Abstract

3D printing of metals has advanced rapidly in the past decade and is used across a wide range of industry. Although laser powder bed fusion (LPBF) has matured the fastest for metals, other technologies such as binder jet and (robotic) wire feed are making substantial progress. Many aspects of the technology are considered to be well understood in the sense that machines make parts and temperature histories with residual stress can be simulated. Nevertheless, key questions remain open as to how to qualify printers and certify parts, how to control defect structures, which includes surface condition and how to implement more sophisticated control systems. At the microscopic scale, more work is required to quantify, understand and predict defect- and micro-structures, which affect properties. Strength, for example, is often at least as good as conventionally processed material whereas defect-sensitive properties such as fatigue are more challenging. Synchrotron-based experiments have been particularly illuminating, e.g., dynamic X-ray radiography (DXR) which provides ultra-high-speed imaging of laser melting of metals and their powders. This has, e.g., enabled the keyhole phenomenon to be quantified, which in turn has demonstrated the importance of power density, as opposed to energy density. Under typical LPBF conditions, there is almost always a keyhole present. If the power density is too high, the keyhole is unstable and sheds pores that are trapped by solidification, which turns out to correspond to a sharp boundary in P-V space. Energy density, while informative, also fails to capture the crucial boundary between full density and lack-of fusion porosity because it does not take account of melt pool overlap. Synchrotron-based 3D X-ray computed microtomography (µXCT) showed that essentially all metal powders exhibit porosity that partially persists into the printed metal. This explanation is reinforced by evidence both DXR and simulation. The links between porosity and process conditions provide a physics-based approach to defining a process window for a given machine which, in turn, suggests a route to qualification by measuring and tracking the location of the process window in power-speed-hatch space for any given powder bed printer. To illustrate the power of machine learning, computer vision (CV) has successfully classified different microstructures, including powders. Machine learning is providing new insights on correlations between welding parameters, microstructure and material properties in laser hot-wire weld deposits to Ti-6Al-4V. High speed synchrotron X-ray diffraction is providing new information on solidification and phase transformation in, e.g., IN718, Ti-6Al-4V and stainless steel. High Energy (X-ray) Diffraction Microscopy (HEDM) experiments also is also providing data on 3D microstructure and local elastic strain in 3D printed materials such as Ni alloys, Ti-6Al-4V and stainless steel.

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Dr. Rollett has been a member of the faculty at Carnegie Mellon University since 1995, including five years as department head. He is the co-director of the Next Manufacturing Center on additive manufacturing. Previously, he worked at the Los Alamos National Laboratory, where he was group leader of metallurgy from 1991-1994 and deputy division director for a year after that. He has been a Fellow of ASM since 1996, a Fellow of the Institute of Physics (UK) since 2004, and a Fellow of TMS since 2011. He received the Cyril Stanley Smith Award from TMS in 2014, was elected as Member of Honor by the French Metallurgical Society in 2015, and became the US Steel Professor of Metallurgical Engineering and Materials Science in 2017. Rollett’s research focuses on microstructural evolution and microstructure-property relationships in 3D, using both experiments and simulations.

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