2016-01-01

Additive manufacturing metrology: State of the art and needs assessment

Koester, Lucas

Additive manufacturing metrology: State of the art and needs assessment

Cite as: AIP Conference Proceedings **1706**, 130001 (2016); https://doi.org/10.1063/1.4940604
Published Online: 10 February 2016

L. Koester, H. Taheri, L. J. Bond, D. Barnard, and J. Gray

Additive Manufacturing Metrology: State of the Art and Needs Assessment

L. Koester[1, a)], H. Taheri[1], L. J. Bond[1], D. Barnard[1], and J. Gray[1]

[1]Center for Nondestructive Evaluation, Iowa State University, 1915 Scholl Rd., 111 ASC II, Ames, Iowa 50011-3041

[a)]lkoester@iastate.edu

Abstract. Additive manufacturing (AM) is a technology that first emerged in 1987 with stereolithography (SL) of plastic materials from 3D Systems. It saw light use for rapid prototyping and very low volume production for a number of years. However, in the past few years AM of metallic materials has become a practical fabrication technology, use is rapidly increasing and is projected to continue with double digit growth in coming years. The promise and flexibility shown by AM has spurred efforts to begin standardization of this type of process. This paper provides an assessment of the state of the art for in-situ process monitoring of AM processes with an emphasis on the production of metallic components. It is seen that with the implementation of proper process control there is potential to create reliable and reproducible materials and geometries previously unachievable using metal removal based means of production. A reliable methodology for detection and control of microstructure and defects would be of great value in terms of enabling broader AM utilization.

INTRODUCTION

Additive manufacturing (AM) is a technology that first emerged in 1987 with stereolithography (SL) of plastic materials from 3D Systems. It saw light use for rapid prototyping and very low volume production for a number of years. However, in the past few years AM of metallic materials has become a practical fabrication technology, use is rapidly increasing and is projected to continue with double digit growth in coming years. Equipment and raw material sales continue to rise as more capital is invested in bringing both the basic technology and applications to commercial fruition. The main obstacles at present include relatively high unit costs for parts fabricated using AM due to expensive raw materials (powders) and the systems, part-part and machine-machine consistency and reject rates for finished parts. Improving these cost related parameters and ensuring adequate finished part performance requires improved process and quality control during the manufacturing process. Inspection after completion of a part, which tend to have complex and difficult to inspect geometry, results intractable challenges for nondestructive evaluation (NDE) and high reject rates [1].

A lack of an adequate understanding of the additive manufacturing process and in-process monitoring can result in mechanical properties that not only vary depending on the machine employed for fabrication, but also on part geometry and the dynamics of the build process. Variations have been found to exist across nearly all material properties of concern for critical components including hardness, phase (in metals), strain to failure, roughness, density, and material microstructure [2, 3, 4]. These parameters also vary with the build direction, layer build height (thickness), processing parameters (including raster speed and power), powder characteristics, and it seems many more process variables! This realization led to attempts to strictly control and quantify the process and its parameters, starting from raw material to final product [5,6], however challenges remain.

The promise and flexibility shown by AM has spurred efforts to begin standardization of this type of process. This standardization has proved difficult due to there being several technologies that can be utilized to build AM parts. For example, powder bed technologies use fine alloy powders, applied in layers and build parts to a final, near net shape. The binding can be achieved by a number of methods, including high power lasers and electron beams [7]. These heat

42nd Annual Review of Progress in Quantitative Nondestructive Evaluation
AIP Conf. Proc. 1706, 130001-1–130001-8; doi: 10.1063/1.4940604

sources generally operate in inert/vacuum environments by either partially (sintered) or completely melting the powder into finished material form. If sintered, the process is then followed by curing at high temperature and pressure. While a complete discussion of AM processes is outside the scope of this review, AM parts generally present the same challenges and issues, regardless of the specific detailed process employed. For simple shapes it has been shown that inspection processes for powder metallurgy fabricated parts are similar to those used for parts formed using other processes and the NDT used is often sufficient to detect and characterize defects considered to be significant [8,9,10]. The definition of a defect and its size that is considered significant however is of course application specific.

In looking at many AM parts the obstacles to adequate inspection include the complex production procedures, the resulting in-homogeneous mechanical properties, and typically geometric complexity of the components [11]. Classical NDE techniques examining finished parts work well for parts fabricated using more traditional lower cost production methods, such as casting and forging, in which geometries and microstructure complexity are at least analyzable, and in many cases there is significant experience and materials and inspection requirements are well understood. In AM, part rejection is costly in terms of nearly all aspects of the process, including loss of raw materials, energy used, and machine time. This fact has led many to seek in-situ on-line process monitoring to initially give insight into what forms the bounds for the processing regime for a given material to give a good part, and eventually to a enable full process control with a closed-loop system incorporating NDE.

In concept, in-situ monitoring can potentially yield information regarding structure and flaws/anomalies throughout the build process, and as such an approach is potentially a tractable means of NDE implementation, but it is not without its own difficulties. The fabrication environments for metal based AM involve elevated temperature, inert or vacuum enclosure, and can be very noisy. These environmental considerations, and desire for non-contact methods, have led many to seek process monitoring with optical methods that can isolate hardware and electronics from these environments. Industrial movers in this area are exemplified by EOS Gmbh Electro Optical Systems' recent partnership with MTU Aero Engines (Germany) to develop an optical tomography monitoring system, Arcam's LayerQam^{TM} a proprietary, patented system, and Concept Laser Gmbh's Laser CUSING^{TM} system with meltpool monitoring [12,13,14].

This paper provides an assessment of the state of the art for in-situ process monitoring of AM processes with an emphasis on the production of metallic components. It is seen that with the implementation of proper process control there is potential to create reliable and reproducible materials and geometries previously unachievable using metal removal based means of production. A reliable methodology for detection and control of microstructure and defects would be of great value in terms of enabling broader AM utilization [15].

TERMINOLOGY

Additive manufacturing is a broad term, where use has until recently led to some confusion in both the commercial and academic literature. For the purposes of this document, terminology is used which follows ASTM F2792 – 12a and key terms and definitions summarized here are taken directly from the standard with added acronyms used where they were not given [16].

- additive manufacturing (AM), n— a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication
- powder bed fusion (PBF), n— an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed
- directed energy deposition (DED), n— an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. "Focused thermal energy" means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited
- additive systems, n—machines used for additive manufacturing
- laser sintering (LS), n— a powder bed fusion process used to produce objects from powdered materials using one or more lasers to selectively fuse or melt the particles at the surface, layer by layer, in an enclosed chamber.

Most LS machines partially or fully melt the materials they process. The word "sintering" is a historical term and a misnomer, as the process typically involves full or partial melting, as opposed to traditional powdered metal sintering using a mold and heat and/or pressure, to give compaction.

These terms will be used to describe the processes discussed in this document. Other terms will be defined when used, and company associated terms and acronyms such as DMLS® and SLS® will be avoided unless discussing items directly related to commercial innovation.

TECHNIQUES

There are many techniques that are available for AM of both polymeric and metallic components. The methods of potential interest to the Center for metal AM are briefly discussed.

Powder bed fusion (PBF) is a technique which selectively fuses regions of powder using directed energy. The source of this energy has some implications for the monitoring and detection modalities adopted, but generally speaking achieve the same end result. These sources include focused, high-power lasers, electron beams (e-beams), and plasma arcs. PBF is analogous to a lithography process in which final part dimensions are achieved by fabrication in a layer by layer manner. Powder is often applied via an arm that sweeps over the build plate from a powder reservoir, depositing a thin, ideally uniform layer. The powder layer is then selectively melted and fused to previous layers and the process is repeated. PBF processes are operated at high temperatures (below melting) and inert or vacuum environments are needed to minimize oxidation and are necessary for some heat sources.

Directed energy deposition (DED) systems apply a similar, lithography style process differing only in the method of supplying the material to be deposited. These generally include powder jets that direct material into the path of the energy source and the powder is melted and deposited. It is most easily visualized as a spraying process with a concurrent melting step.

Wire-fed additive manufacturing is a method where the feedstock is wire, and this is melted and deposited in a line/layer-wise fashion. It enables high deposition rates and minimal material waste. The process must be performed in high vacuum for systems using electron beam energy sources. Other systems employ what is effectively a wire in gauge welder with precision power and positional monitoring.

Regardless of the method employed, AM parts often produce surface roughness which is relatively greater than that found with forged or even cast parts. In addition the localized high energy sources produce high thermal gradients which, when combined with geometry and process structure, influence part cooling and hence the resulting stress and microstructure. These varied cooling rates can cause high residual stresses and non-uniform material microstructure. A summary of systems, both commercially available and those under development is given in Table 1.

STATE OF THE ART

Numerous organizations have invested, some heavily, in additive manufacturing as it is seen as a transformational and disruptive technology. DARPA was involved in AM development from the beginning. It was associated with the initial patent application and its engagement continues with ongoing research and development funding. Emphasis is placed on increasing throughput, expanding the build envelope, process control, and providing design tools [17]. In the USA a number of other Federal agencies have been involved in AM's development, including the National Science Foundation (NSF), National Institute of Standards and Technology (NIST), and the Office of Naval Research (ONR) [18]. There are also parallel efforts in a number of other countries.

RAW MATERIAL CHARACTERIZATION

Raw material characterization for PBF systems consists of measuring chemical content and particle size distribution. Various methods used for such characterization include optical methods, laser diffraction, X-Ray CT, X-Ray diffraction, scanning electron microscopy, and many more have been considered [6]. This aspect of the process is quite well developed and many commercial systems now offer online laser diffraction systems to monitor powder particle size distributions. An area that could use additional development is the detection and quantification of porosity in the metal powders. It has been shown that large volumes (5%-60%) of some particles consist of entrapped gas bubbles that would not be detected by an optical system [19].

TABLE 1. Summary of commercial methods including source, environment, pros/cons.

Method	Heat Source	Environment	Advantages	Disadvantages
POWDER BED	---	---	---	---
ARCAM Electron Beam Melting	Up to 3.5 kW EB	Vacuum, 700-1000 C	RS, MP, BR	SR, PM
EOS Direct Metal Laser Sintering	200 or 400 W W-Yb Laser	Inert	SR	BR, RS, AN, PHT
Concept Laser Laser Cusing	200 W Fiber Laser	Inert	SR	Marking and Cutting
MTT Selective Laser Melting	100 to 400 W W-Yb Fiber Laser	Inert w/ Vacuum Purging	OS, DA	---
Phenix Systems Selective Laser Sintering	200 W W Yb-Fiber Laser	Inert or Vacuum	DA	---
LASER POWDER INJECTION	---	---	---	---
Optomec Laser Engineered Net Shaping	0.5, 1, or 2 kW IPG-Fiber Laser	Inert	R	---
POM Direct Metal Deposition	1kW -5kW fiber or diode laser	Inert Shielding	---	---
Accufusion Laser Consolidation	Laser	Inert	SR	
FREE FORM FABRICATION (FFF)	---	---	---	---
Sciaky Electron Beam FFF	60 kW/60 kV EB welder	Vacuum	BR, SR, BV	---
MER Plasma Transferred Arc Selective FFF	PTA Torch	Inert Shielding	BV, BR	---
Honeywell Ion Fusion Formation	Plasma Arc	Inert Shielding	BV, BR	PM
Rolls Royce Shaped Metal Deposition	Gas tungsten arc welding (GTAW)	---	---	---
EWI Hot Wire-GTAW	Hot wire gas tungsten arc welding (HT-GTAW)	---	BV, BR	---
Ultrasonic Additive Manufacturing (UAM)	Very High Power UAM (VHP-UAM)	---	BR, BV, RS, MP	---

RS=residual stress, MP=material properties(compared to wrought), BR=build rate, SR=surface roughness, PM=post-machining, PHT=post-heat treating, AN=anisotropy, OS=open system, DA=dimensional accuracy, R=repair of existing components, BV=build volume

OPTICAL TECHNIQUES

Metrology to assess net-shape is also an important consideration given potential part warping due to large residual stresses. Classical methods for QA/QC have been performed on finished AM parts, including optical dimensional tracking techniques [20].

The topic of process monitoring in AM has seen renewed interest for the reasons stated previously. Many of the current methods and systems use optical or infrared cameras to image the building process. Optical tomography has a primary use in the imaging and study of semi-transparent materials, such as biological materials. Optical tomography, as it is mentioned in this context, is rather a tracking of features in the plane of an opaque material. Melting processes generally produce enough visible light to monitor the shape of the melt pool due to sufficient energy being radiated in the visible spectrum [21]. This allows for the indirect monitoring of temperature based on the visible light emission from the surface. Calibrating then gives a measurement of true temperature that can then be mapped spatially and temporally over the volume of the part as shown in Fig. 1.

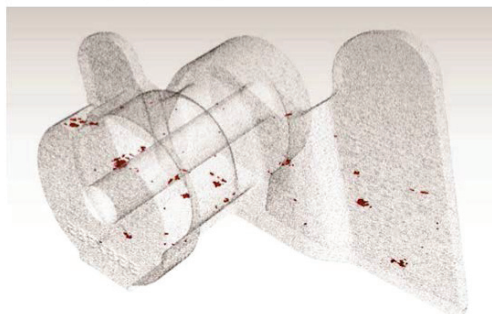

FIGURE 1. Optical tomography is an imaging tool that provides high resolution radiation data from the melting process and depicts areas with deviations in geometry and temperature [Reprinted with permission from C. Volker, *AIP Conference Proceedings,* Vol. 1650, No. 177, pp. 171-176, (2015), Copyright 2015, American Institute of Physics].

In a powder metal – additive part the temperature history is obviously dependent upon diffusion of heat into the item after melting and this can be used to measure indirectly disturbances of the diffusion process with depth in a very similar fashion to that which is achieved with infrared imaging cameras.

The optical and thermal data can then be quantified, either in an integral value over time, or used in the physical characterization of the melt pool [22]. Plotting of whatever metric in space can give a region whose cooling is differentiated from the bulk is likely able to localize areas of concern [23, 24]. These regions of concern can then be linked through mechanical testing to defects, such as porosity or regions with a lack of fusion and these can be relatively easily visualized using custom software or commercially available computed tomography (CT) software [25, 26]. This process is depicted in Fig. 2.

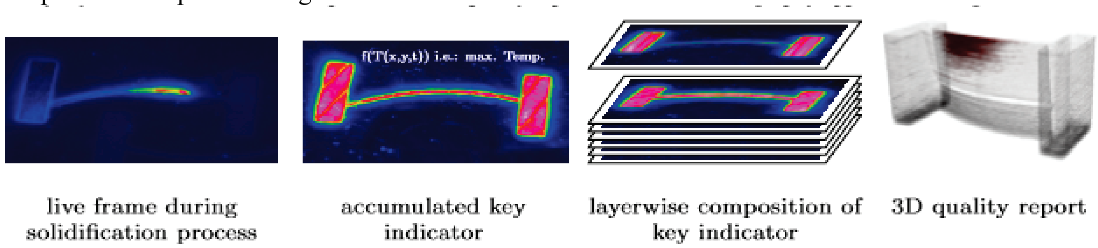

FIGURE 2. Data processing steps to create a 3D quality report from thermographic data [Reprinted with Permission from H. Krauss, T. Zeunger, M. F. Zaeh, *AIP Conference Proceedings,* Vol. 1650, No. 177, pp. 177-183, (2015). Copyright 2015, American Institute of Physics].

Mapping of this data has also been used to adjust the parameters of the build process to provide more uniform temperatures at the end of the build. This method has been shown to be able to detect defects on the order of 100 microns in size by comparison with X-Ray CT data [21]. Often, this is sufficient if the part is to be post processed using hot isostatic pressing (HIP) to consolidate voids left by the AM process.

OTHER TECHNIQUES

Various alternate methods of NDE, such as scanning laser ultrasonic measurements or spatially resolved acoustic spectroscopy have been performed ex-situ on representative defects [27, 28, 29]. These have been applied with some success but have not yet been integrated into process control, at least not in what is available in the open literature. None of the known methods utilize the heat source as a concurrent source for acoustic energy generation. This method has also been incorporated in-situ by attaching ultrasonic laser sources and receivers on the same stage as the heat source, but are not performed during the build [30]. An excellent review which considers mostly optical and thermal methods and complications commonly encountered due to non-uniform or unpredictable emissivity is given by Krauss et al [31].

An overview of the state of non-destructive evaluation (NDE) tools for the characterization of materials from powder to part in metal powder processing is provided by Bond et al [32]. It shows that there are abundant needs for quality assurance/quality control (QA/QC) to be employed to add value to many types of powder metallurgy parts. Possible types of properties or characteristics that may be measured by the nondestructive or non-interacting methods for process or product (inspection) evaluation are identified for stages in powder metallurgy processing include initial shape forming steps that may be the root cause of defects which can be potentially be detected before additional processing cost is expended. NDE for adding value to materials from metal powder processing.

SUMMARY

Additive manufactured components present a unique combination of challenges for nondestructive evaluation. Classical approaches to inspection, such as those used for castings or forged parts, can and are used currently to optimize system and material parameters on a particular combination of additive machine and alloy. Complex part shapes and high performance alloy utilization drive the development of AM systems and methods. These types of parts are typically difficult to inspect once produced. Development of in-situ characterization techniques largely circumvents the geometric considerations and is worthy of further investigation. Standardization of characterization techniques for AM parts would also allow for objective comparison of AM processes and performance.

REFERENCES

1. "Future Developments for the European Powder Metallurgy Industry," *The European PM Industry Roadmap*, January, 2015, retrieved from www.epma.com, (Accessed: June 15, 2015).
2. B. Buafeld, O. Van der Biest, and R. Gault, *Materials and Design*, **31**, S106-S111 (2010).
3. K. Mumtaz and N. Hopkinson, *Rapid Prototyping Journal*, **15** (2), 96-103 (2009).
4. W. E. Luecke and J. A. Slotwinski, *J. of Res. N.I.S.T.*, **119**, 398-418 (2014).
5. A. B. Spierings and M. Schneider, *Rapid Prototyping Journal*, **17** (5), 380-386 (2011).
6. J. A. Slotwinski, E. J. Garboczi, P. E. Stutzman, C. F. Ferraris, S. S. Watson, and M. A. Peltz, *J. of Res. N.I.S.T.* **119**, 460-493 (2014).
7. F. P. Kruth, P. Mercelis, F. Van Vaerenbergh, L. Froyen, and M. Rombouts, *Rapid Prototyping Journal*, **11** (1), 26-36 (2005).
8. J. A. Slotwinski and S. Moylan, "Applicability of Existing Materials Testing Standards for Additive Manufacturing Materials," NISTIR 8005, June, 2014.
9. S. Moylan and J. A. Slotwinski, "Assessment of Guidelines for Conducting Round Robin Studies in Additive Manufacturing," in *Proceedings of the 2014 ASPE Spring Topical Meeting--Dimensional Accuracy and Surface Finish in Additive Manufacturing*, (American Society for Precision Engineering, Raleigh, NC), **57**, 82-85 (2014).
10. J. A. Slotwinski and S. Moylan, "Metals-Based Additive Manufacturing: Metrology Needs and Standardization Efforts," in *Proceedings of the 2014 ASPE Spring Topical Meeting--Dimensional Accuracy and Surface Finish in Additive Manufacturing*, (American Society for Precision Engineering, Raleigh, NC), **57**, 11-12 (2014).

11. R. R. Dehoff, M. M. Kirka, and F. A. List III, K. A. Unocic, W. J. Sames, *Materials Science and Technology*, **31**, (8), 939-944 (2014).
12. "EOS and MTU: Strategic Partnership for Quality Control in Metal-based Additive Manufacturing," Press Release, January 20, 2015, Website: http://www.eos.info/eos_mtu_strategic_partnership_quality_control_dmls, (Accessed: June 9, 2015).
13. "Arcam Growth Spurred by Order Increase," Metal Powder Report, Materials Today (Article). July 24, 2013. Website:http: //www.materialstoday.com/additive-manufacturing/news/arcam-growth-spurred-by-order-increase/, (Accessed: July 7, 2015).
14. "LaserCUSING® - Laser melting with metals," Article, Website: http://www.nyp.edu.sg/web/epic/Digital_Manufacturing.pdf, (Accessed: July 8, 2015).
15. R.R. Dehoff, M. M. Kirka, W. J. Sames, H. Bilheux, A. S. Tremsin, L. E. Lowe, S. S. Babu, *Materials Science and Technology*, **31** (8), 931-938 (2015).
16. ASTM Standard F2792 12a, 2012, "Standard Terminology for Additive Manufacturing Technologies," ASTM International, West Conshohocken, PA, doi: 10.1520/F2792-12A.
17. M. Maher, A. Smith, and J. Margiotta, "A synopsis of the Defense Advanced Research Projects Agency (DARPA) investment in additive manufacture and what challenges remain," in *Proc. SPIE 8970, Laser 3D Manufacturing,* 897002 (9p), (March 6, 2014); doi:10.1117/12.2044725.
18. K. Cooper, "Laser Additive Manufacturing: Where it has been, where it needs to go," in *Proc. SPIE 8970, Laser 3D Manufacturing*, 897003 (6p) (March 6, 2014); doi: 10.1117/12.2044255.
19. L. J. Bond, "Needs and opportunities: nondestructive evaluation for energy systems," in *Proc. SPIE 9439, Smart Materials and Nondestructive Evaluation for Energy Systems 2015,* 943902 (14p), (March 27, 2015); doi:10.1117/12.2086279.
20. M. Mani, B. Lane, A. Donmez, S. Feng, S. Moylan, and R. Fesperman, "Measurement Science Needs for Real-time Control of Additive Manufacturing Powder Bed Fusion Processes," NISTIR 8036, February, 2015.
21. C. Volker, "Monitoring System for the Quality Assessment in Additive Manufacturing," in *Review of Progress in Quantitative Nondestructive Evaluation,* eds. D. E. Chimenti and L. J. Bond, (American Institute of Physics 1650, Melville, NY) **34**, 171-176 (2015).
22. T. Craeghs, S. Clijsters, J. P. Kruth, F. Bechmann, and M. C. Ebert, *Physics Procedia*, **39**, 753-759 (2012).
23. S. Moylan, E. Whitenton, B. Lane, and J. Slotwinski, "Infrared Thermography for Laser-Based Powder Bed Fusion Additive Manufacturing Processes," in *Review of Progress in Quantitative Nondestructive Evaluation,* eds. D. E. Chimenti, L. J. Bond, and D. O. Thompson, (American Institute of Physics 1581, Melville, NY) **33**, 1191-1196 (2015).
24. S. Clijsters, T. Craeghs, S. Buls, K. Kempen, J. P. Kruth, *Int. J. Adv. Manuf. Technol.*, **75**, 1089-1101 (2014).
25. H. Krauss, T. Zeunger, M. F. Zaeh, "Thermographic process monitoring in powderbed based additive manufacturing," in *Review of Progress in Quantitative Nondestructive Evaluation,* eds. D. E. Chimenti and L. J. Bond (American Institute of Physics 1650, Melville, NY) **34**, 177-183 (2015).
26. G. Zensinger, J. Bamberg, A. Ladewig, T. Hess, B. Henkel, W. Satzger, "Process Monitoring of Additive Manufacturing by Using Optical Tomography," in *Review of Progress in Quantitative Nondestructive Evaluation,* eds. D. E. Chimenti and L. J. Bond (American Institute of Physics 1650, Melville, NY) **34**, 164-170, (2015).
27. E. Rodriguez, F. Medina, D. Espalin, T. Cesar, D. Muse, C. Henry, E. MacDonald, R. B. Wicker, "Integration of a Thermal Imaging Feedback Control System in Electron Beam Melting," in *Proceedings of the Solid Freeform Fabrication Symposium*, Retrieved from http://sffsymposium.engr.utexas.edu/, (2012).
28. R. J. Smith, W. Li, J. Coulson, M. Clark, M. G. Somekh, and S. D. Sharples, *Meas. Sci. and Tech.*, **25**, 055902-055913 (2014).
29. J. Rudlin, D. Cerniglia, M. Scafidi, C. Schneider, "Inspection of Laser Powder Deposited Layers," *11th European Conference on Non-Destructive Testing (ECNDT 2014)*, October 6-10, 2014, Retrieved from www.ndt.net.
30. S. P. Santospirito, R. Lopatka, D. Cerniglia, K. Slyk, B. Luo, D. Panggabean, J. Rudlin, "Defect detection in laser powder deposition components by laser thermography and laser ultrasonic inspections," in *Proc. SPIE 8611, Frontiers in Ultrafast Optics: Biomedical, Scientific, and Industrial Applications XIII*, 86111N (10p), (March 15, 2013); doi:10.1117/12.2006361.
31. H. Krauss, C. Eschey, M. Zaeh, "Thermography for monitoring the selective laser melting process," in *Proceedings of the Solid Freeform Fabrication Symposium*, Retrieved from http://sffsymposium.engr.utexas.edu/, (2012).

32. L.J. Bond, J.N. Gray, F.J. Margetan, D. Utrata, and I.E. Anderson, (2014) NDE for adding value to materials from metal powder processing. Advances in Powder Metallurgy & Particulate Materials – 2014. Proceedings, PM2014, Compiled by R.A. Chernenkoff and W.B. James, Metal Powder Industries Federation, Part 11, (pages 11.1-15), pp 1944-1959.