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Data Management and Data Curation for Additive Manufacturing: Annual Report

prepared by William Underwood, Mark Conrad, Greg Jansen, and Richard Marciano
University of Maryland
College Park, MD

under contract W911NF2020222

NOTICES

Disclaimers

The DEVCOM Army Research Laboratory (DEVCOM ARL) sponsors this research under Cooperative Agreement W911NF2020222 with the University of Maryland entitled UMD-ARL Alliance for Additive Manufacturing Science. The findings in this report should not be construed as an official DEVCOM ARL position unless so indicated by other authorized documentation.

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14. ABSTRACT

This report describes key research issues in additive manufacturing (AM) data management that are important to the US Army and the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL). It also presents a research plan addressing some of these issues.

The ability to manage the metadata and data of an additively manufactured part throughout its life cycle is key to achieving the Army's vision of a more adaptive, agile defense supply base. The Additive Manufacturing Data Management Working Group (AM DM WG) has begun addressing this need by developing a Common Data Dictionary for AM, which is nearing completion and will be published as a standard by ASTM International. In FY21, the authors participated in AM DM WG activities to develop an AM common data model and an AM ontology. They also became acquainted with the powder bed fusion method of AM. The research plan for FY22 includes (1) participating in AM DM WG, (2) prototyping an AM research data management application, and (3) collecting DEVCOM ARL and University of Maryland (UMD) AM product and research data. Our longer-range research plan includes (1) developing a tool to support construction of an AM data package for submission to an AM data repository, (2) prototyping an AM data repository for use by DEVCOM ARL and UMD researchers, and (3) federating the prototype AM repository with other AM data repositories.

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1. Introduction

Additive manufacturing (AM) is a manufacturing process that creates parts layer-by-layer from 3D object models. AM provides an opportunity for huge reductions in cost for manufacturing parts when compared to traditional subtractive manufacturing methods. Significant investments are being made in R&D to additively manufacture parts and research new materials and processes. These programs generate huge amounts of data on materials, process parameters, and parts qualification.

In January 2021, the Office of Under Secretary of Defense for Research and Development released a special report titled *Department of Defense Additive Manufacturing Strategy*, where DoD identified AM as "a versatile technology that provides technical advantages across a range of defense applications, essential to modernize national defense systems, increase materiel readiness and enhance warfighter innovation and capability" (Joint Defense Manufacturing Council, 2021). The report outlines the vision that "AM will enable a more agile, adaptable and aligned defense supply base to outpace adversarial threats. AM will be a widely accepted manufacturing technology used across DoD and defense industrial base." The vision statement further identifies that for DoD, "The **digital thread**, an ecosystem of interconnected systems, software and data, will accelerate use of AM by connecting information to physical processes more effectively, using advanced technologies like modeling and simulation, artificial intelligence, and machine learning."

This report describes research issues in AM data management that have been identified as important to the US Army and the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) and outlines a research plan for addressing these issues.

Section 2 describes the need for metadata standards for AM and our participation in activities addressing this need. Sections 3 describes an AM case study. Section 4 describes some of the data elements in the Common Data Dictionary (CDD) discussed in Section 2.1. These were identified during the case study in Section 3. Section 5 describes some research issues that were identified and a research plan for addressing these issues in the following years.

2. Additive Manufacturing Data Standards Development

The ability to manage the metadata and data of a part throughout its life cycle is key to achieving the Army's vision of a more adaptive, agile defense supply base.

The Additive Manufacturing Data Management Working Group (AM DM WG) is developing AM data standards. The working group is led by Yan Lu of the National Institute of Standards and Technology (NIST). The working group includes other members of the NIST Systems Integration Division.[*] The group includes members from ASTM International, which develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services.[†] Titles of a number of International Organization for Standardization (ISO) and American Society for Testing and Materials (ASTM) standards in AM are provided in the Appendix. The working group also includes members of ASM International, founder of the Computational Materials Data Network,[‡] and SAE International, a developer and maintainer of Aerospace Material Specifications and Aerospace Standards for AM.[§] The ASTM Additive Manufacturing Center of Excellence hosts the Annual ASTM International Conference on Additive Manufacturing (ASTM ICAM 2021).[**] The working group also has members from other federal agencies, DoD components, the materials and manufacturing industries, and academia, particularly in the fields of Material Science, Mechanical Engineering, and Computer Science.

2.1 Common Data Dictionary

The draft ASTM standard WK72172, *New Practice for Additive Manufacturing – General Principles – Overview of Data Pedigree,* builds on the base of the CDD work done by the NIST AM DM WG (forthcoming). The dictionary has identified classes of AM data and important terms for data that fit within those classes. The scope of this standard is to use this dictionary to create a practice for standardizing data elements that are collected during an AM process. The CDD will include the data element names, definitions, data types, and ranges needed to establish a base for sharing AM data across organizations. The data elements defined in the CDD are grouped into 15 information modules as shown in Fig. 1.

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[*] www.nist.gov/el/systems-integration-division-73400

[†] www.astm.org/

[‡] www.asminternational.org/web/cmdnetwork

[§] www.sae.org/works/committeeHome.do?comtID=TEAAMSAM

[**] https://amcoe.org/icam2021

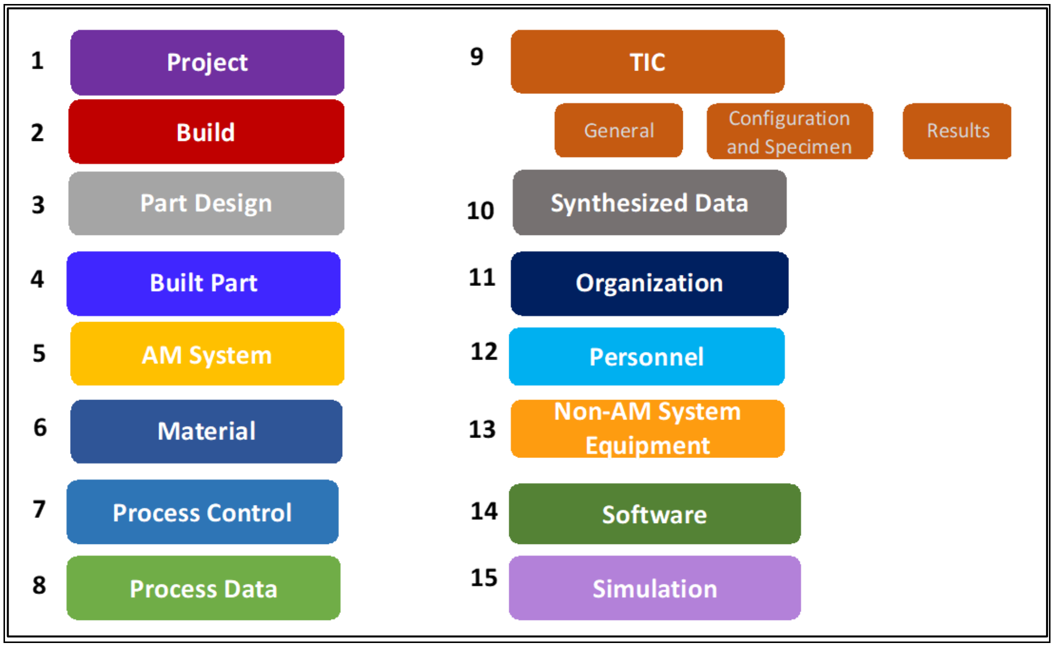
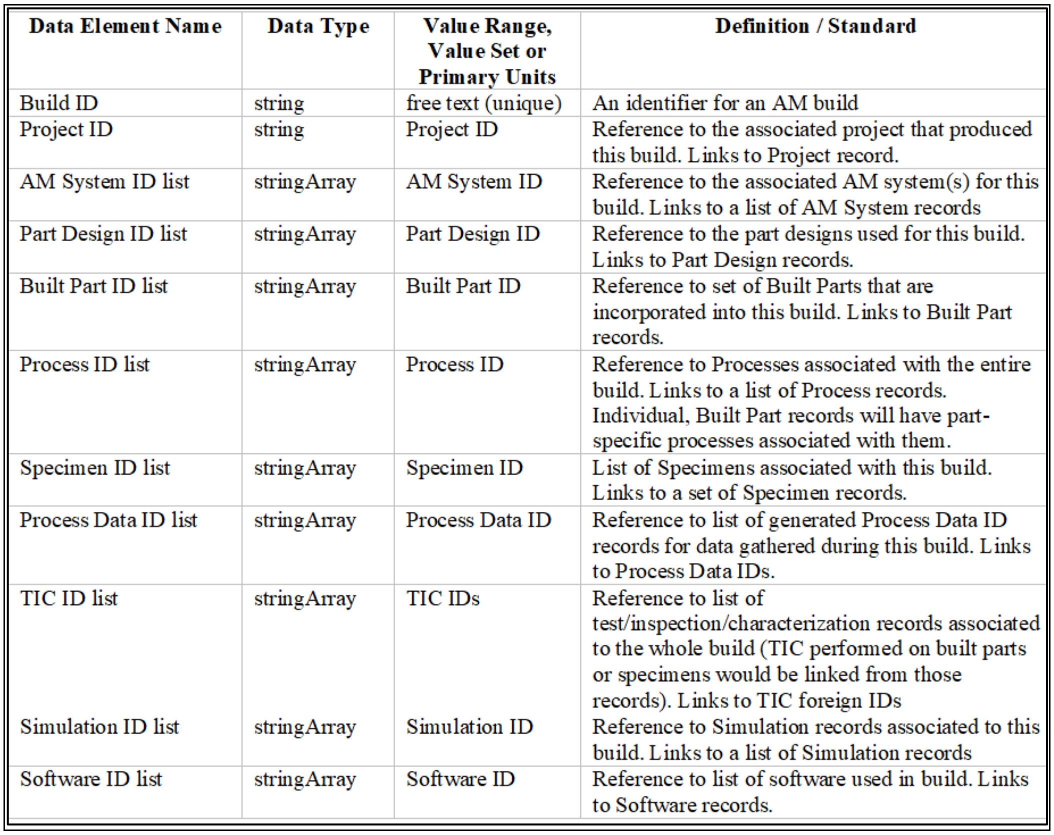


Fig. 1 **AM module names**

The definition of one of these modules, *Build*, is as follows (ASTM, forthcoming):

> Build: All the information generated during a single, AM process cycle during which one or more components are 'built up' in layers inside the process chamber of the additive manufacturing system. The Build data module acts as a central reference point for all data related to a build. It contains reference links to other modules involved in the build process (e.g., Material for feedstock information, Parts for information about parts produced in the build).

Some of the Build data elements are shown in Fig. 2.



Data Element Name	Data Type	Value Range, Value Set or Primary Units	Definition / Standard
Build ID	string	free text (unique)	An identifier for an AM build
Project ID	string	Project ID	Reference to the associated project that produced this build. Links to Project record.
AM System ID list	stringArray	AM System ID	Reference to the associated AM system(s) for this build. Links to a list of AM System records
Part Design ID list	stringArray	Part Design ID	Reference to the part designs used for this build. Links to Part Design records.
Built Part ID list	stringArray	Built Part ID	Reference to set of Built Parts that are incorporated into this build. Links to Built Part records.
Process ID list	stringArray	Process ID	Reference to Processes associated with the entire build. Links to a list of Process records. Individual, Built Part records will have part-specific processes associated with them.
Specimen ID list	stringArray	Specimen ID	List of Specimens associated with this build. Links to a set of Specimen records.
Process Data ID list	stringArray	Process Data ID	Reference to list of generated Process Data ID records for data gathered during this build. Links to Process Data IDs.
TIC ID list	stringArray	TIC IDs	Reference to list of test/inspection/characterization records associated to the whole build (TIC performed on built parts or specimens would be linked from those records). Links to TIC foreign IDs
Simulation ID list	stringArray	Simulation ID	Reference to Simulation records associated to this build. Links to a list of Simulation records
Software ID list	stringArray	Software ID	Reference to list of software used in build. Links to Software records.

Fig. 2 Data elements in the Build information module

2.2 Common Data Model for Additive Manufacturing

The working group is beginning to develop a common data model (CDM) for AM. A precept of the working group is that the data that needs to be collected, managed, and preserved is dependent on the subsequent use of the data. Two of the primary uses of AM data are process repeatability and part-to-part reproducibility (Kim et al. 2017). Maintaining consistency across AM builds is a major challenge due to the effect that subtle variations in process, material, and geometry can have on part characteristics. Kim et al. (2017) propose the adoption of the concepts of digital provenance and digital thread to constrain and manage the variability across the life cycle of an additively manufactured part.

There are many definitions of digital provenance. Perhaps one of the best in this context is one in which provenance is based on metadata. Per the Provenance Working Group, “[P]rocess-centered provenance [is] capturing the actions and steps taken to generate the information in question. For example, a chart may have been generated by invoking a service to retrieve data from a database, then extracting certain statistics from the data using some statistics package, and finally processing these results with a graphing tool” (2013).

Understanding the concepts of a digital twin and the digital thread is key to understanding the AM data management requirements. As explained in the article "What Are Digital Twins and Digital Threads?" (Gould 2018):

> A digital twin is basically a virtual version of a physical entity, whether product, factory, or some other type of asset or system. The digital twin unites business, contextual and sensor data to represent the physical object. . . . Digital threads refer to the digitization and traceability of product 'from cradle to grave.' The digital thread connects all the various capabilities in the digital twin back to the part designs, requirements and software that goes into the product represented by the digital twin.

Digital thread and full traceability across a life cycle are synonymous.

Based on these concepts, Kim et al. (2017) have identified an AM digital thread. They establish data models that will support the manageability and traceability of digital data sets with an emphasis on the powder bed fusion process. They present an AM information map (Fig. 3).

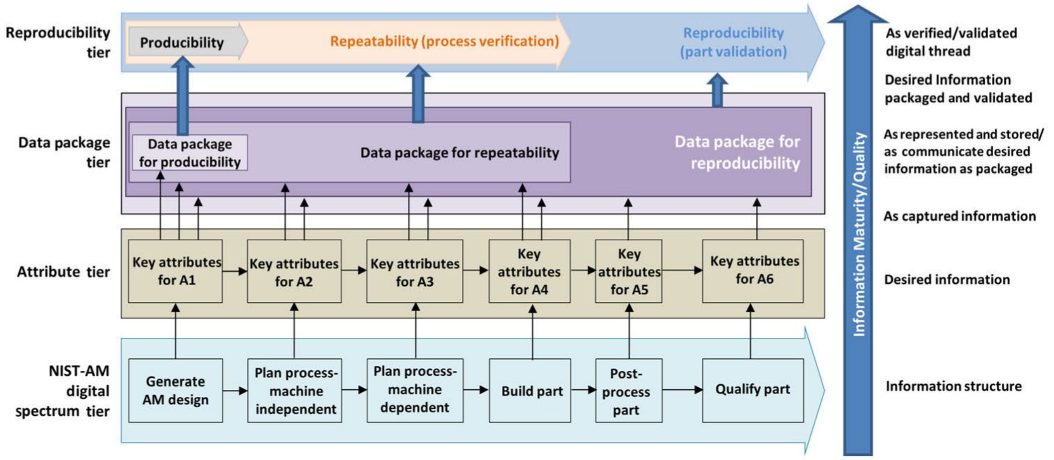
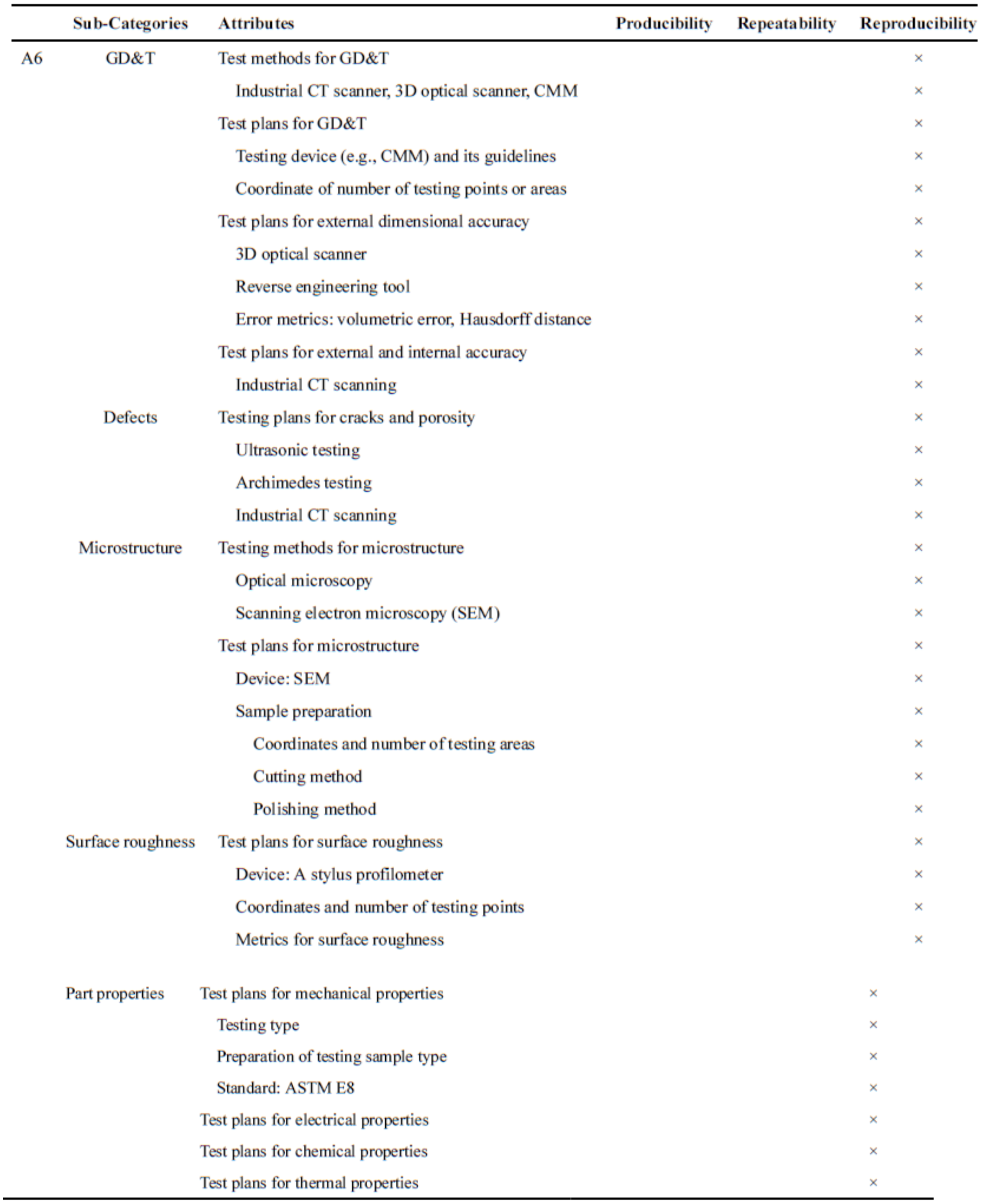


Fig. 3 AM information map consisting of four tiers

The AM digital spectrum tier consists of six activities: (A1) generate AM design, (A2) plan process–machine independent, (A3) plan process–machine dependent, (A4) build part, (A5) post-process part, and (A6) qualify part.

Figure 4 shows the key attributes for part-to-part reproducibility in relation to A6, the testing and qualification process of a part, essential for measuring reproducibility. The key attributes are divided into five subcategories: geometric dimensioning and tolerancing, defects, microstructure, surface roughness, and part properties. From the identified key attributes, they develop conceptual data models to support the establishment of digital provenance through a digital thread.



	Sub-Categories	Attributes	Producibility	Repeatability	Reproducibility
A6	GD&T	Test methods for GD&T			×
		Industrial CT scanner, 3D optical scanner, CMM			×
		Test plans for GD&T			×
		Testing device (e.g., CMM) and its guidelines			×
		Coordinate of number of testing points or areas			×
		Test plans for external dimensional accuracy			×
		3D optical scanner			×
		Reverse engineering tool			×
		Error metrics: volumetric error, Hausdorff distance			×
		Test plans for external and internal accuracy			×
		Industrial CT scanning			×
	Defects	Testing plans for cracks and porosity			×
		Ultrasonic testing			×
		Archimedes testing			×
		Industrial CT scanning			×
	Microstructure	Testing methods for microstructure			×
		Optical microscopy			×
		Scanning electron microscopy (SEM)			×
		Test plans for microstructure			×
		Device: SEM			×
		Sample preparation			×
		Coordinates and number of testing areas			×
		Cutting method			×
		Polishing method			×
	Surface roughness	Test plans for surface roughness			×
		Device: A stylus profilometer			×
		Coordinates and number of testing points			×
		Metrics for surface roughness			×
	Part properties	Test plans for mechanical properties			×
		Testing type			×
		Preparation of testing sample type			×
		Standard: ASTM E8			×
		Test plans for electrical properties			×
		Test plans for chemical properties			×
		Test plans for thermal properties			×

Fig. 4 Key attributes of reproducibility in A6

Figure 5 presents a high-level data package in terms of a product, process, and resources model. Reproducibility is the most inclusive and, thus, includes the entire data sets from the six processes.

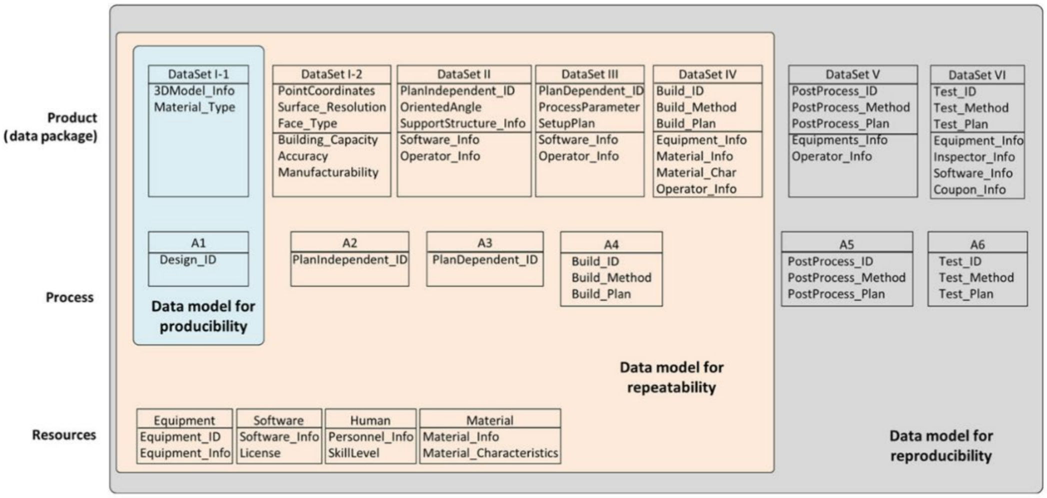


Fig. 5 Conceptual data model of producibility, repeatability, and reproducibility

Figure 6 shows the XML schema of the data package for activity A6, which is related to the conceptual data model for reproducibility in Fig. 5 (DataSets I–VI). The six data sets form a baseline data model. Three case studies are presented that demonstrate the producibility, repeatability, and reproducibility concepts.

```xml
        <Product>
            <Header>
                <ProductType>SPEC</ProductType>
                <Name>NIST TEST Artifact Build Spec</Name>
                <Application>Adobe PDF</Application>
                <Author>Peter Johnson</Author>
                <Description>Build specification for NIST Diamond shape Test Artifact</Description>
                <Units>um</Units>
                <LastModified>2006-05-04</LastModified>
            </Header>
            <Spec>
                <SurfaceMax>50</SurfaceMax>
                <SurfaceAve>10</SurfaceAve>
            </Spec>
        </Product>
        <Product> [196 lines]
        <Product>
            <Header>
                <ProductType>TESTREPORT</ProductType>
                <Name>NISTDiamonShapeArtifactTestReport</Name>
                <Application>Adobe</Application>
                <Author>Michael Edmondson</Author>
                <Description>NIST Diamond Shape Artifact Surface Roughness test</Description>
                <LastModified>2015-07-30</LastModified>
            </Header>
            <TestReport id="TestReport1">
                <TestData>
                    <SurfaceMax>37.5</SurfaceMax>
                    <SurfaceAve>8.6</SurfaceAve>
                </TestData>
                <File>NISTSRT.pdf</File>
            </TestReport>
        </Product>
```

Fig. 6 XML schema of data package for reproducibility

2.3 Additive Manufacturing Ontology

The working group plans to develop an ontology for AM. They are currently reviewing prior and current research in manufacturing ontologies. An AM ontology consists of generic, domain-independent knowledge that applies to all domains and encodes expert knowledge specific to the AM domain. Generally, an ontology of a domain consists of both generic and specific knowledge. A data model of a domain represents the specific attributes and relationships of the domain, and the database itself represents the facts of the domain. Since the ontology formally encodes both generic and specific knowledge of a domain, it is possible to automatically reason about that domain to include facts in the domain. For instance, one might be able to reason from the test results of an additively manufactured part the degree to which it met the part specification.

An upper ontology (aka top-level ontology) is an ontology that consists of very general terms (such as “object”, “property”, “relation”) that are common across all domains. An upper ontology supports semantic interoperability among domain-specific ontologies by providing a common starting point for the formulation of definitions. A number of upper ontologies have been proposed, including the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) (Masolo et al. 2003) and the Basic Formal Ontology (BFO) (Arp et al. 2015).

The working group is investigating the use of the BFO as an upper ontology. In the BFO there are two primary entities: continuant entities, such as 3D enduring objects, and occurrent entities (primarily processes) conceived as unfolding in successive phases through time. Interrelations are defined between the two types of ontologies. A continuant domain ontology descending from BFO consists of entities existing at a time. Each occurrent ontology consists of processes unfolding through a given interval of time. BFO is a hierarchy of concepts as illustrated in Fig. 7.

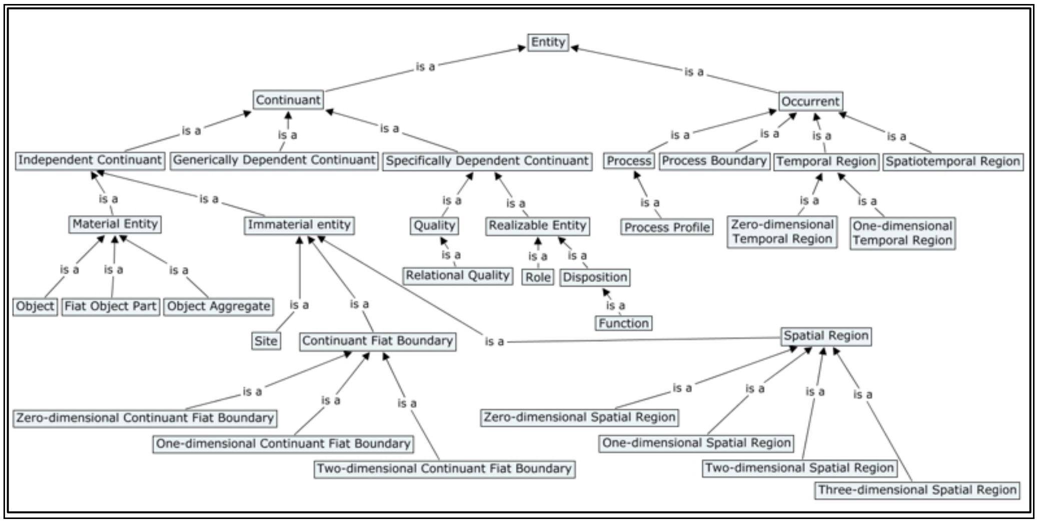


Fig. 7 BFO hierarchy

One of the languages used to represent BFO is the Web Ontology Language (OWL). The OWL representation can be loaded into the ontology editor Protégé[*] where it can be used to define other ontologies and be combined with other ontologies.

BFO serves as the upper ontology of the ontologies being developed by the Industrial Ontologies Foundry, a group of industrial and academic organizations that are creating libraries of reference ontologies for reuse (Kulvatunyou et al. 2018).[†] Hagedorn et al. (2019) present an ontology based on BFO, Relation Ontology[‡], and Functional Basis Ontology (Fernandes et al. 2007) for additively manufacturing joint prosthesis. Ali et al. (2019) present an AM ontology based on BFO, the Information Artifact Ontology[§] and the Common Core Ontology[**] with applications in dentistry product manufacturing.

Sanfilippo et al. (2019) have developed an ontology for AM using the DOLCE upper ontology. In the DOLCE upper ontology, there are two kinds of entities, *endurants* and *perdurants.* Masolo et al. define the entities as follows (2003, p. 11):

> Classically, endurants (also called continuants) are characterized as entities that are "in time", they are "wholly" present (all their proper parts are present) at any time of their existence. On the other hand, perdurants (also called occurrents) are entities that "happen in time", they extend in time by accumulating different "temporal parts", so that, at any time *t* at which they exist, only their temporal parts

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[*] https://protege.stanford.edu/
[†] www.industrialontologies.org/welcome-to-the-iof/
[‡] www.obofoundry.org/ontology/ro.html
[§] www.obofoundry.org/ontology/iao.html
[**] www.cubrc.org/index.php/data-science-and-information-fusion/ontology

at *t* are present. For example, the book you are holding now can be considered an endurant because (now) it is wholly present, while “your reading of this book” is a perdurant because, your “reading” of the previous section is not present now.

The taxonomy of concepts in DOLCE is illustrated in Fig. 8. (Masolo et al. 2003, p. 14).

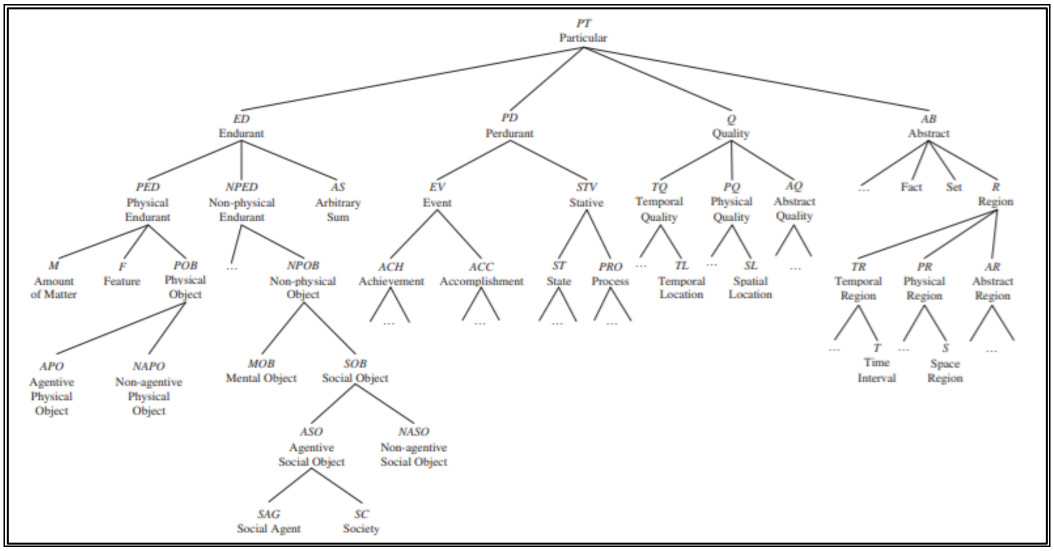


Fig. 8 Categories in the DOLCE ontology

3. DEVCOM ARL Direct Metal Laser Sintering Case Study

This case study describes an experiment conducted in DEVCOM ARL’s AM laboratory (Aberdeen Proving Ground, Maryland); the 3D printing process is known as direct metal laser sintering (DMLS) (Khaing Fuh 2000), also known as powder bed fusion. The diagram shown in Fig. 9 illustrates the computer-aided design file processed to produce the input to the 3D printer, machines used to measure and characterize the metal powder feedstock, and the analysis of part properties. In this case, an impeller is the part to be produced.

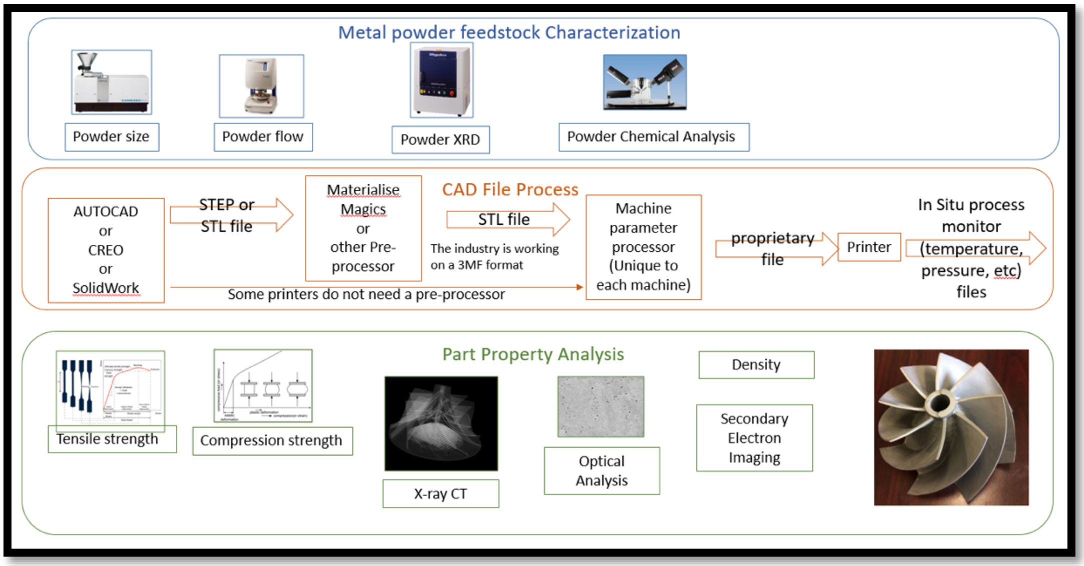
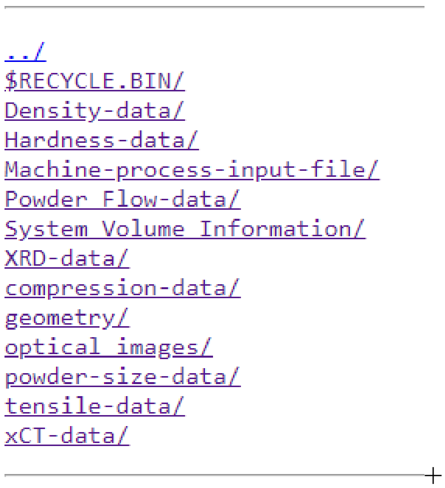


Fig. 9 Direct metal laser sintering flow chart

Figure 10 shows directories containing data from this DMLS experiment.



```
../
$RECYCLE.BIN/
Density-data/
Hardness-data/
Machine-process-input-file/
Powder Flow-data/
System Volume Information/
XRD-data/
compression-data/
geometry/
optical images/
powder-size-data/
tensile-data/
xCT-data/
```

Fig. 10 Directories of the DMLS case study data

Solid modelling software such as AUTOCAD (AutoDesk 2021), SolidWorks (SolidWorks 2010), or CREO (PTC 2020) is used to create digital 3D model designs. In this case, the output of the software is a stereolithography (STL) file (Burns 1993). The geometry directory shown in Fig. 10 contains a file defining the 3D object. In Fig. 11, an STL viewer is used to display the object defined in the file.

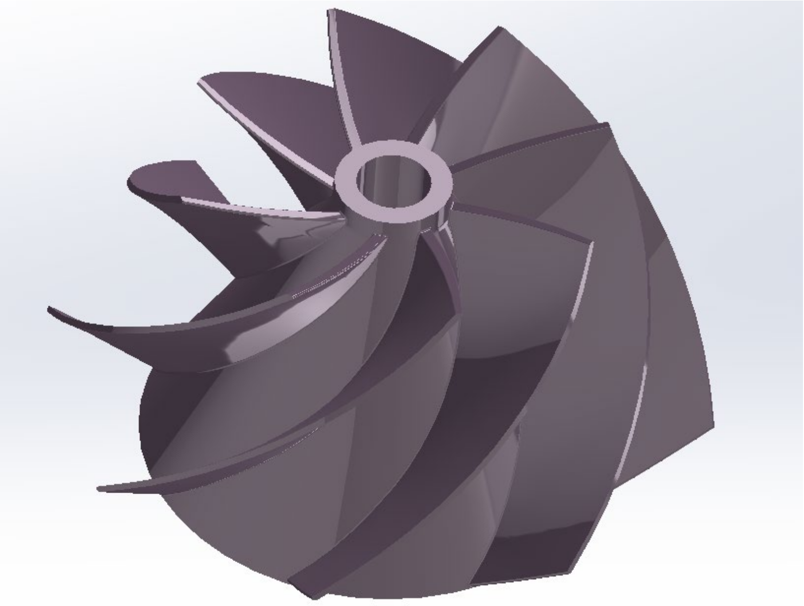


Fig. 11 Image of the impeller

The STEP file referred to in Fig. 9 is another file format for 3D models, and the letters in the name stand for “Standard for the Exchange of Product Data” (ISO/ASTM 2021).

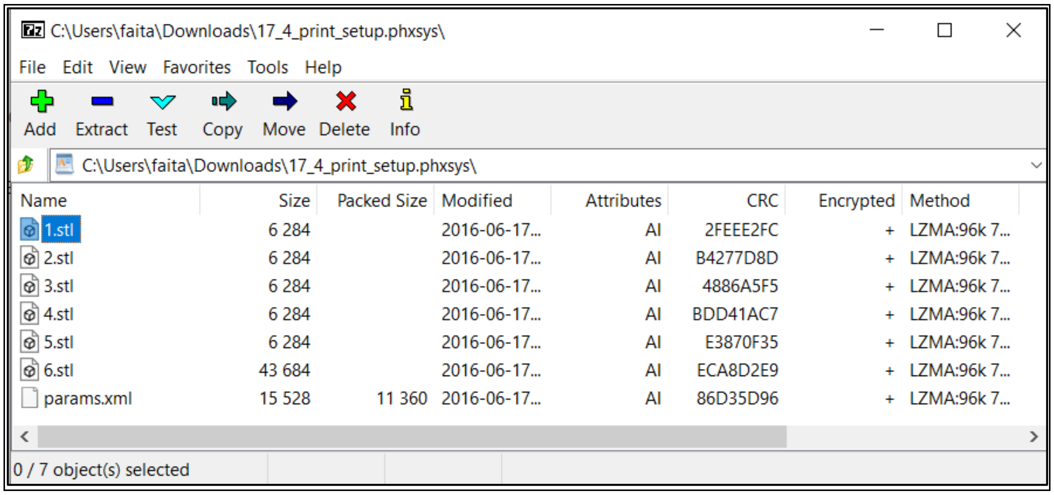
Some 3D printers need software such as Materialise Magic to preprocess the STL file to produce a printer-specific file (Materialise 2017). The geometry directory also includes a setup.magic file whose content is displayed with a viewer as shown in Fig. 12 (FileXT 2021).

```
 preview_128x128
 vertices_ox000002249C2686E0E
 surfaces_0x000002249C2686E0M
 00007FFD3E55F64000000224A3F70730
 vertices_ox000002249C269BE0E
 surfaces_0x000002249C269BE0M
 00007FFD3E55F64000000224A3F157D0
 vertices_ox000002249C4152F0E
 surfaces_0x000002249C4152F0M
 00007FFD3E55F64000000224A3F181D0
 vertices_ox00000224A3F149D0E
 surfaces_0x00000224A3F149D0M
 00007FFD3E55F64000000224A3F16250í× ytNg
 vertices_ox00000224A3F15450E
 surfaces_0x00000224A3F15450M
 00007FFD3E55F64000000224A3F17050
 vertices_ox00000224A3F15B50E
 surfaces_0x00000224A3F15B50M
 00007FFD3E55F640000002249C268A60¥  KHTq
 vertices_ox00000224A3F17750E
 surfaces_0x00000224A3F17750M
 00007FFD3E55F640000002249C413A70
 vertices_ox00000224A3F703B0EÓ OHTQ
 surfaces_0x00000224A3F703B0M
 00007FFD3E55F64000000224A3F6DD30
 blob_0000cd``(
 header.xml
 vfNy 34*uUj
 preview_128x128MT vertices_ox000002249C2686E0MT
surfaces_0x000002249C2686E0MT 00007FFD3E55F64000000224A3F70730MT
vertices_ox000002249C269BE0MT surfaces_0x000002249C269BE0MT
00007FFD3E55F64000000224A3F157D0MT vertices_ox000002249C4152F0MT
surfaces_0x000002249C4152F0MT 00007FFD3E55F64000000224A3F181D0MT
vertices_ox00000224A3F149D0MT surfaces_0x00000224A3F149D0MT
00007FFD3E55F64000000224A3F16250MT vertices_ox00000224A3F15450MT
surfaces_0x00000224A3F15450MT 00007FFD3E55F64000000224A3F17050MT
vertices_ox00000224A3F15B50MT surfaces_0x00000224A3F15B50MT
00007FFD3E55F640000002249C268A60MT vertices_ox00000224A3F17750MT
surfaces_0x00000224A3F17750MT 00007FFD3E55F640000002249C413A70MT
vertices_ox00000224A3F703B0MT surfaces_0x00000224A3F703B0MT
00007FFD3E55F64000000224A3F6DD30MT
 blob_0000MT
 header.xmlMT
```

Fig. 12 Contents of geometry/setup.magics file

The industry is developing a standard 3MF for input to 3D printers (3MF Consortium 2018). 3MF is an XML-based format designed specifically for AM. It includes information that cannot be represented in the STL format.

Each 3D printer has a machine parameter processor that produces a proprietary file unique to that printer; the processor contains parameters such as temperature and scan speed. In this case, STL files are stored in the file Machine-Process-input-file/slices/17-4 print_setup.phxsys. The contents of this file are shown in Fig. 13.

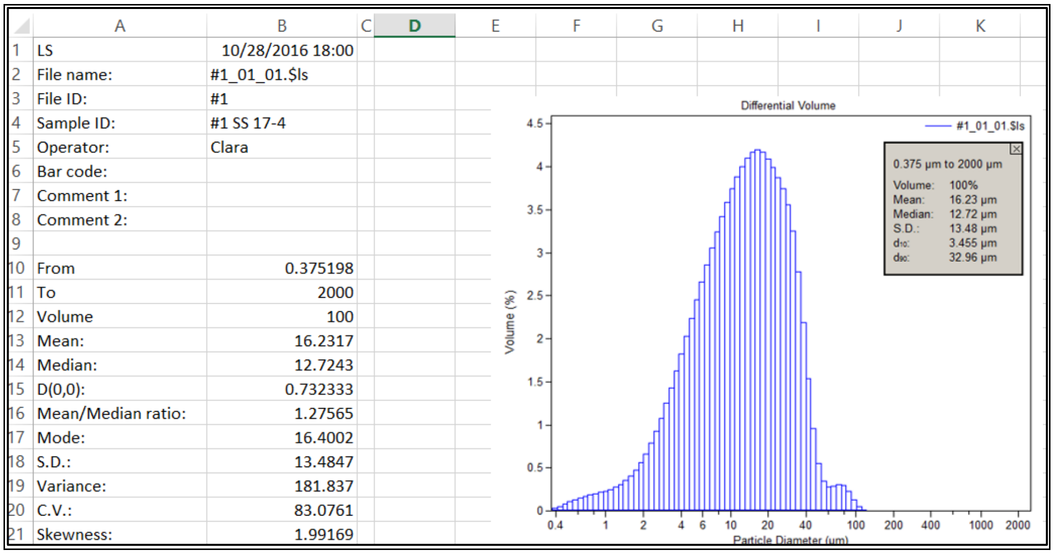


Name	Size	Packed Size	Modified	Attributes	CRC	Encrypted	Method
1.stl	6 284		2016-06-17...	AI	2FEEE2FC	+	LZMA:96k 7...
2.stl	6 284		2016-06-17...	AI	B4277D8D	+	LZMA:96k 7...
3.stl	6 284		2016-06-17...	AI	4886A5F5	+	LZMA:96k 7...
4.stl	6 284		2016-06-17...	AI	BDD41AC7	+	LZMA:96k 7...
5.stl	6 284		2016-06-17...	AI	E3870F35	+	LZMA:96k 7...
6.stl	43 684		2016-06-17...	AI	ECA8D2E9	+	LZMA:96k 7...
params.xml	15 528	11 360	2016-06-17...	AI	86D35D96	+	LZMA:96k 7...

Fig. 13 Contents of file 17_4_print_setup.phxsys

The 3D printer is printing 2D slices to fill the 3D model volume. The STL files shown in Fig. 13 contain instructions on how to print each slice. The printer is a DMLS 3D printer. This printer uses lasers to fuse powdered metal to fabricate parts. The powder used in this case is stainless steel.

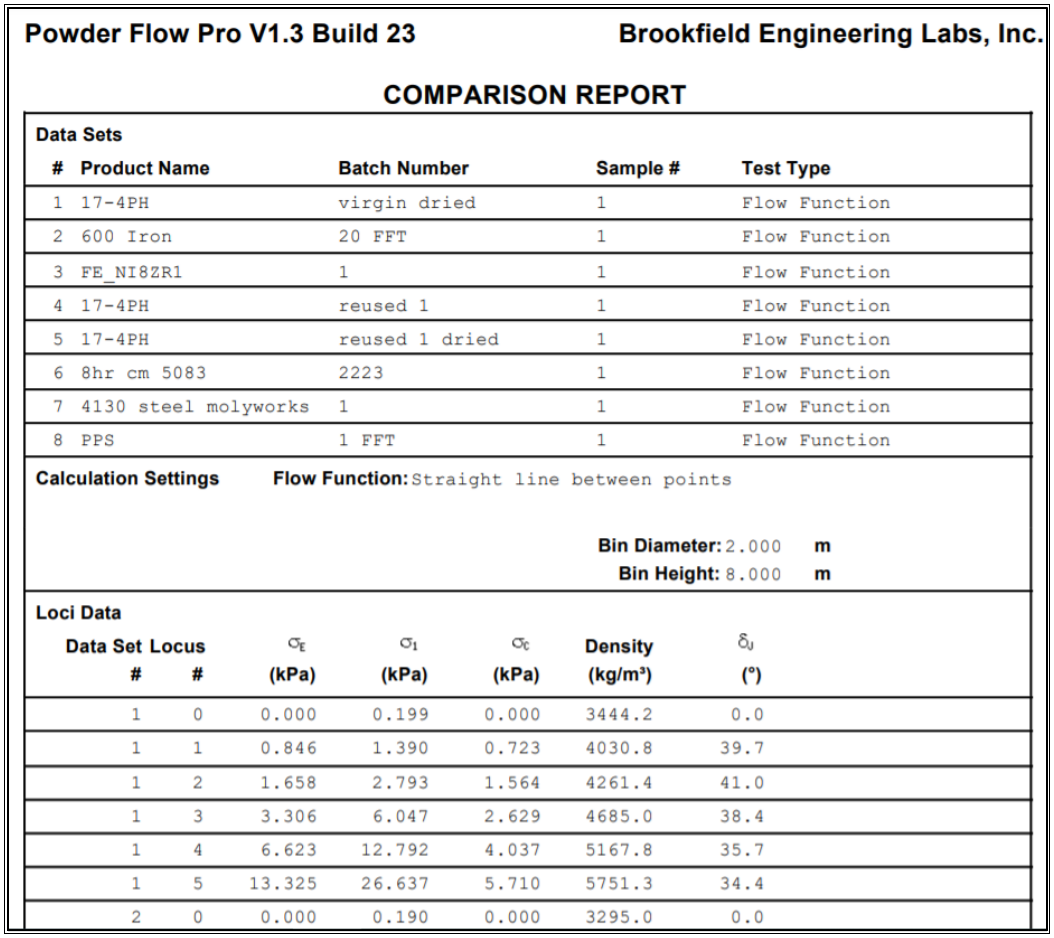
There are machines that measure and characterize the inputs to the process. For example, a particle sizer measures particle size and outputs a powder particle size file, in this case the file powder-size-data/SS 17-4 powder Brandon.xlsx shown in Fig. 14.



	A	B
1	LS	10/28/2016 18:00
2	File name:	#1_01_01.$ls
3	File ID:	#1
4	Sample ID:	#1 SS 17-4
5	Operator:	Clara
6	Bar code:	
7	Comment 1:	
8	Comment 2:	
9		
10	From	0.375198
11	To	2000
12	Volume	100
13	Mean:	16.2317
14	Median:	12.7243
15	D(0,0):	0.732333
16	Mean/Median ratio:	1.27565
17	Mode:	16.4002
18	S.D.:	13.4847
19	Variance:	181.837
20	C.V.:	83.0761
21	Skewness:	1.99169

Fig. 14 SS 17-4 powder Brandon.xlsx file

There is also a machine that measures powder flow. This measurement aids in determining the adequacy of the spread of the material. Figure 15 shows a report produced by such a machine.



Powder Flow Pro V1.3 Build 23 **Brookfield Engineering Labs, Inc.**

COMPARISON REPORT

Data Sets

#	Product Name	Batch Number	Sample #	Test Type
1	17-4PH	virgin dried	1	Flow Function
2	600 Iron	20 FFT	1	Flow Function
3	FE_NI8ZR1	1	1	Flow Function
4	17-4PH	reused 1	1	Flow Function
5	17-4PH	reused 1 dried	1	Flow Function
6	8hr cm 5083	2223	1	Flow Function
7	4130 steel molyworks	1	1	Flow Function
8	PPS	1 FFT	1	Flow Function

Calculation Settings **Flow Function:** Straight line between points

Bin Diameter: 2.000 **m**
Bin Height: 8.000 **m**

Loci Data

Data Set #	Locus #	σ_E (kPa)	σ_1 (kPa)	σ_C (kPa)	Density (kg/m³)	δ_J (°)
1	0	0.000	0.199	0.000	3444.2	0.0
1	1	0.846	1.390	0.723	4030.8	39.7
1	2	1.658	2.793	1.564	4261.4	41.0
1	3	3.306	6.047	2.629	4685.0	38.4
1	4	6.623	12.792	4.037	5167.8	35.7
1	5	13.325	26.637	5.710	5751.3	34.4
2	0	0.000	0.190	0.000	3295.0	0.0

Fig. 15 Powder flow-data/comparison report.pdf

X-ray powder diffraction (XRD) is a routine analysis for powder characterization. “XRD analysis, by way of the study of the crystal structure, is used to identify the crystalline phases present in a material and thereby reveal chemical composition information. . . . X-ray diffraction is useful for evaluating minerals, polymers, corrosion products, and unknown materials” (Element Materials Technology 2021).

Dutrow and Clark explain, “The analyzed material is finely ground, homogenized, and average bulk composition is determined. . . . XRD peaks are produced by constructive interference of a monochromatic beam of X-rays scattered at specific angles from each set of lattice planes in a sample” (2020). Figure 16 shows the plot for XRD data for the 17-4 steel powder.

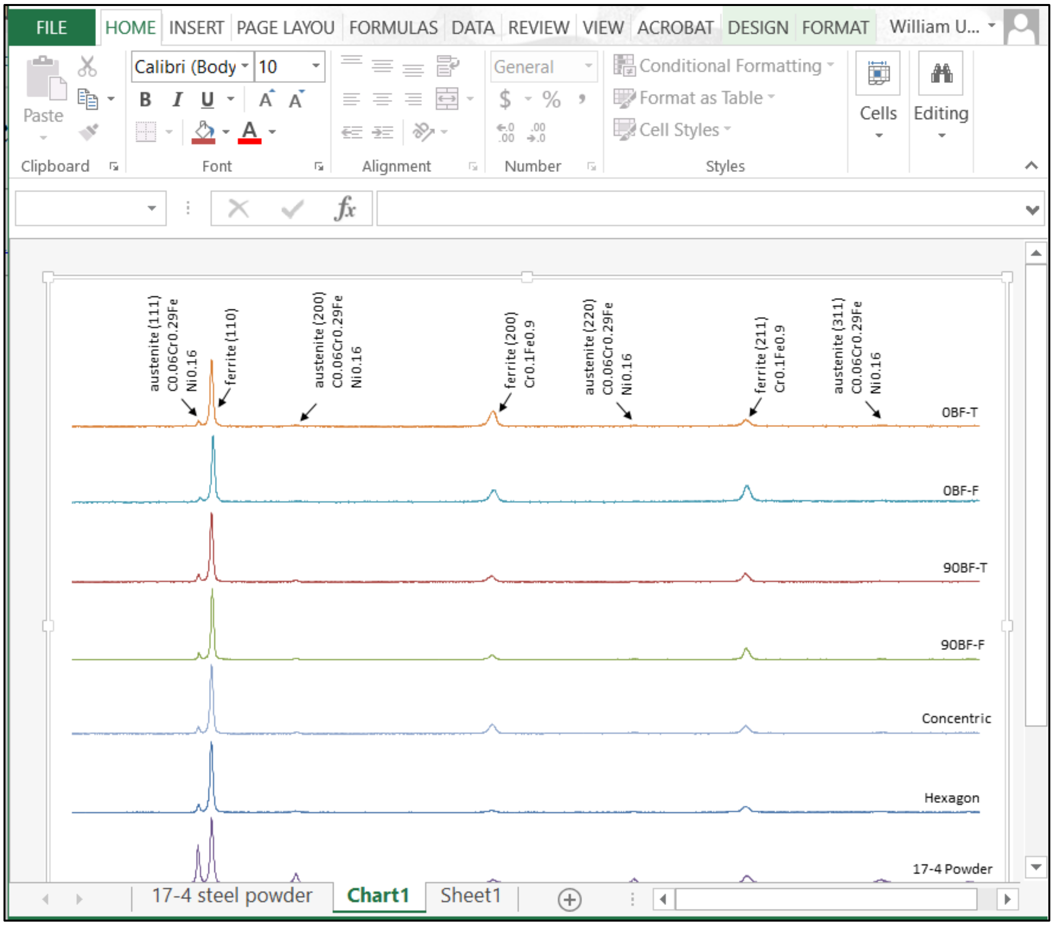
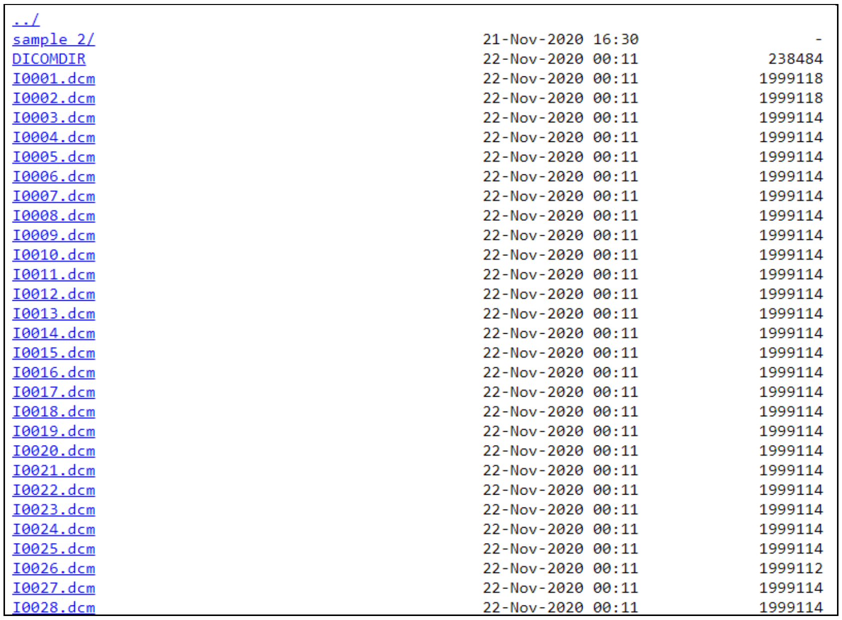


Fig. 16 XRD-data/17-4 steel powder.xlsx plot

The diagram in Fig. 9 indicates that a chemical analysis of the powder can be performed to determine if it meets the specification for 17-4 stainless steel powder. 17-4 powder is a type of stainless steel and its specification indicates its chemical composition as percentages of iron, carbon, nickel, and so on. We do not have data for the chemical analysis of the powder.

The next steps are to look at the properties of the object manufactured. One of these analyses is X-ray computed tomography (CT). This is a nondestructive technique for visualizing interior features within solid objects and for obtaining digital information on their 3D geometries and properties. A CT image corresponds to what the object being scanned would look like if it were sliced open along a plane. The gray levels in a CT slice image correspond to X-ray attenuation, which reflects the proportion of X-rays scattered or absorbed as they pass through the slice (Ketcham 2017). Filenames containing xCT slices are shown in Fig. 17.



```
../
sample 2/                                            21-Nov-2020 16:30                   -
DICOMDIR                                             22-Nov-2020 00:11              238484
I0001.dcm                                            22-Nov-2020 00:11             1999118
I0002.dcm                                            22-Nov-2020 00:11             1999118
I0003.dcm                                            22-Nov-2020 00:11             1999114
I0004.dcm                                            22-Nov-2020 00:11             1999114
I0005.dcm                                            22-Nov-2020 00:11             1999114
I0006.dcm                                            22-Nov-2020 00:11             1999114
I0007.dcm                                            22-Nov-2020 00:11             1999114
I0008.dcm                                            22-Nov-2020 00:11             1999114
I0009.dcm                                            22-Nov-2020 00:11             1999114
I0010.dcm                                            22-Nov-2020 00:11             1999114
I0011.dcm                                            22-Nov-2020 00:11             1999114
I0012.dcm                                            22-Nov-2020 00:11             1999114
I0013.dcm                                            22-Nov-2020 00:11             1999114
I0014.dcm                                            22-Nov-2020 00:11             1999114
I0015.dcm                                            22-Nov-2020 00:11             1999114
I0016.dcm                                            22-Nov-2020 00:11             1999114
I0017.dcm                                            22-Nov-2020 00:11             1999114
I0018.dcm                                            22-Nov-2020 00:11             1999114
I0019.dcm                                            22-Nov-2020 00:11             1999114
I0020.dcm                                            22-Nov-2020 00:11             1999114
I0021.dcm                                            22-Nov-2020 00:11             1999114
I0022.dcm                                            22-Nov-2020 00:11             1999114
I0023.dcm                                            22-Nov-2020 00:11             1999114
I0024.dcm                                            22-Nov-2020 00:11             1999114
I0025.dcm                                            22-Nov-2020 00:11             1999114
I0026.dcm                                            22-Nov-2020 00:11             1999112
I0027.dcm                                            22-Nov-2020 00:11             1999114
I0028.dcm                                            22-Nov-2020 00:11             1999114
```

Fig. 17 File list of the folder for xCT-data/17-4 density/sample2/

The CT slices are stored in the dicom file format (NEMA 2021). Figure 18 shows the CT image of one of these slices.

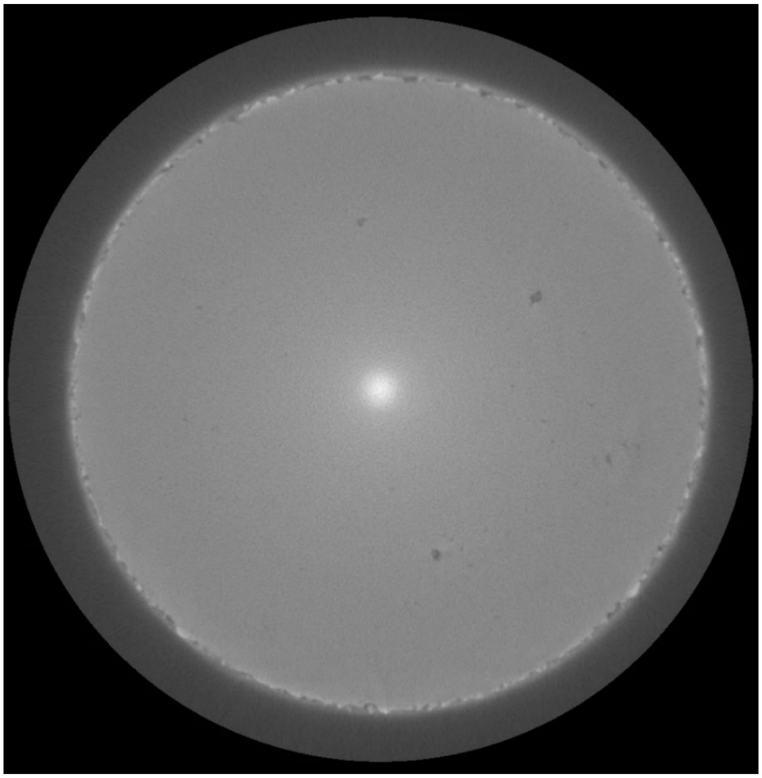


Fig. 18 XCT scan of the DMLS specimen file name: I0001.dcm

A microscopic optical analysis of the part can be performed. The directory of optical images collected for this part is shown in Fig. 19. The images can be collected in .tiff or .jpg format files.

```
../
ARL 1 10 X 2 bottom of L.jpg
ARL 1 10 X 2 random area.jpg
ARL 1 10 X 2.jpg
ARL 1 10 X a top.jpg
ARL 1 10 X.jpg
ARL 1 20 X random area.jpg
ARL 5 10 X A.jpg
ARL 5 10 X l.jpg
ARL 5 10 X random.jpg
ARL 5 20 X arl.jpg
ARL 5 20 X random.jpg
ARL 6 10 X a.jpg
ARL 6 10 X r.jpg
ARL 6 20 X l.jpg
ARL 6 20 X not l.jpg
ARL 7 10 X 2.jpg
ARL 7 10 X 3.jpg
ARL 7 10 X 4.jpg
ARL 7 10 X.jpg
ARL 7 100x 2.jpg
ARL 7 100x 3.jpg
ARL 7 100x.jpg
ARL 7 150x b.jpg
ARL 7 150x.jpg
ARL 7 150xa.jpg
ARL 7 2.5 X L.jpg
ARL 7 2.5 X.jpg
ARL 7 50X 2.jpg
ARL 7 50X 3.jpg
ARL 7 50X.jpg
```

Fig. 19 Files in optical images directory

An example of an optical image of the manufactured part is shown in Fig. 20.

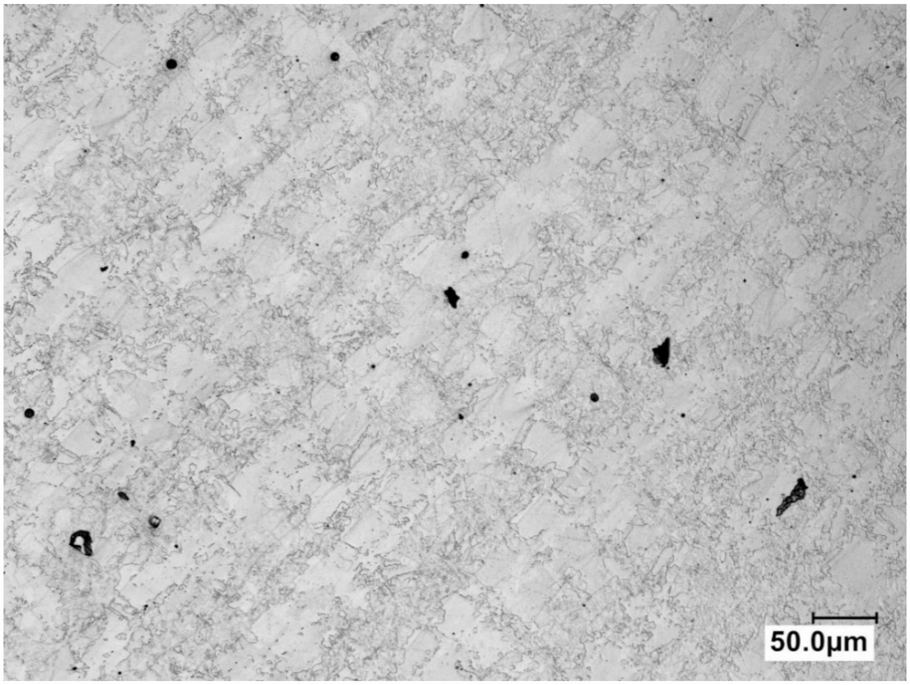


Fig. 20 Micrograph of the DMLS surface specimen file name: ARL 5 20 Rx Random.jpg

In addition to the primary part being manufactured, a specimen part is printed that is used in destructive testing to determine tensile strength (Fig. 21) and compression strength (Fig. 22).

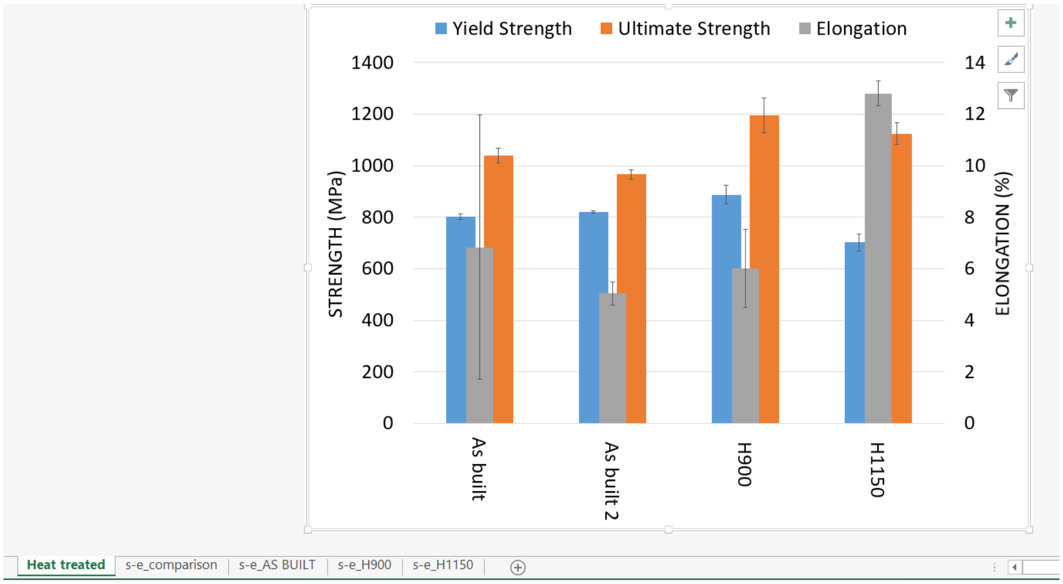
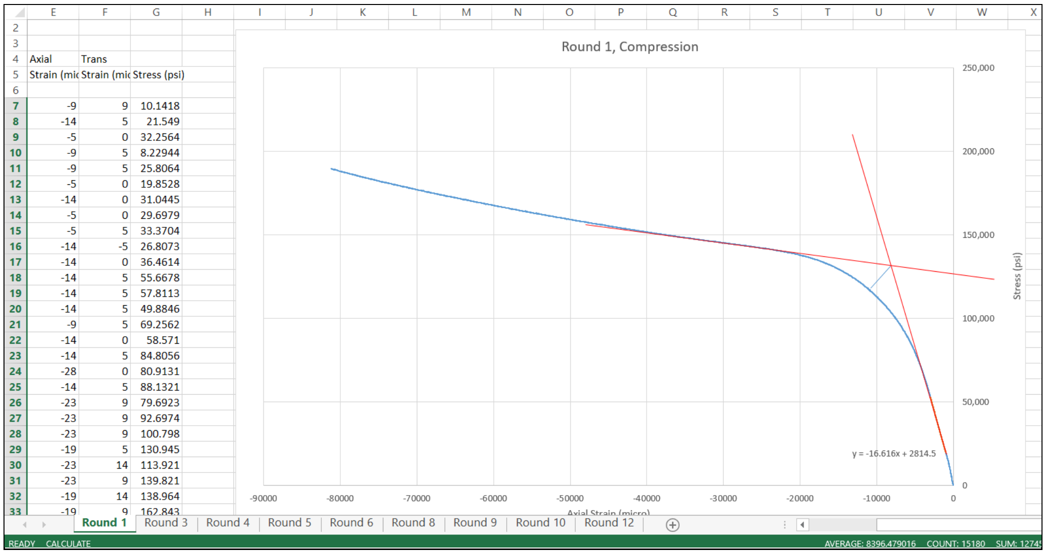


Fig. 21 Tensile-data/SS17-4_summary_properties.xlsx



	E	F	G	H
2				
3				
4	Axial	Trans		
5	Strain (mic	Strain (mic	Stress (psi)	
6				
7	-9	9	10.1418	
8	-14	5	21.549	
9	-5	0	32.2564	
10	-9	5	8.22944	
11	-9	5	25.8064	
12	-5	0	19.8528	
13	-14	0	31.0445	
14	-5	0	29.6979	
15	-5	5	33.3704	
16	-14	-5	26.8073	
17	-14	0	36.4614	
18	-14	5	55.6678	
19	-14	5	57.8113	
20	-14	5	49.8846	
21	-9	5	69.2562	
22	-14	0	58.571	
23	-14	5	84.8056	
24	-28	0	80.9131	
25	-14	5	88.1321	
26	-23	9	79.6923	
27	-23	9	92.6974	
28	-23	9	100.798	
29	-19	5	130.945	
30	-23	14	113.921	
31	-23	9	139.821	
32	-19	14	138.964	
33	-19	9	162.843	

Fig. 22 Compression-data/ARL ROUND DATA.xlsx

Density and hardness tests are conducted to determine whether the part is within specification. Results of these tests are illustrated in Figs. 23 and 24.

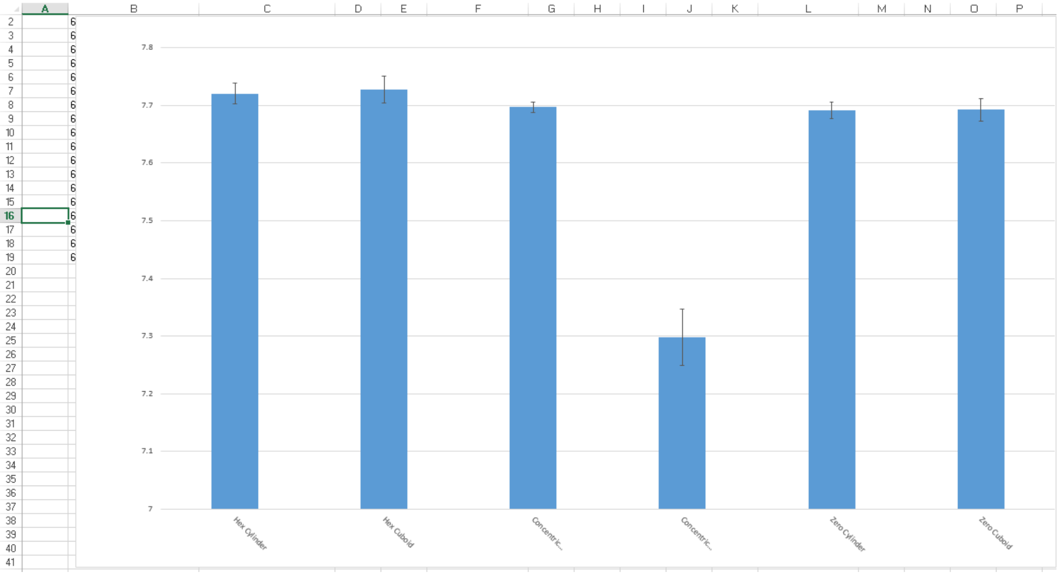
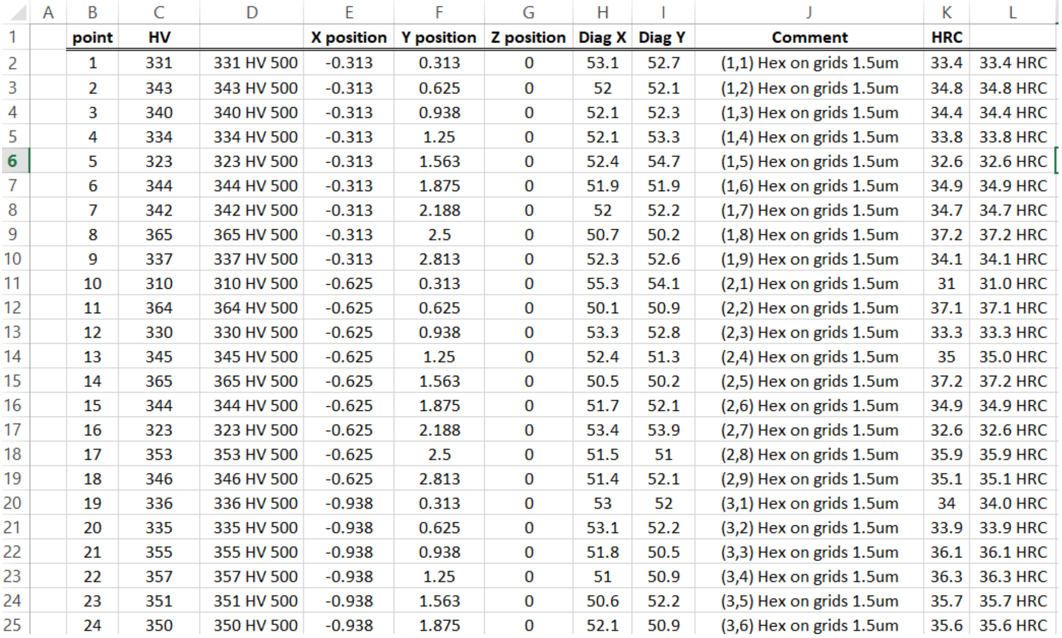


Fig. 23 Density-data/compression 17-4 samples archemedies.xlsx



	A	B	C	D	E	F	G	H	I	J	K	L
1		point	HV		X position	Y position	Z position	Diag X	Diag Y	Comment	HRC	
2		1	331	331 HV 500	-0.313	0.313	0	53.1	52.7	(1,1) Hex on grids 1.5um	33.4	33.4 HRC
3		2	343	343 HV 500	-0.313	0.625	0	52	52.1	(1,2) Hex on grids 1.5um	34.8	34.8 HRC
4		3	340	340 HV 500	-0.313	0.938	0	52.1	52.3	(1,3) Hex on grids 1.5um	34.4	34.4 HRC
5		4	334	334 HV 500	-0.313	1.25	0	52.1	53.3	(1,4) Hex on grids 1.5um	33.8	33.8 HRC
6		5	323	323 HV 500	-0.313	1.563	0	52.4	54.7	(1,5) Hex on grids 1.5um	32.6	32.6 HRC
7		6	344	344 HV 500	-0.313	1.875	0	51.9	51.9	(1,6) Hex on grids 1.5um	34.9	34.9 HRC
8		7	342	342 HV 500	-0.313	2.188	0	52	52.2	(1,7) Hex on grids 1.5um	34.7	34.7 HRC
9		8	365	365 HV 500	-0.313	2.5	0	50.7	50.2	(1,8) Hex on grids 1.5um	37.2	37.2 HRC
10		9	337	337 HV 500	-0.313	2.813	0	52.3	52.6	(1,9) Hex on grids 1.5um	34.1	34.1 HRC
11		10	310	310 HV 500	-0.625	0.313	0	55.3	54.1	(2,1) Hex on grids 1.5um	31	31.0 HRC
12		11	364	364 HV 500	-0.625	0.625	0	50.1	50.9	(2,2) Hex on grids 1.5um	37.1	37.1 HRC
13		12	330	330 HV 500	-0.625	0.938	0	53.3	52.8	(2,3) Hex on grids 1.5um	33.3	33.3 HRC
14		13	345	345 HV 500	-0.625	1.25	0	52.4	51.3	(2,4) Hex on grids 1.5um	35	35.0 HRC
15		14	365	365 HV 500	-0.625	1.563	0	50.5	50.2	(2,5) Hex on grids 1.5um	37.2	37.2 HRC
16		15	344	344 HV 500	-0.625	1.875	0	51.7	52.1	(2,6) Hex on grids 1.5um	34.9	34.9 HRC
17		16	323	323 HV 500	-0.625	2.188	0	53.4	53.9	(2,7) Hex on grids 1.5um	32.6	32.6 HRC
18		17	353	353 HV 500	-0.625	2.5	0	51.5	51	(2,8) Hex on grids 1.5um	35.9	35.9 HRC
19		18	346	346 HV 500	-0.625	2.813	0	51.4	52.1	(2,9) Hex on grids 1.5um	35.1	35.1 HRC
20		19	336	336 HV 500	-0.938	0.313	0	53	52	(3,1) Hex on grids 1.5um	34	34.0 HRC
21		20	335	335 HV 500	-0.938	0.625	0	53.1	52.2	(3,2) Hex on grids 1.5um	33.9	33.9 HRC
22		21	355	355 HV 500	-0.938	0.938	0	51.8	50.5	(3,3) Hex on grids 1.5um	36.1	36.1 HRC
23		22	357	357 HV 500	-0.938	1.25	0	51	50.9	(3,4) Hex on grids 1.5um	36.3	36.3 HRC
24		23	351	351 HV 500	-0.938	1.563	0	50.6	52.2	(3,5) Hex on grids 1.5um	35.7	35.7 HRC
25		24	350	350 HV 500	-0.938	1.875	0	52.1	50.9	(3,6) Hex on grids 1.5um	35.6	35.6 HRC

Fig. 24 Hardness-data/DMLS Tensile bar hardness Mapping.xlsx

A digital photo of the additively manufactured part is shown in Fig. 25.

Fig. 25 Image of additively manufactured part

4. CDD Data Elements and Values from the DMLS Case Study

While this case study was not conducted to collect CDD metadata, it will be used to illustrate some of the issues. CDD data elements were identified by searching the text of the CDD for terms from the case study filenames and terms in the content of the files. For example, in the Material Module, *17-4 Stainless Steel Powder* is a value for the data element *Material Name*. In the AM System Module, *Direct Metal Laser Sintering* is a value for the data element *AM System Process Type*. The CDD does not include specific data elements for the details of AM technologies such as DMLS. Some CDD data element values are available for the Test/Inspection/Characterization Module (Table 1).

Table 1 Case study data elements for TIC module

CDD ID	MAIN/sub bucket	Data element	File name/data value
TIC 8-1	Tensile Test Results		Tensile data/SS17-4_summary_properties.xslx
TIC 8-1-1		Ultimate Tensile Strength	See Fig. 21 Ultimate Strength Tab
TIC 8-1-2		Tensile 0.2% Yield Strength	See Fig. 21 Yield Strength Tab
TIC 8-1-3		Tensile 0.02% Yield Strength	See Fig. 21 Yield Strength Tab
TIC 8-1-5		Tensile Yield Point Elongation	See Fig. 21 Elongation
TIC 8-7	Hardness Test Results	Hardness Value	Hardness-data/ DMLS Tensile Bar hardness mapping.xlsx See Fig. 24 column HV
TIC 8-9	Density Characterization Results		Density Data/ compression 17-4 samples Archimedes. xlsx
TIC 8-9-1		Density	See Fig. 23
TIC 8-10	Particle Size Distribution Results		Particle size data/SS 17-4 Powder Brandon.xslx
TIC 8-10		Particle Size distribution	See Fig. 14 Plot
TIC 8-10		Particle Size distribution mean	See Fig. 14 Mean
TIC 8-10		Particle Size distribution median	See Fig. 14 Median
TIC 8-10		Particle Size distribution mode	See Fig. 14 Mode
TIC 8-10		Particle Size distribution Standard Deviation	See Fig. 14 S.D.
TIC 8-10		Particle Size distribution Skewness	See Fig. 14 Skewness

Additional data elements and values were identified by analyzing the contents of files. The authors of this report plan to improve on this process by developing a user interface to an AM data records management application that captures essential information about an AM project. This task will be described in the next section of this report. This application will be used in validating the CDM with data from AM projects. However, the intended purpose is that it be used in managing the data of AM projects.

5. Additive Manufacturing Data Management Research Plan

5.1 Actively Participate in the AM DM WG

As described earlier, the AM DM WG is a major player in the development of AM data standards and data management research and development in the United States. Its members are from NIST, other government agencies, manufacturing companies, professional organizations, and academic institutions. The research activities described in this section will contribute to achieving the working group's objectives. These planned activities will also contribute to the AM data management needs of DEVCOM ARL and the University of Maryland (UMD) AM research team.

5.2 Prototype an AM Research Data Records Application

At the time an AM research project or manufacturing project is initiated, there should be an application for defining, capturing, organizing, and maintaining the data that will be created during the project. This task is to prototype an application with a user interface for capturing the data about an AM research or production project. The initial prototype will be based on the types of information that are being developed in the AM CDM. The interface will be refined by use in entering data from DEVCOM ARL and UMD projects and possibly other AM research and production projects.

ISO/ASTM 52900 defines seven process classifications for AM: Binder Jetting, Directed Energy Deposition, Material Extrusion, Material Jetting, Powder Bed Fusion, Sheet Lamination, and Vat Photopolymerization (2021).

Per the SME Additive Manufacturing Glossary (SME.org 2021):

> [Powder bed fusion involves] the selective fusing of materials in a granular bed. The technique fuses parts of the layer, and then moves the working area downwards, adding another layer of granules and repeating the process until the piece has built up. A laser is typically used to sinter the media into a solid. Examples include selective laser sintering (SLS), with both metals and polymers, and DMLS. Selective Laser Melting (SLM) does not use sintering for the fusion of powder granules but will completely melt the powder using a high-energy laser to create fully dense materials in a layerwise method. Electron beam melting (EBM) manufactures parts by melting metal powder layer by layer with an electron beam in a high vacuum.

The case study described in Section 3 of this report involves DMLS. The user interface will capture data for that process as well as for other powder fusion processes.

The purpose of this prototype is to support the creation of the CDM. It is a research tool that will reduce the number of metadata values research and manufacturing staff must enter for an AM project. It will be refined to automatically import data values from data files or the machine interface if that capability becomes available. The evolving prototype facilitates the development of the automated capture of metadata. The prototype will not be a single centralized data management application, but a data management application for each project.

5.3 Collect DEVCOM ARL and UMD AM Product and Research Data

AM is an evolving process that is highly subject to R&D. DoD, the National Science Foundation, and the National Institutes of Health have started to require data management plans for their sponsored research. Because the data is not stored and maintained in consistent formats and is not easily accessible, the data is seldom reused. In addition to capturing AM data for parts, we plan to collect data from AM research projects.

On 11–12 August 2021, a number of university researchers presented their research in AM, material science, and data management to DEVCOM ARL. The UMD research topics are shown in Fig 26.


UNIVERSITY OF MARYLAND

Task	Title	PI's
1	Program Management	JC Zhao
7	Next-Generation Fuze Systems via Inertial Microfluidic Logic	Ryan Sochol
8	Quantification of the Thermo-soluto-fluidics in Aerosol Jet and Syringe Printing: Process-Structure Analysis for Printed Hybrid Electronics Applications	Siddhartha Das, Abhijit Dasgupta
9	Qualification of 3D Printed Hybrid Electronics (PHEs) with Soldered MEMS Components in Extremely High Accelerations	Abhijit Dasgupta, Siddhartha Das
10	Next Generation Thermal Management Utilizing Multi-Scale Design and Shape Topology Optimization, Additive Manufacturing, and Machine Learning	Michael Ohadi, JC Zhao
11	Light, Conformal, and Ultra Efficient Cooling of High-Energy Pulsed Power and Electronics Systems Utilizing Design Topologies, Embedded Cooling, and Additive Manufacturing	Michael Ohadi, Patrick McCluskey, Ichiro Takeuchi
12	Desktop Fatigue and X-ray Characterization Techniques to Support the Design and Qualification of Metal Parts for Hybrid AM Processes	Hugh Bruck, Mark Fuge, Huapeng Huang
13	ARL AM Digital Curation and Data Management	Richard Marciano, William Underwood

Fig. 26 UMD presentations to the DEVCOM ARL AM Alliance Review

We plan to collect data from such research projects as listed in Fig. 26. It is believed that the metadata attributes for these projects will be the same as for AM of parts. Additional metadata, such as paper titles and citations, will be included as well.

5.4 Develop a Tool to Support Construction of an AM Data Package for Submission to AM Data Repository

Information developed during AM research projects may be relevant to the development of new products, reduce research redundancy, and inform researchers addressing similar research issues. An information package will be designed to capture data from AM research projects for submission to an AM data repository. The package will likely also be the container for the data stored in the repository and the data distributed from the repository.

Java Archive (JAR) files will be explored as an AM dataset packaging option. JAR files are zip-compressed files that include a Java-specific manifest file. Jar files can also include XML files. Upon creation or modification by approved authorities, JAR files can be digitally signed. The JAR itself is not signed, but instead every file inside the archive is listed along with a secure hash algorithm value for each file. It is these secure hash algorithm values in the manifest that are signed. When the Java runtime loads signed JAR files, it can validate the secure hash algorithm values. Thus, modifications to files can be detected. Also, unauthorized additions and deletions of files from the JAR can be detected.

The applicability of the Open Document Format (ODF) for packaging xml data will also be investigated. ODF is an open standard file format for spreadsheets, charts, presentations, and word processing documents using zip-compressed XML files. The standard was developed by a technical committee in the Organization for the Advancement of Structured Information Standards (OASIS) consortium. In addition to being an OASIS standard, it was published as an ISO/IEC international standard ISO/IEC 26300 – Open Document Format for Office Applications (OpenDocument).[*][†][‡]

AM research projects generate large volumes of data in Excel, PDF, and proprietary file formats. Proprietary 3D design formats, with some limitations,[§] can be converted to neutral file formats such as STEP, STL, OBJ, AMF, and 3MF.

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[*] https://www.iso.org/standard/66363.html

[†] https://www.iso.org/standard/66375.html

[‡] https://www.iso.org/standard/66376.html

[§] See the MBx Implementor Forum https://www.cax-if.org/index.php

Microsoft Excel can import XML data and map XML elements from an XML schema to worksheet cells, and export worksheet cells to XML data.

The applicability of Adobe XML data packages will also be investigated. An XML data package is an XML file format that allows PDF content and/or Adobe XML Forms Architecture resources to be packaged within an XML container.

5.5 Prototype an AM Research Data Repository

The authors of this report plan to extend previous research by developing an AM research data repository prototype based on the DRAS-TIC Fedora architecture that supports linked data repositories and petabyte-scale collections (Jansen and Marciano 2019). Fedora does not include search indexing for discovery and delivery of records in the repository. Apache Solr can facilitate faceted search services for the content of a Fedora digital repository (O'Steen 2008). Additionally, Blacklight is an open source user interface web application with Solr support.* Solr and Blacklight can be used to develop a user interface for searching and using the indexed metadata.

5.6 Create a Common Research Data Web Portal across AM Research Data Repositories

Many different companies produce additively manufactured parts for DoD services. Rather than migrating the data sets for producing these parts to a single system, there is the option to leave those data sets with the original manufacturers in separate AM research data repositories while pooling their descriptive metadata in a single Blacklight and Solr web portal. The same holds for data sets of AM research projects with different material or processes or product types. A research data web portal would support searching for data sets across manufacturers and research groups using uniform metadata fields. It would provide standard network protocols for data requests, authentication, and authorization, and employ neutral data exchange formats.

Initially, we will focus on AM research data repositories of AM research projects rather than data sets for additively manufactured products.

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*Blacklight: A multi-institutional open-source collaboration building a better discovery platform framework. https://projectblacklight.org/

6. Summary of Results

This year, we began participating in the AM DM WG led by Yan Lu of NIST. The working group is completing an AM CDD to be published as an ASTM International standard. Recently, they began work on a CDM and an ontology for AM. Such a model provides common metadata for sharing data about AM processes and tests. An AM ontology can provide a common representation for sharing knowledge and for automated reasoning about AM process and test data.

In 2021, the research literature was reviewed to identify issues in managing AM metadata. A research plan was formulated for addressing some of these issues. A CDM is needed to facilitate sharing and reuse of AM data. We are collecting both AM product data and research data, and using the CDD to assist the AM DM WG in creating a CDM for AM.

In future years we will prototype an AM repository for data sets from completed AM production and research projects. We will also investigate packaging structures for AM data sets.

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Appendix. Select International Organization for Standardization (ISO) Standards Related to Additive Manufacturing

This appendix lists some of the current (published) ISO standards related to additive manufacturing. This is not an exhaustive list.

ISO 10303-242:2020

Industrial Automation Systems and Integration – Product Data Representation and Exchange – Part 242: Application Protocol: Managed Model-Based 3D Engineering

ISO/TS 10303-442:2019

Industrial Automation Systems and Integration – Product Data Representation and Exchange – Part 442: Application Module: AP242 Managed Model Based 3D Engineering

ISO/TS 10303-1835:2019

Industrial automation systems and integration – Product data representation and exchange – Part 1835: Application module: Additive manufacturing part and build information

ISO 14649-17:2020

Industrial automation systems and integration – Physical device control – Data model for computerized numerical controllers – Part 17: Process data for additive manufacturing

ISO 17296-2:2015

Additive manufacturing – General principles – Part 2: Overview of process categories and feedstock

ISO 17296-3:2014

Additive manufacturing – General principles – Part 3: Main characteristics and corresponding test methods

NOTE: Will be replaced by ISO/ASTM CD 52927 Additive Manufacturing – General Principles – Main Characteristics and Corresponding Test Methods currently under development.

ISO 22910:2020

Corrosion of metals and alloys – Measurement of the electrochemical critical localized corrosion temperature (E-CLCT) for Ti alloys fabricated via the additive manufacturing method

ISO 27547-1:2010

Plastics – Preparation of test specimens of thermoplastic materials using mouldless technologies – Part 1: General principles, and laser sintering of test specimens

NOTE: Will be replaced by ISO/ASTM DIS 52936-1 Additive manufacturing of polymers – Powder bed fusion – Part 1: General principles and preparation of test specimens for PBF-LB currently under development.

ISO 28219:2017

Packaging – Labelling and Direct Product Marking with Linear Bar Code and Two-Dimensional Symbols

ISO/ASTM 52900:2021

Additive manufacturing – General principles – Terminology

ISO/ASTM 52901:2017

Additive manufacturing – General principles – Requirements for purchased AM parts

ISO/ASTM 52902:2019

Additive manufacturing – Test artifacts – Geometric capability assessment of additive manufacturing systems

NOTE: A newer version is currently under development.

ISO/ASTM 52903-1:2020

Additive manufacturing – Material extrusion-based additive manufacturing of plastic materials – Part 1: Feedstock materials

ISO/ASTM 52903-2:2020

Additive manufacturing – Material extrusion-based additive manufacturing of plastic materials – Part 2: Process equipment

NOTE: A newer version is currently under development.

ISO/ASTM 52904:2019

Additive manufacturing – Process characteristics and performance – Practice for metal powder bed fusion process to meet critical applications

NOTE: A newer version is currently under development.

ISO/ASTM 52907:2019

Additive manufacturing – Feedstock materials – Methods to characterize metal powders

ISO/ASTM 52910:2018

Additive manufacturing – Design – Requirements, guidelines and recommendations

NOTE: A newer version is currently under development.

ISO/ASTM 52911-1:2019

Additive manufacturing – Design – Part 1: Laser-based powder bed fusion of metals

ISO/ASTM 52911-2:2019

Additive manufacturing – Design – Part 2: Laser-based powder bed fusion of polymers

ISO/ASTM TR 52912:2020

Additive manufacturing – Design – Functionally graded additive manufacturing

ISO/ASTM 52915:2020

Specification for additive manufacturing file format (AMF) Version 1.2

NOTE: A W3C XML schema definition (XSD) for the AMF is available from ISO from http://standards.iso.org/iso/52915 and from ASTM from www.astm.org/MEETINGS/images/amf.xsd.

ISO/ASTM 52921:2013

Standard terminology for additive manufacturing – Coordinate systems and test methodologies

NOTE: A newer version is currently under development.

ISO/ASTM 52941:2020

Additive manufacturing – System performance and reliability – Acceptance tests for laser metal powder-bed fusion machines for metallic materials for aerospace application

ISO/ASTM 52942:2020

Additive manufacturing – Qualification principles – Qualifying machine operators of laser metal powder bed fusion machines and equipment used in aerospace applications

There are several subgroups within ISO that have been developing these standards. Each of these subgroups have their own scope and their own perspective on standards development related to additive manufacturing. The two subgroups listed below have produced the majority of published ISO standards related to AM.

ISO Technical Committee (TC) 261

ISO TC 261 has developed 19 ISO Standards (including updates), and they currently have another 34 standards under development. The scope of their work is, "Standardization in the field of Additive Manufacturing (AM) concerning their processes, terms and definitions, process chains (Hard- and Software), test procedures, quality parameters, supply agreements and all kind of fundamentals."[*] There are 26 member organizations participating in TC 261 activities, including the American National Standards Institute (ANSI) representing the United States.

ISO TC 184/ Sub-Committee (SC) 4

ISO TC 184/SC 4 has developed 777 ISO standards (including updates), and they currently have another 34 standards under development. The scope of their work is, "Standardization of the content, meaning, structure, representation and quality management of the information required to define an engineered product and its characteristics at any required level of detail at any part of its life-cycle from conception through disposal, together with the interfaces required to deliver and collect the information necessary to support any business or technical process or service related to that engineered product during its life-cycle."[†] In recent years ISO TC 184/SC 4 has produced several standards that tie additive manufacturing into the Standard for the Exchange of Product Data (STEP) family of standards – ISO 10303. ISO TC 184/SC 4 has also developed several standards that are currently going through the review process prior to publication that should be of interest. They are listed on the following page.

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[*] International Organization for Standardization, Technical Committee 261, (https://www.iso.org/committee/629086.html)

[†] ISO/TC 184/SC 4 Industrial Data (https://committee.iso.org/home/tc184sc4)

ISO/FDIS 23247-1

Automation systems and integration – Digital twin framework for manufacturing – Part 1: Overview and general principles

ISO/FDIS 23247-2

Automation systems and integration – Digital twin framework for manufacturing – Part 2: Reference architecture

ISO/FDIS 23247-3

Automation systems and integration – Digital twin framework for manufacturing – Part 3: Digital representation of manufacturing elements

ISO/FDIS 23247-4

Automation systems and integration – Digital twin framework for manufacturing – Part 4: Information exchange

List of Symbols, Abbreviations, and Acronyms

3D	three-dimensional
AM	additive manufacturing
AM DM WG	Additive Manufacturing Data Management Working Group
ARL	Army Research Laboratory
ASTM	American Society for Testing and Materials
BFO	Basic Formal Ontology
CDD	Common Data Dictionary
CDM	common data model
CT	computed tomography
DEVCOM	US Army Combat Capabilities Development Command
DMLS	direct metal laser sintering
DoD	Department of Defense
DOLCE	Descriptive Ontology for Linguistic and Cognitive Engineering
EBM	electron beam melting
ISO	International Organization for Standardization
JAR	Java Archive
NIST	National Institute of Standards and Technology
OASIS	Organization for the Advancement of Structured Information Standards
ODF	Open Document Format
OWL	Web Ontology Language
R&D	research and development
SLM	selective laser melting
SLS	selective laser sintering
STL	stereolithography
XML	Extensible Markup Language
XRD	X-ray powder diffraction

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
1 (PDF)	DEVCOM ARL FCDD RLD DCI TECH LIB
1 (PDF)	DEVCOM ARL FCDD RLW MD J YU