Additive Manufacturing: Overview and NDE Challenges[1]

J. A. Slotwinski

National Institute of Standards and Technology, Engineering Laboratory
Intelligent Systems Division
100 Bureau Drive, Gaithersburg, MD 20899

Abstract. Additive manufacturing (AM) processes are capable of producing highly complex and customized parts, without the need for dedicated tooling, and can produce parts directly from the part design information. These types of processes are poised to revolutionize the manufacturing industry, yet there are several challenges that are currently preventing more widespread adoption of AM technologies. Traditional Non-Destructive Evaluation (NDE) methods could be utilized in both in-process and post-process applications to help overcome these challenges, although currently there are very few examples of *in-situ* sensors for monitoring AM processes. This paper gives an overview of AM technology, and discusses the potential benefits and challenges of using NDE in AM applications.

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ADDITIVE MANUFACTURING

According to ASTM-I F2792: Standard Terminology for Additive Manufacturing Technologies [1], Additive Manufacturing is defined as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive methodologies. Synonyms for Additive Manufacturing include additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication." Despite the widespread use of the term "3D Printing" in the popular press to represent all additive manufacturing processes, 3D printing actually refers only to a subset of AM processes that deposit material through a print head, nozzle, or other printer-like mechanism [1]. Figure 1 demonstrates conceptually the difference between conventional manufacturing processes, such as milling or turning, where material is removed from a block of larger material until the desired part geometry is realized, and additive manufacturing processes, where the desired part geometry is built-up one thin layer at a time.

[1]Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

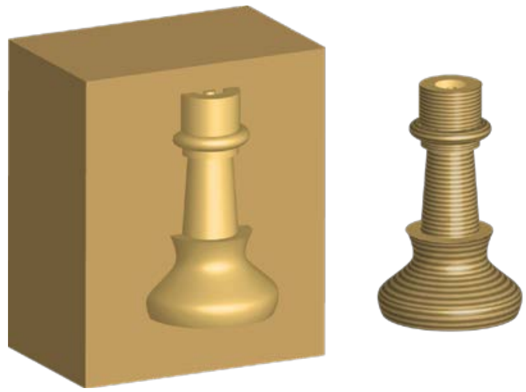

FIGURE 1. Identical parts conceptually made from traditional removal processes (left) and additive manufacturing processes (right).

Conventional processes require part fixturing and sometimes dedicated tooling in order to realize parts. In addition, the tool's physical geometry may limit the types and sizes of features that can be made. A part with internal features, for example, may be difficult or even impossible to make with traditional subtractive processes. Parts made via additive manufacturing can easily realize complex structure and internal features, since the part is constructed one thin layer at a time and is not limited by tool accessibility or geometry. In addition, additive processes generally consume only the amount of input material that is required for the part; any excess material can usually be recycled and used in subsequent builds. This is advantageous compared to subtractive processes, where the unwanted material is turned into chips or other scrap that generally cannot be easily reused.

ASTM-I F2792 generally groups all AM processes into seven basic categories [1]:

- Binder Jetting
- Directed Energy Deposition
- Material Extrusion
- Material Jetting
- Powder Bed Fusion
- Sheet Lamination
- Vat Photopolymerization

While the specifics of each of these processes is beyond the scope of this paper, the key common aspect of all of them is the build-up of a part one thin layer at a time. This type of fabrication results in several advantages of AM processes that are not easily realized in traditional subtractive processes. These include:

- Parts that have complex geometries, internal features, and/or engineered porosity
- High levels of customization that make AM suitable for small lot sizes (even lot sizes of one)
- Relative ease to go directly from digital design to part
- No required tooling or path planning, making it easy and inexpensive to effect design changes

THE VISION OF ADDITIVE MANUFACTURING

In recent years, additive manufacturing has received significant visibility, both in the popular media as well as in scientific journals. In fact, the number of publications on additive manufacturing, including 3D-printing, jumped from approximately 1,600 in 2011 to over 16,000 in 2012 [2]. The vision for additive manufacturing is simultaneously imaginative, outrageous, and inspiring. If the vision is to be believed, in the near future not only will additive systems revolutionize military part logistics and repair, and be present on deep space missions, but everyone will have their own additive machine in their home. In this fantastic future, additive systems will also be used to make everything from replacement organs such as kidneys and hearts, to airplanes and cars, to robots that walk themselves off of the additive machine platforms moments after they are built.

While it is difficult to predict the scope of the future impact of additive manufacturing, one thing is certain: additive manufacturing will have an impact, and that impact could be potentially disruptive. Jeremy Hsu summed up the expectations for additive manufacturing best when he said:

> *The technology could end up affecting every major industry – aerospace, defense, medicine, transportation, food, fashion – and have an even bigger impact on U.S. manufacturing than the robot revolution.* [3]

In modern history there has been a very short list of technologies that have such widespread industrial impact. The next few years could reveal whether additive manufacturing makes it onto that list. Certainly the recent and predicted market growth statistics suggest that additive manufacturing is worthy of consideration:

- 26.2 % compound annual growth rate during the last 23 years
- Total market size of $1.3 billion in 2010 (up from $1.0 billion in 2009)
- Predicted worldwide market sales of $3 billion in 2016 and $5 billion in 2020
- Over 23,000 personal 3D printers sold in 2011, up from roughly 6,000 in 2010 [2,4]

TECHNICAL CHALLENGES

While the vision of AM is impressive, there are technical challenges that must first be overcome if this vision is to be fully realized. Several AM roadmapping efforts to identify the most important industrial technical challenges have occurred over the last five years, including efforts sponsored by the National Science Foundation and the National Institute of Standards and Technology [5,6]. From these reports, the top technical challenge areas currently facing the AM industry were identified as:

- Understanding of material properties
- Having limited types of materials suitable for AM
- Process understanding and performance, need for in-process, *in-situ* monitoring
- Need for qualification and certification of AM processes and parts
- Part accuracy
- Surface finish of contoured surfaces
- Fabrication speed
- Build volumes/part size
- Lack of AM standards
- Data formats

Issues regarding material properties and process measurements using *in-situ* sensors to improve the process are consistently touted as among the most significant technical challenges by those in the AM industry. This perspective was used in forming the initial AM research program within the Engineering Laboratory at the National Institute of Standards and Technology, which was begun in 2011.

NDE FOR AM: POTENTIAL APPLICATIONS AND CHALLENGES

There are many difficult technical challenges in additive manufacturing and successfully solving these challenges will require a multi-disciplinary approach. The high-priority material properties and process sensing needs in AM potentially match well with the NDE expertise that already exists within the United States. Multi-disciplinary approaches that include expertise from both the AM and NDE communities could lead to solutions for the challenges identified above, which in turn would lead to a wider adoption of AM technologies.

There are potential applications for NDE in both of the high-priority areas mentioned above: materials characterization and *in-situ* process monitoring. For materials characterization, NDE can be used to measure the properties of both the raw input materials, such as metal powder, and the properties of parts produced by an AM process. Potentially measureable powder properties include particulate size, size distribution, morphology, and chemical composition. For parts, NDE techniques could be used in their traditional application for defect detection, but might also have applicability for measuring part dimensions, mechanical properties, residual stresses, and chemical composition.

In the *in-situ* sensing area, NDE sensors could be used to measure and monitor the temperature and size of the melt pool in metal-based powder bed fusion systems. If sensors could be successfully integrated into the build chamber of production systems, they might also be able to detect the presence of defects, and measure the part dimensions, *for each layer* immediately after it is formed. This type of sensing capability, if successfully realized, would have a profound impact on the AM industry since it would potentially allow for real-time adjustments and improvements of the part fabrication process while the part is still being produced. This is compared to post-process inspection, where no amount of NDE inspection, no matter how sophisticated, will lead to improvements in the part – only rejection of flawed, completed parts.

There are several challenges that must be overcome while considering the use of NDE-type systems for these kinds of applications in AM. AM powders, especially metal powders, have associated safety issues that must be addressed. These include minimizing the possibility of combustion, and avoiding human inhalation of and skin exposure to the fine metal powders.

In-situ measurements of AM processes, such as metals-based powder bed fusion processes, also have challenges. The extremely localized, very rapid melting and cooling of the powders, using high-power energy sources such as lasers and electron-beams, make high-fidelity detection difficult. Measurements are also difficult because the movement of the heat source is typically at high velocities (~ 1 m/s) and with high accelerations. Sensor insertion into the build chamber cannot interfere with machine operations, such as the internal systems for spreading or laying down powders, and most machines are not designed for easy sensor integration. These same build chambers also require certain environmental conditions (e.g., inert atmospheres) and safety systems (e.g., laser protections) that cannot be compromised by either sensors or any wires associated with the sensors. Finally, most commercial systems do not have open controllers, making sensor feedback for real-time control and adjustment very difficult.

Materials characterization of AM parts is challenged by machine variability, both machine-to-machine as well as day-to-day on any given machine. This variability can lead to inconsistent mechanical properties. In addition, the large number of process variables can make materials pedigree difficult to ascertain, making the inter-comparisons necessary for material qualification difficult.

CONCLUSIONS

Despite the significant visibility of AM in the media, there are many difficult measurement problems in additive manufacturing that have prevented greater proliferation of the technology. These problems will likely require a multi-disciplinary approach in order to reach a solution. Properties of AM materials and AM process sensing are high priority needs for the additive manufacturing industry that match well with the expertise of the NDE community.

Successes in these areas will lead to wider adoption of AM technologies. The papers presented at the Quantitative Non-Destructive Evaluation 2013 AM session help point the way for NDE applications applied to AM.

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