US Army Use of MaterialCenter for **Metals Additive Manufacturing Data Management**

Based on an Interview with **the United States Army Combat Capabilities Development Command Armaments Center**

The United States Army Combat Capabilities Development Command (CCDC) Armaments Center is the US Army's primary research and development arm for armament and munitions systems. It is a leading defense facility for Additive Manufacturing (AM) of Metals and is located in New Jersey. Armaments Center has been investigating AM for a number of years now with programs aimed at exploiting the novel capabilities of additive manufacturing. The facility has a number of AM systems at their disposal including a laser powder bed fusion EOS M290 machine that prints in Steel (4340/4140/17-4), Inconel, and Cobalt Chrome; and an E-Beam system, an ARCAM A2X machine that prints in Titanium, Inconel, and Cobalt Chrome. In addition, there is access to a wide range of support and testing equipment for powder synthesis (Plasma Reactors, High Energy Mills), post processing (HIP, Heat Treatment, Surface Finishing), machining in a full machine shop (EDM, CNC, etc.), testing (Tensile, Charpy Impact, Hardness), and part characterization (Scanning Electron Microscopy, Particle Size Analysis, X-Ray Fluorescence & Diffraction, Oxygen/Nitrogen Analysis).

Armaments Center is interested in using AM equipment to prototype, develop, and fabricate metal parts via a layer by layer powder bed laser sintering process. AM has the potential to provide a wide range of design flexibility over traditional manufacturing methods allowing for rapid prototyping, part weight reduction, novel part design, reduced time to product, and overall manufacturing flexibility. The benefits of AM include a reduced logistics footprint and time-to-field for replacement parts, manufacturing options to reduce single point failures, and creation of novel and improved part designs for reduced weight while meeting or exceeding performance requirements. In turn AM results in a manufacturing process for providing parts on rapid response, and on-demand basis.

Armaments Center has identified six practical areas of interest for additive manufacturing technologies in the US Army (see Figure 1):

1. Novel Materials: Novel powder synthesis for Non-COTS materials,
2. Rapid Prototyping: Multiple build iterations on the same build plate for design optimization. Small runs for prototype testing,
3. Replacement Parts: Investigating component replacements which match properties but can be delivered in an accelerated timeframe,
4. Novel Designs: Investigating novel weapons systems components with designs difficult or impossible with traditional machining,
5. Rapid Fielding: Investigating Additive Technologies to overcome the challenges of bringing metals additive to the field, and
6. Process Monitoring: Working to develop custom In-Situ Monitoring Hardware which can be retrofit on existing equipment.

For AM benefits to be fully realized, processes must be developed and qualified for part acceptance for use in armament systems meaning design and manufacturing process data required to support repeatable additive manufacturing production must be defined. Several examples of additively manufactured armaments produced are shown in Figure 2.

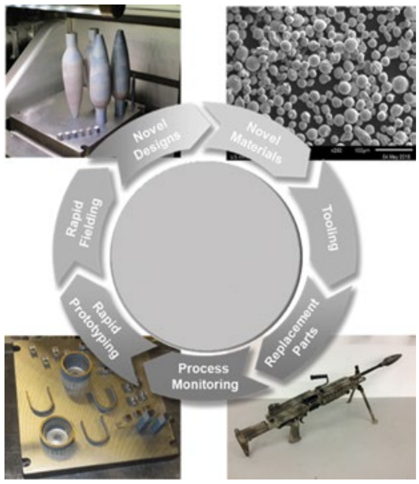

Figure 1: **Additive Manufacturing Areas of Interest to the US Army**

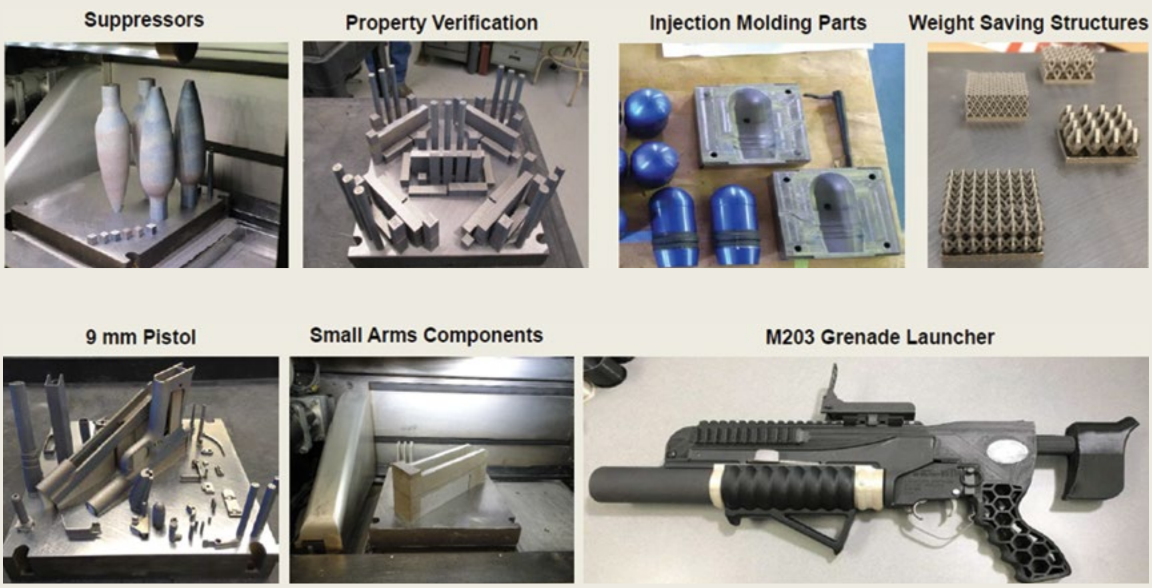

Figure 2: **Metals AM Build Examples for the US Army at CCDC Armaments Center**

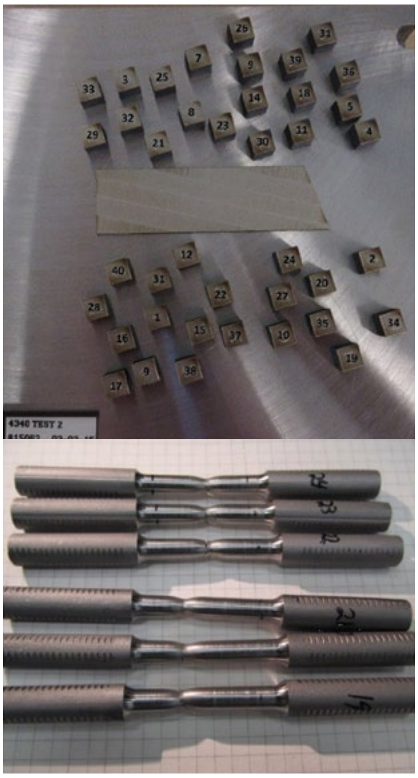

Figure 4: **Selection of some of our 325 AM Benchmark samples and parts**

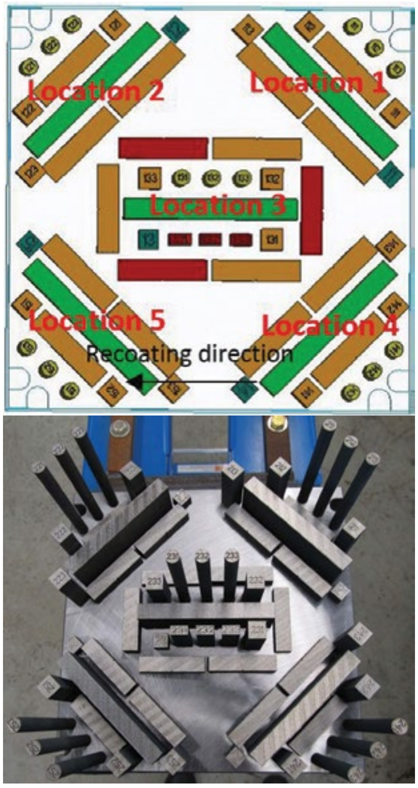

Figure 5: **Benchmark Steel 3d Printing Test showing Locations of Parts of the Base Plate**

What is the L-PBF Quality Strategy?

CCDC Armaments Center at Picatinny, NJ, have focused on additive manufacturing process development for AM materials and parameters along with the development of Quality Assurance provisions and requirements to develop manufacturing guidelines for robust and reliable new build L-PBF components. To do this, test components for new build demonstration and testing were selected. The team wanted to establish a process for qualification and certification of AM components, then transition the process on to internal government facilities and the AM industry with a manufacturing guide. In addition, the US Army wanted to share knowledge of the additive manufacturing process and create a knowledge base of AM products aligning to their roadmap.

What are the Challenges to the Use of Additive Manufacturing in the Military?

First and foremost, part acceptance for US DoD (Department of Defense) applications relies on a process for qualification and certification. However, the relationship between AM materials properties, processing parameters, and component performance are extremely complex, and complicated further by unique part geometries. There is also an extremely large pool of materials and AM equipment to choose from, raw materials must be readily available and trusted to manufacturer or internal specifications, processing condition windows must be defined to ensure part quality, In-Situ Monitoring technology must be utilized and improved upon, and a recognition that technology advancement might introduce previously unforeseen manufacturing variables.

It is fair to say that AM standards are still in development. There is a clear need for continuing collaboration between academia, industry, government agencies, and others to push standards adoption. Moreover, with respect to design for AM there is a need to educate and inform part designers of new principles and the constraints for AM. Today, widespread adoption of the AM process is limited due to a combination of these many challenges. Finally, with respect to utilization of Digital Product Data in AM, a system for controlled electronic data management and sharing must be implemented - software types used and digital file control must be set prior to manufacturing initiation.

CCDC Armaments Center Additive Manufacturing Benchmark Demonstration

A CCDC Armaments Center goal is to qualify powder bed fusion AM technologies as a viable alternative manufacturing process to fabricate armament systems components. To do this, multiple areas in the total manufacturing process need developmental efforts addressed to them to be able to produce an accepted additively manufactured component. An additive manufacturing benchmark testing method was devised using 4340 Steel Powder due to its chemistry, particle size, and flow characteristics. AM processing parameters were developed focusing on energy density ranges, and a DoE (Design of Experiment) was established that looked at the following parameters over 325 samples that were fabricated (see Figure 4):

1. Laser Power
2. Scan Speed
3. Hatch Distance
4. Energy Density Range

The resultant AM parts were evaluated based on microstructure, density, porosity, and hardness. Their mechanical properties were compared to wrought steel after stress relief, quench and temper heat treatment.

For each mechanical test specimen, four identical consecutive builds were printed to assess process reliability. The team focused on variations in location and orientation within and across builds, while collecting tensile, hardness, density, and toughness data. The team normalized samples with heat treatments per the AMS 2759 standard.

Sample Description	Modulus (Mpsi)	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (%)	Standard Deviation of % Elongation (%)
Typ. Wrought Prop.	29	220	270	11	N/A
Build 1	29	222	285	10.5	0.7
Build 2	29	223	280	9.0	1.6
Build 3	29	223	282	11.5	0.7
Build 4	29	221	279	9.9	1.2
Location 1	29	222	281	10.7	1.3
Location 2	29	221	280	9.2	2.1
Location 3	29	223	282	10.6	0.8
Location 4	29	223	283	10.2	1.4
Location 5	29	223	281	10.3	1.0
Overall Z	29	222	281	10.2	1.4
Overall X-Y	29	223	283	11.6	1.0

Figure 6: **Benchmark AM Printing Sample Mechanical Property Results for the different print locations in Figure 5**

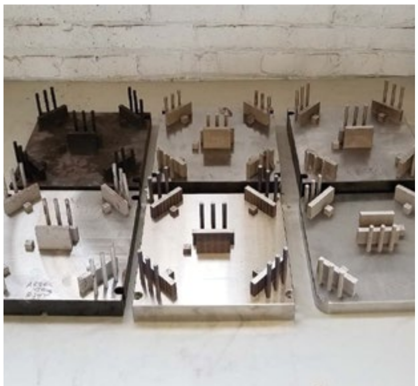

Figure 7: **Six AM Printer Machine results for the same set of parts being printed the same way**

AM Benchmark Results and Lessons Learned

The tests indicated that parts printed in the XY direction had 12% higher elongation values than parts built in the Z direction. Ultimate Tensile Strength (UTS), Density, and Hardness values matched wrought steel properties. The parts printed at Location 2 (top left of Figure 5) had the lowest mechanical properties (~9% less) of all builds. Build locations 2 and 4 had Z oriented tensile data with the lowest values (see table in Figure 6). This was because gas flow worsened when the machine's filters were nearly full. In addition, many AM process conditions needed to be taken into account such as powder coverage, build plate material/condition, recirculating gas filtration, gas flow rates, part orientation, and part location on the underlying build plate and these parameters must be controlled for consistent AM part mechanical properties. Hence, a manufacturing plan with defined operating windows is needed to ensure parts are consistently made to specification.

The Effect on the AM Benchmark Tests on Using Different Machine Types

To check for the effect of different additive machines, six AM commercial machines were chosen to print the same parts in a "round robin" demonstration of variability (see Figure 7):

- Equipment chosen included an EOSM290, ProX320, SLM, and the EOSM280
- 4340 steel powder was procured from a single lot to minimize variance
- A manufacturing guide was written and disseminated to all participants outlining all major aspects of the manufacturing process
- The aim of this round robin test was to observe variance in material properties as a function of orientation and plate location across equivalent and different equipment types, with the same or equivalent process parameters.

AM Engineering Simulation Digital Data Storage Challenges

In particular, given the sensitive nature of military parts, data security is critical in AM – how is digital data adequately protected in additive manufacturing? How is data sharing implemented especially if different network security protocols exist, where cloud-based solutions are not widely adopted? Moreover, in terms of data classification where data aggregation could raise the classification, there is a need for a controlled system. Invariably, different formats occur across a wide variety of OEM machines for metals AM with no standardized software or file format.

In terms of data organization, a unified file structure does not in general exist. With AM, large amounts of data generation will occur. Complex data sets can be generated from even a single build. Hence, data storage solutions are needed where process monitoring solutions require large file storage spaces and bandwidth. In effect, AM processing pedigrees are required. There is a need for historical records of print builds to exist for data tracking and analysis to relate back to field performance without duplicating efforts, allowing teams to learn from mistakes or successes. To do all this raises big questions over IT infrastructure issues. If there is no uniform software and network system across different branches and centers, then it will be difficult for approvals and data sharing to happen with additively manufactured parts.

MSC's MaterialCenter as the AM Data Management Solution at CCDC Armaments Center

To overcome digital data challenges of additive manufacturing, a software solution is necessary for traceability, storage, and analysis of simulation material data. Armaments Center used MSC Software's MaterialCenter (Figure 8) and developed an additive manufacturing schema to enable the storage of all printer machine parameters along with corresponding material properties. It utilizes M/S Excel integration in order to map and import custom templates. The data collected is:

- Machine Information
- Part Data (CAD/STL/MAGICS Files)

- Starting powder properties
- Machine Build Parameters
- Build Layout and Orientation
- Laser Parameters
- Post Processing
- Metallographic Analysis
- Mechanical Testing Data

The data stored using MSC Software's MaterialCenter involves a flexible schema for different applications, an automated method for input of material process information, data analysis to compare and contrast properties and understand how to optimize them, and finally allowing traceability of test data.

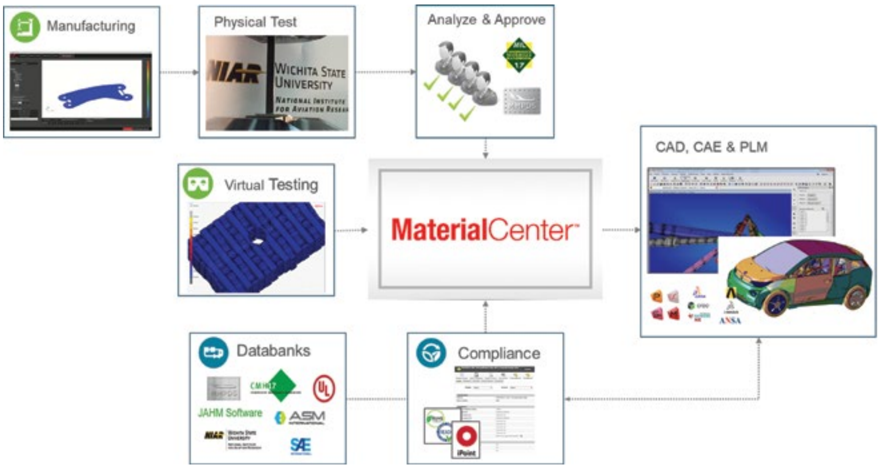

Figure 8: **MSC MaterialCenter in the center of the entire AM Material Lifecycle workflow**

Capturing the Entire AM Material Lifecycle

Figure 8 shows the data tracking process for additive manufacturing and Figure 9 depicts the two parts of the AM process:

1. "Left of Test" where manufacturing inputs that are used to create a part or specimen are captured. This side of the test leverages MaterialCenter's Work Request, Pedigree and Process features. MSC Software's MaterialCenter tracks the test specimen from raw material through the complete specimen build process (Figure 10). The team tracked the materials & the environment, Batch/ Specimen numbers and the Part Inspection.
2. "Right of Test" where Material products are tracked from *test to export.*

Finally, PTC Windchill was chosen as the ePDM system for this application and the overall central data system for AM at CCDC Armaments Center - this is shown schematically in Figure 11 where the integration between Windchill and MaterialCenter for additive manufacturing is shown pictorially. The benefits of this system are that it is always up-to-date for version control tracking; it leads to less duplication of efforts and therefore reduced costs; it is a common file system for traceability, file security, historical storage, etc; it provides for a better collaborative environment in order to coordinate efforts; it allows for quicker fabrication of hard to replace parts with standardized file systems and organization; it yields common data models for standardization and validation; it is a single source of data for linkage between systems; and it provides true lifecycle configuration management for additive manufacturing. In short, for us to make Additive Manufacturing as "available" as traditional manufacturing techniques, materials and process data, it must be linked to part data using this enterprise ePDM approach.

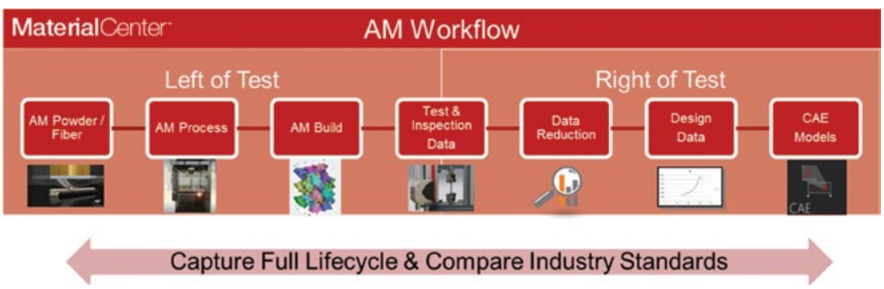

Figure 9: **Data management applied to additive manufacturing process**

This additive manufacturing ePDM workflow helps to deal with the management of data issue and can become a US Army Standardized Tool for Lifecycle support when printing a component. It provides confidence through validation to the end user of part performance. Everything is in the chain from raw material, files, machines, and post treatment and it is validated to perform as designed. In terms of Data Capture, automated processes to feed into the data management system were enabled. In terms of On-Demand Manufacturing, the team has qualified and authorized personnel with access to the data. In terms of Predictive Modeling, knowing how a part will perform before printing is invaluable. In terms of Cooperation & Data Sharing, it will lead to the saving of money and time by building on the most up-to-date work. And, lastly, in terms of Data Analysis, the team can optimize process parameters via statistical modeling and understand the relationship between key AM process parameters.

Future Focus of Additive Manufacturing in the US Army

The US Army CCDC Armaments Center is aiming at integrating material data management with other enterprise software, eg. PLM, and collaboration with other services such as the US Air Force, US Navy, etc. Ultimately, this approach can be expanded to other manufacturing processes and the capture of legacy manufacturing data with the creation and storage of new data libraries. It is also looking at new materials systems (functionally graded materials, novel alloys, hybrid materials), the fielding of AM parts and AM systems for on-demand Battlefield manufacturing, a wide range of qualification & certification of materials, processes and parts via additive manufacturing, and advanced fabrication integration with sensors and electronics.

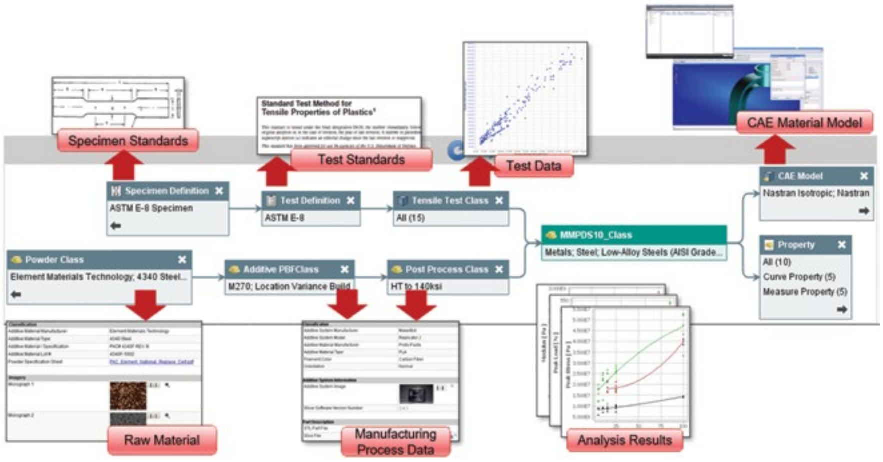

Figure 10: **Overall Flowchart of Additive Manufacturing Data**

Reference

"Army Efforts in Metals Additive Manufacturing & Data Management", R. Carpenter, SME Smart Manufacturing Series – Additive Manufacturing, 07 June 2018

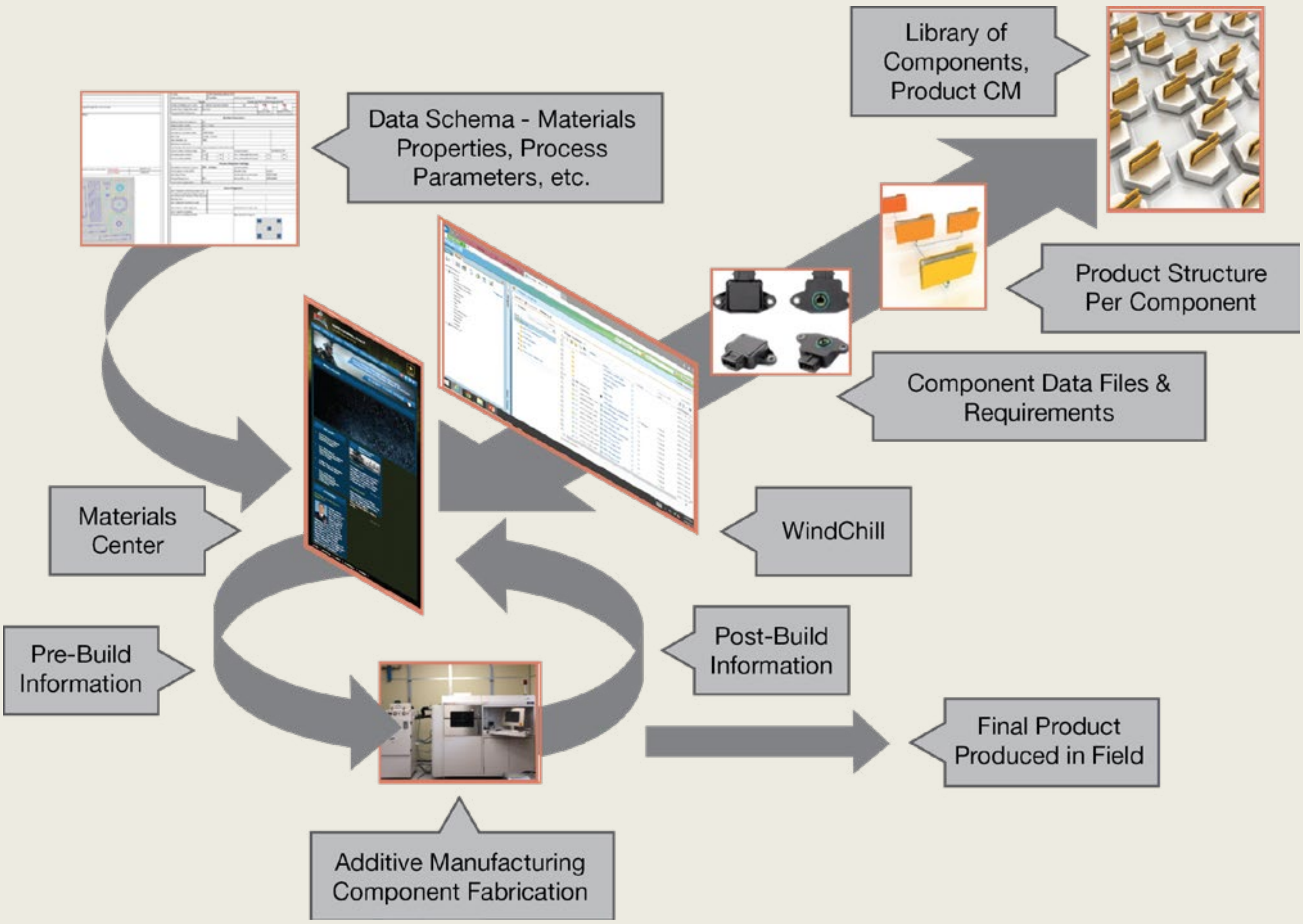

Figure 11: **PTC Windchill and MSC MaterialCenter integration ePDM system for Additive Manufacturing Data**