacturing is comparable to multi-pass fusion welding and its resulting properties, including grain structures, phase balance, and textures depend on similar process parameters (Fig.1). It follows that challenges in both welding and additive manufacturing are metallurgical identical, and past experienced acquired from welding may therefore be used to accelerate the understanding of additive manufacturing. In the following is highlighted some of the materials science in additive manufacturing, borrowing from the well-established science and technology of welding. With respect to additive manufacturing, this paper is based on multi-year experience with CLAD, and is focused on metallurgical aspects of the process only.

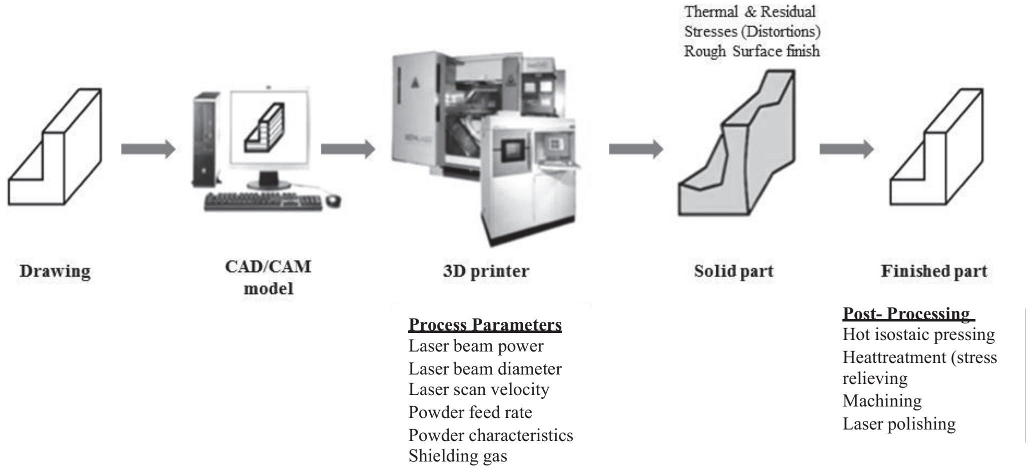

Figure 1. Flow diagram for additive manufacturing along with a list of major process parameters.

MANUFACTURING PROCESS CONSTRAINTS

From material and metallurgical viewpoints, heat source (laser beam, electron beam, arc), feedstock (i.e., wire, powder, and ribbon), and displacement parameters (including scan trajectory and scan velocity) are all important parameters influencing deposit properties. Though a hierarchy amongst these parameters may be difficult to establish to cover all deposition scenarios, the feedstock probably needs to be considered first. For powder blown additive manufacturing technologies such as CLAD both intrinsic (e.g., morphology, grain size, gas content, apparent density, trapped porosity) and extrinsic (e.g., oxygen contamination, hydrogen pickup) characteristics of powders along with their flow dynamics in the carrying gas also deserve some attention. For instance, irregular powder injection has been found to introduce unstable deposits including high porosity, under-fills, and non-melted and consolidated powders (Fig.2).

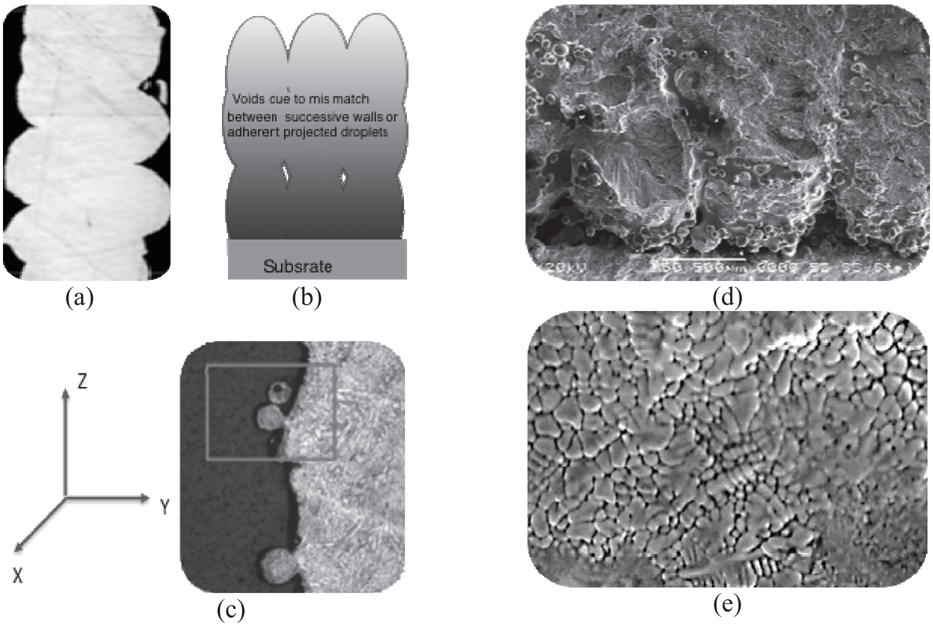

Figure 2. (a) Irregular wall built from single scans along the z-axis, (b) Irregular walls with internal under-fills resulting from improper layer matching, (c) Spatter sticking to the outer wall (on 316L), (d) Under-filled zones resulting from incomplete melting, and (e) dendritic solidification structure in a Stellite 6 deposit.

Controlling the properties of the powder via well-specified qualifications and documented procedures remains a pre-requisite to guaranteeing deposit properties and for the industry to further adopt additive manufacturing. Powder storage, in particular the long-term protection of powders against its surrounding (including moisture and water condensates) is another important concern and known to be a source of part-to-part variabilitys, especially for moderately reactive metals. For metals with high oxygen affinity such as titanium and its alloys, the powder stocks must be packed and stored in an inert-gas protective atmosphere, and always away from humidity. For ferrous metals, moisture is also concern due to hydrogen-induced cracking (HIC), particularly the higher-strength grades such as martensitic steels (e.g. 41xx, 410-familly) and precipitation hardened (PH) martensitic stainless steels (e.g. 17-4PH, 15-5PH). For aluminum and its alloys, the presence of a refractory oxide along with humidity may potentially be at the origin of incomplete melting and porosity, as aluminum is one of those metals characterized by a large hydrogen solubility gap between liquid and solid phases. An important of area of research in the 1980s that also serves as "lesson-learnt" relates surface-tension driven flow, also referred as Marangoni flow (Heiple et al, 1994). Now well understood, it may be anticipated that ppm variations in oxygen in liquid carbon and low-alloy steels, stainless steels, and titanium alloys can affect interfacial tension, in particular its variation with temperature, the consequence being variable morphologies of molten droplets, variable wetting and eventually inconsistent melt deposit geometries. This concern, though not yet proven and in welding avoided by well controlled chemistry practices for elements like sulfur, phosphorus, or others that counterbalance oxygen (e.g., thermally-stable oxide formers) may be further constraining feedstock selection; i.e., its origin and its quality control, both implying that feedstock will likely be restricted to selected and qualified suppliers.

In the case of functionally-graded materials, as for consecutively blown powders having different densities, programmed (i.e., machine command) and actual powder flows may differ due to the AM system response time and dissimilar powder flow behaviors. Figure 3 illustrates differences between programmed and observed blend deposit of 316L with Stellite 6 during the vertical build up of a single thickness wall (El Cheikh et al, 2012). In the described test, the powder feed of 316L and Stellite 6 was linearly changed after each layer. Through SEM analyzes, the concentrations of Co and Fe were measured in the mid section along the wall height (Mognol et al, 2011 Hascoët et al, 2011). Despite the forced linear command for the two powder injection, the effective transition is only limited to the mid height section. Interestingly, in the earlier sections of the buildup, Stellite was absent and from 6-mm onwards it increased in concentrations. Also note that in the last segment of the buildup, traces of iron from the stainless were still found, thereby demonstrating gradual dilution effects. Overall, the results of Figure 3 reveal a practical difficulty with functionally-graded materials. In the absence of real-time monitoring and controls of the deposit composition, experimental results such as those shown in Fig.3 must be integrated in the machine programming, a process that overall is so-far cumbersome because heavily relying on destructive material analyses. The challenge presented in Figure 3 may be expanded to other powders and metal combinations, with each of these combinations necessitating specific command corrections and transfer functions (Mognol et al, 2011). Figure 3 also indirectly highlights the importance of dynamic flow behavior of powders with a given nozzle design. The jet cone for a given feed rate remains to be controlled and adjusted offline using high-speed imaging.

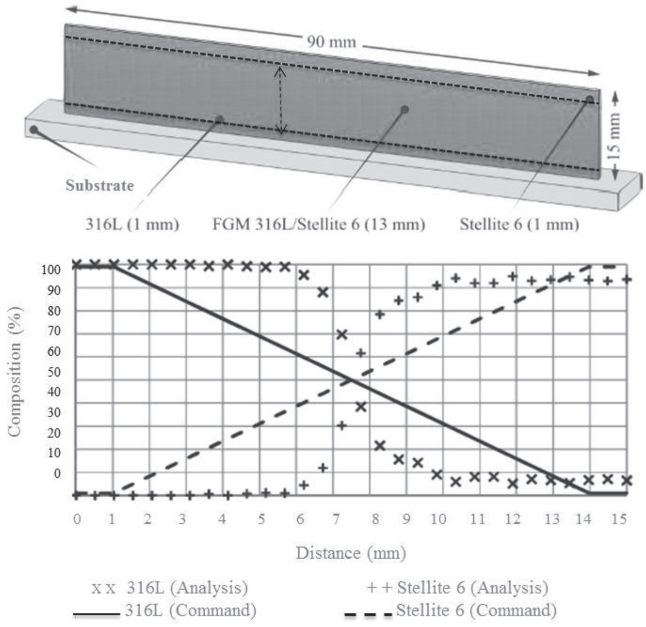

Figure 3. Chemical composition at mid-wall along an entire 15.mm deposit. 316L and Stellite were co-deposited, starting with only 316L and linearly increasing percentage of Stellite. Differences between programmed and actual concentration point out a challenge for functionally-graded materials.

From process perspectives, additive manufacturing brings into sight complex interacting physical phenomena such as heat transfer, mass transfer (fluid mechanics), phase transformations (melting, solidification, solid-state allotropic transformations), atomic diffusion (including grain growth), interfacial phenomena, among others. Additional complexity arises as a great number of parameters, including the materials themselves, interact to control the deposit such as its dimensions, morphology, internal stresses, defects (e.g., under-fills, voids and lack of fusion), micro-segregation (chemical heterogeneities) and microstructures. Sequentially, sufficient heat is transferred to the powder from the laser beam by photon absorption to produce some melting while the resulting molten powder droplets are simultaneously projected to a predefined position before consolidation and rapid solidification take place.

Additive-manufactured parts have fairly unique microstructures, mechanical and electrochemical properties, and overall performances that typically differ from their cast, sintered, or wrought counterparts. Differences include density, residual stresses, defects (type, size, and concentration), mechanical properties (e.g., anisotropy, in addition to being defect-related), non-equilibrium microstructures and crystallographic textures. The microstructures and phase transformations maybe be reasonably predicted with a complete description (full mapping) of the transient thermal cycles (e.g. temperature vs. time at any x,y,z coordinate) and a detailed characterization of the deposits. In addition to variations in chemical compositions (micro-segregation, evaporation losses), AM deposits develop some anisotropy (crystallographic and mechanical), typically small but yet quite different from that of well recognizable extruding direction for an extrusion or rolled-made product for instance. In additive manufacturing, directional solidification occurs approximately following the heat source maximal thermal gradients, irrespective of constitutional and curvature undercooling and fluid shear stresses in the solidifying melt. Moreover, the dilution (a consequence of the process parameters) generates chemical heterogeneities, in particular in the first scans. Specific laser beam tracks and layer sequencing during a product built up may help control such heterogeneities, in addition to residual stresses (Mercelis et al., 2006) and resulting distortions; however, a great many investigations are need to shed some light on additive manufacturing.

CONCLUSIONS

From the foregoing discussion, which lists some of the important basic mechanisms intervening in AM, a proposal of further exploratory investigations and research topics may be established as follows:

- Influence of the base substrate, onto which the first layers are built and partly diluted, and overall impact on the mechanical and electrochemical properties. Spatial mapping and correlation of chemical composition, microstructure and properties is required.
- Influence of feed stock and process parameters: beam power, beam size), laser height/stitching shifts, scan speed and path, substrate temperature, overall heat input and feedstock feed rate on deposit characteristics, surface finish, defect formation, textures including thermal and residual stresses along with their spatial and temporal mapping during the part build up.
- Influence of rapidly solidified fine grain structures on deposit mechanical strength (expected to be greater that wrought or cast counterparts due to Hall-Patch strengthening), ductility (expected to be lesser than wrought products due to the absence of forging and metal-working and heat-treatment), fracture toughness (expected to be much lower than wrought due to the presence of defects and unconsolidated powders), including impact or dynamic mechanical properties. Further work is needed to investigate overlapping zones from different layers. Due to the small size of the build-up layer (1 to 2 mm), overlapping metallurgical zones pay a significant role on the deposit properties.
- Influence of post-deposition treatments (e.g., heat treatment, hipping, machining) on final mechanical and electrochemical properties of AM parts.

The above list proposes research topics to better comprehend fundamentals of additive manufacturing along with design rules to properly utilize additive manufactured to engineering products. Not only additive manufacturing must be cost and time competitive with conventional processes, it must also deliver parts with sufficient and repeatable mechanical properties. Going a step forward, monitoring the process via temperature control followed by online NDT may ensure a greater confidence in the technology. An important point to be considered is whether conventional alloys designed for thermo-mechanical processing are entirely viable candidates for additive manufacturing. Theoretically, it appears more appropriate to first confine additive manufacturing to alloys also designed for casting; in such instance, the finer structure of additive manufactured parts can lead to property enhancements. For instance, additive manufactured 316L (with no post-treatment) have exhibited greater yield strength (400MPa) and tensile strength (770MPa) with elongations in excess of 35% compared to accepted respective values of 170MPa, 440MPa and over 40% for solution annealed 316L in cast or wrought condition. While hot-isotatic pressing is useful to collapse internal defects, especially porosity, and provide some homogenization in the structure, future development in AM-specific alloys, powders, deposition technologies and advanced systems with feed-back controls will likely bring significant improvements to AM. Further, when combining with existing deformation processes such as peening, friction stir surfacing, one may already be observing enhanced properties that can meet the engineering requirements of existing industrial parts.

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