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FY 2024 Multidimensional Data Correlation Platform Data Management Infrastructure Progress: Materials Laboratory

Sarah Graham
Stephanie Cooper
Vincent Paquit

September 2024

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Advanced Materials and Manufacturing Technologies Program

FY 2024 MULTIDIMENSIONAL DATA CORRELATION PLATFORM DATA MANAGEMENT INFRASTRUCTURE PROGRESS: MATERIALS LABORATORY

Sarah Graham
Stephanie Cooper
Vincent Paquit

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
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ABBREVIATIONS

AMMT	Advanced Materials and Manufacturing Technologies
CAD	computer-aided design
CT	computed tomography
EC	export control
JSON	JavaScript Object Notation
MDDC	Multidimensional Data Correlation
MDF	Manufacturing Demonstration Facility
ORNL	Oak Ridge National Laboratory
ORS	Object Research Systems
SEM	scanning electron microscopy

ABSTRACT

This report provides an inventory of the equipment available at the Oak Ridge National Laboratory's (ORNL's) Manufacturing Demonstration Facility (MDF) for sample preparation and material characterization, including both destructive and nondestructive techniques that generate critical data to support the development of the Multidimensional Data Correlation (MDDC) framework. The success of the MDDC framework depends heavily on the quality and completeness of the data it can access. Therefore, it is essential to establish a comprehensive inventory of the technologies available to the Advanced Materials and Manufacturing Technologies (AMMT) program multilaboratory team. This goal started by gathering information about the types of data the teams produce, the data collection and transfer protocols used, file formats, and data storage requirements for experiments. This information was then carefully evaluated to create the operations and trackables elements of the Damara Tern platform, which is the foundation of the MDDC framework.

This report marks the completion of FY 2024 milestone M4CT-24OR1305053: Deliver Whitepaper of Data Management Infrastructure Progress.

1. INTRODUCTION

This report provides an inventory of the equipment available at the ORNL MDF for sample preparation and material characterization, including both destructive and nondestructive techniques that generate critical data to support the development of the MDDC framework. The MDDC framework is an attempt by the AMMT program to develop data-driven methodologies to support the certification and qualification of the manufacturing processes and parts produced with state-of-the-art advanced manufacturing systems. The framework aims at understanding the behavior of materials in nuclear environments combined with the materials processing characteristics occurring during the additive manufacturing process.

The success of the MDDC framework depends heavily on the quality and completeness of the data it can access. Therefore, it is essential to establish a comprehensive inventory of the technologies available and to gather information about the types of data they produce, the data collection and transfer protocols used, file formats, and data storage requirements for experiments. This information is crucial for creating the operations and trackables elements of the Damara Tern platform, which is the foundation of the MDDC. Additionally, the information helps in creating the data management infrastructure—both hardware and software—necessary to streamline data collection and establish a site-wide digital discipline.

This report focuses on material characterization equipment and is intended to read as a comprehensive list. Although it stands on its own, this report will eventually become part of the broader data management system for this equipment within the Damara Tern platform.

2. METALLOGRAPHY LABORATORY

Metallography is the study of the underlying physical structure and composition of materials through close examination with a variety of tools and techniques. This examination can be performed over a wide range of length scales, from macro to atomic. Highly productive metallography laboratories are configured with the equipment necessary to perform the typical sample preparation workflow, from sectioning to mounting and polishing and, finally, characterization.

3. MATERIAL CHARACTERIZATION AND TESTING EQUIPMENT

3.1 X-RAY COMPUTED TOMOGRAPHY

3.1.1 METROTOM 1

The METROTOM 1 with ZEISS INSPECT measures part dimensions using volume visualization and inspecting scan data.

METROTOM 1 has the following characteristics:

- "3D scanning of small to medium components
- Accurate measurement
- Quality inspection and assurance
- Deep analysis of rejects
- Checking components against their computer-aided design (CAD)" [1]

Figure 1. METROTOM 1.

Category	Value
Approximate Data Volume per *Operation* (GB)	8–15
Approximate Number of *Operations* per Year	1,000
Associated Software Tools	Cera (ZEISS Reconstruction software), GOM Volume Inspect, VGStudio, IC3D

3.1.1.1 Data Collection and Transfer

Currently, ex situ data are manually retrieved from the METROTOM using an unencrypted hard drive. This hard drive is then hand-delivered to one or more desktop computers located inside or outside of the export control (EC) office space. Data are currently stored in an uncentralized manner by principal investigators. Metadata are currently not tracked but are available provided that OEM files are maintained.

3.1.1.2 Imaging

A 2K x-ray detector (size: 1,840 × 1,456 pixels) was installed and is maintained by Zeiss. It is an industrial computed tomography (CT) system for measuring and inspecting complete components made of plastic or metals. It avoids the challenges associated with traditional measuring technology, which can inspect hidden structures only after the time- and cost-consuming process of destroying the component layer-by-layer. At the MDF, the system has been mainly used for defect/pore detection and metrology, among other applications.

3.1.1.3 Data Visualization and Analysis

The analysis software GOM Volume Inspect is being used for complete CT data analysis in 3D. Geometries, shrinkage holes, or internal structures and assemblies can be analyzed precisely. Defects become visible through individual sectional images and can be automatically evaluated according to various criteria. Volumetric data of several components can be loaded into a project, and the user can perform a trend analysis and compare the analysis with CAD data, which is beneficial to determine and document the quality of the component. Cera is the main software being used by the system for image reconstruction from the 3D raw projection volume. IC3D is being developed by ZEISS and is frequently being tested on the parts being manufactured at the MDF for image analysis applications such as segmentation, detection, and registration.

The MDF digital team is developing AI-based Simurgh software that allows for fast and very high-quality reconstruction of metal additively manufactured parts. Leveraging CAD models of the parts along with physics-based information, the software allows for significant improvement for defect detection (threefold so far) and resolution while reducing the scan time (fourfold so far).

3.1.2 Xradia 620 Versa

Xradia 620 Versa has the ability to quickly image samples of various sizes with good resolution.

- Improves scan speed and accuracy of large or irregular samples with advanced acquisition techniques, such as high aspect ratio tomography
- Enables seamless filter changing without manual intervention with the automated filter changer, which can have selections programmed and recorded for each recipe
- Can produce crystallographic information using the optional LabDCT [2]

Figure 2. Xradia 620 Versa.

Category	Value
Approximate Data Volume per *Operation* (GB)	15–20
Approximate Number of *Operations* per Year	750
Associated Software Tools	Dragonfly, ZEISS reconstruction software, IC3D

3.1.2.1 Data Collection and Transfer

Currently, ex situ data are manually retrieved from the Xradia 620 Versa using an unencrypted hard drive. This hard drive is then hand-delivered to one or more desktop computers located inside or outside of the EC office space. Data are currently stored in an uncentralized manner by principal investigators. Metadata are currently not tracked but are available provided that OEM files are maintained.

3.1.2.2 Imaging

The Xradia Versa family of submicron x-ray microscopy uses patented x-ray detectors within a microscope objective turret to enable increased magnification on various sample types and sizes with spatial resolution down to 500 nm. The system provides high resolution across a broad range of sample types, sizes, and working distances. It can also provide in situ imaging for nondestructive characterization of microstructures in controlled environments and over time (stop-and-shoot 4D CT). Akin to other x-ray CT systems, this method avoids the challenges associated with traditional measuring technology, which can inspect hidden structures only after the time- and cost-consuming process of destroying the component layer-by-layer. At the MDF, the system has been mainly used for high-resolution defect/pore/void and high-*z* inclusion detection, metrology, and detailed shape, size, and volume distribution analysis of powder bed particles to determine proper process parameters.

3.1.2.3 Data Visualization and Analysis

The Scout-and-Scan software is being used for reconstruction of the measured x-ray CT data. It also allows for easily scouting a region of interest and specifying scanning parameters within the Scout-and-Scan Control System. Furthermore, it can be used for aligning multiresolution scans of the same part and better characterization of defects in additive manufacturing. Additionally, the Dragonfly Pro from Object Research Systems (ORS) is being used for analysis and visualization of 3D data acquired by the system.

Available exclusively through ZEISS, ORS Dragonfly Pro offers a toolkit for visualization and analysis of large, 3D, grayscale data. Dragonfly Pro allows for navigation, annotation, and creation of media files, including video production, of the 3D data. It can also be used to perform image processing, segmentation, and object analysis to quantify results. The MDF digital team is developing AI-based Simurgh software that allows for fast and very high-quality reconstruction of metal additively manufactured parts. The software allows for significant improvement for defect detection (threefold so far) and resolution and reduces the scan time (fourfold so far).

3.2 METALLOGRAPHIC SAMPLE PREPARATION

3.2.1 Sectioning Equipment

3.2.1.1 Allied TechCut 4 Precision Low Speed Saw (I, II)

The TechCut 4 is a precision low-speed saw. The instrument was designed to cut smaller and more delicate samples that cannot tolerate the increased heat of high-speed sectioning. The instrument has a cutting arm that pivots during sectioning with adjustable weights to provide weight or counterbalance with downward force. To cool the sample during cutting, cutting fluid is used via a reservoir in the instrument. Samples up to 2 in. thick can be sectioned because of the 3 to 6 in. blade range [3].

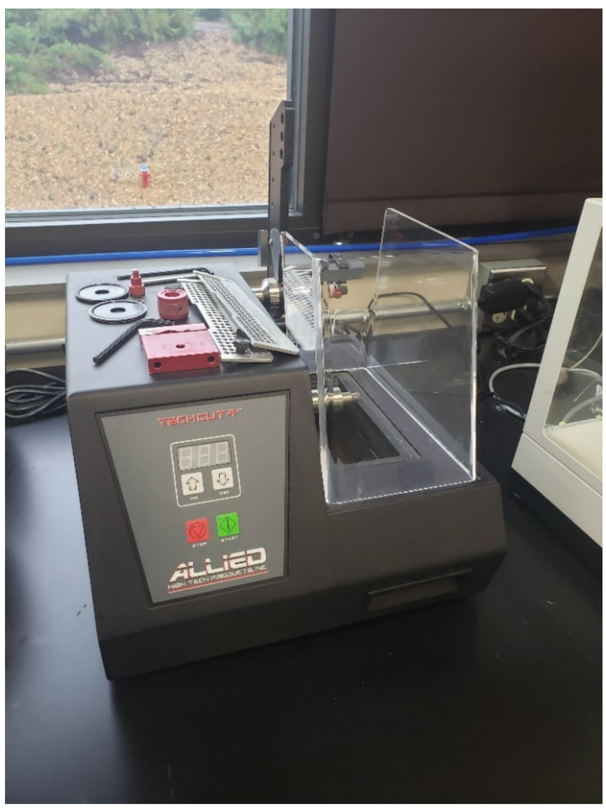

Figure 3. TechCut 4 Precision Low Speed Saw.

Category	Value
Approximate Data Volume per *Operation* (GB)	0
Approximate Number of *Operations* per Year	15–20
Associated Software Tools	LabArchives, Damara Tern

3.2.1.2 Allied TechCut 5 Precision High Speed Saw (I, II, III)

The TechCut 5 precision high-speed saw cuts a wide variety of materials, as well as multiple sizes of materials. It quickly and automatically sections materials and is programmable. The system controls sample feed rate, distance, and force with a microprocessor. The system automatically adjusts the feed rate as the cutting conditions change because of varying thickness or material differences in the sample. When sectioning is complete, the table automatically retracts the sample to the home position and stops blade rotation and coolant usage [4].

Figure 4. TechCut 5 Precision High Speed Saw.

Category	Value
Approximate Data Volume per *Operation* (GB)	0
Approximate Number of *Operations* per Year	200+
Associated Software Tools	LabArchives, Damara Tern

3.2.1.3 Buehler AbrasiMet L Pro Automated Abrasive Cutting Saw

The AbrasiMet L Pro automatic abrasive cutter is a high-performance cut-off saw that measures 14 in. The MDF has a floor standing model utilizing Buehler abrasive blades. The saw is reliable, has optimal sample quality, and shortens processing time [5].

Figure 5. AbrasiMet L Pro Automated Abrasive Cutting Saw.

Category	**Value**
Approximate Data Volume per *Operation* (GB)	0
Approximate Number of *Operations* per Year	100+
Associated Software Tools	LabArchives, Damara Tern

3.2.2 Mounting Equipment

3.2.2.1 Buehler SimpliMet 4000 Automatic Mounting Press (I, II)

The automatic SimpliMet 4000 mounting press is a benchtop instrument. Molds of 1.25 in. and 50 mm are available. The SimpliMet 4000 mounting press is reliable in continuous use environments [7].

Figure 6. Buehler SimpliMet 4000 Automatic Mounting Press.

Category	**Value**
Approximate Data Volume per *Operation* (GB)	0
Approximate Number of *Operations* per Year	130+
Associated Software Tools	LabArchives, Damara Tern

3.2.2.2 Allied VacuPrep Epoxy Impregnation System

This system removes trapped air from uncured epoxy. Removing the air creates a solid polishing surface and can fill open pores and cavities in samples, which maximizes bonding and support. Filling open pores and cavities also maintains sample integrity when preparing the abrasive, which reduces cracking and delamination [8].

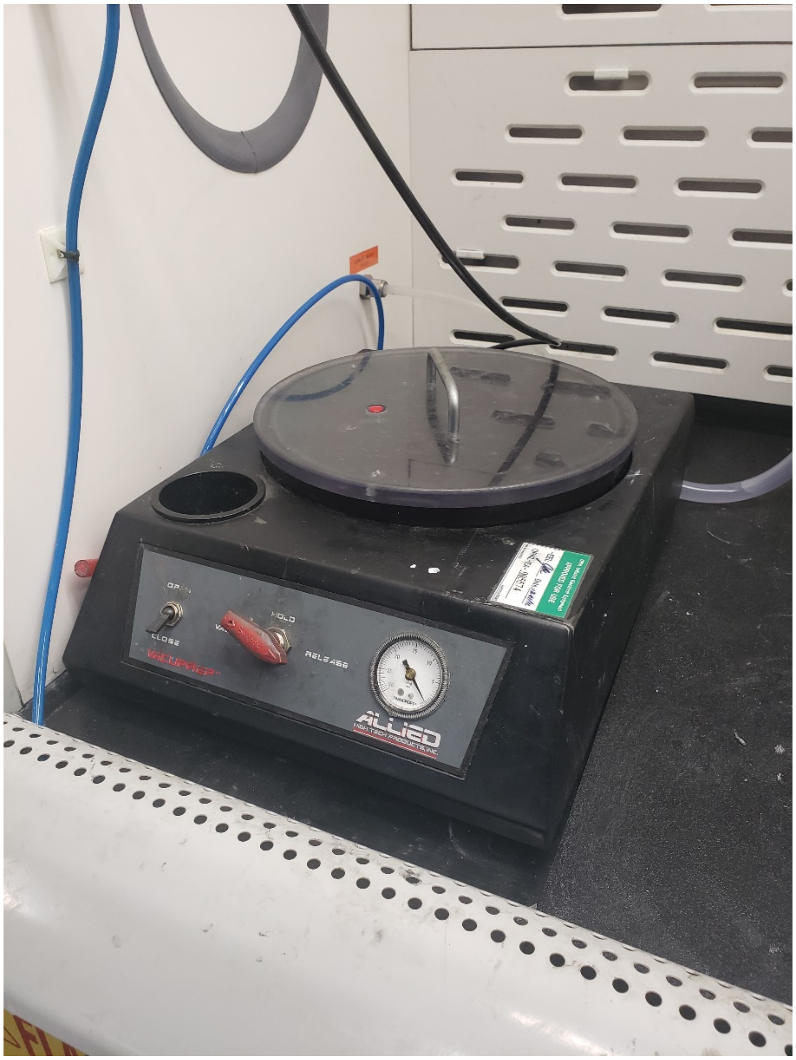

Figure 7. VacuPrep Epoxy Impregnation System.

Category	Value
Approximate Data Volume per *Operation* (GB)	0
Approximate Number of *Operations* per Year	75+
Associated Software Tools	LabArchives, Damara Tern

3.2.3 Polishing Equipment

3.2.3.1 Buehler AutoMet 300 Pro (I, II)

The AutoMet 300 Pro can prepare samples manually or automatically. Many applications can be accommodated [9]. At MDF, this system is paired with a programmable lubricant and abrasive dispensing unit for increased efficiency and reduced waste of polishing consumables.

Figure 8. AutoMet 300 Pro.

Category	Value
Approximate Data Volume per *Operation* (GB)	0
Approximate Number of *Operations* per Year	500+
Associated Software Tools	LabArchives, Damara Tern

3.2.3.2 Allied MultiPrep Polishing System

The MultiPrep System prepares samples semiautomatically for various materials to examine them using microscopic methods (e.g., optical, scanning electron microscopy [SEM], focused ion beam, transmission electron microscopy, atomic force microscopy). The system can do parallel, angle, and site-specific polishing. Dual micrometers control the pitch and roll to adjust the sample tilt relative to the abrasive plane. The *Z*-indexing spindle ensures that the predefined geometric orientation remains the same throughout the process. Quantifiable material removal is possible with digital indicators. Artifacts are minimized and the whole disk is used because of variation in the speed of the rotation and oscillation. Small (i.e., delicate) to large samples can be used on this system. [10].

Figure 9. Allied MultiPrep Polishing System.

Category	Value
Approximate Data Volume per *Operation* (GB)	0
Approximate Number of *Operations* per Year	10+
Associated Software Tools	LabArchives, Damara Tern

3.2.3.3 Buehler VibroMet Vibratory Polisher (I, II)

The VibroMet 2 Vibratory Polisher prepares polished surfaces on various materials, including for electron backscatter diffraction. Horizontal motion at 7,200 cycles per minute produces a very effective polishing action, providing surfaces with less deformation and more flatness [11].

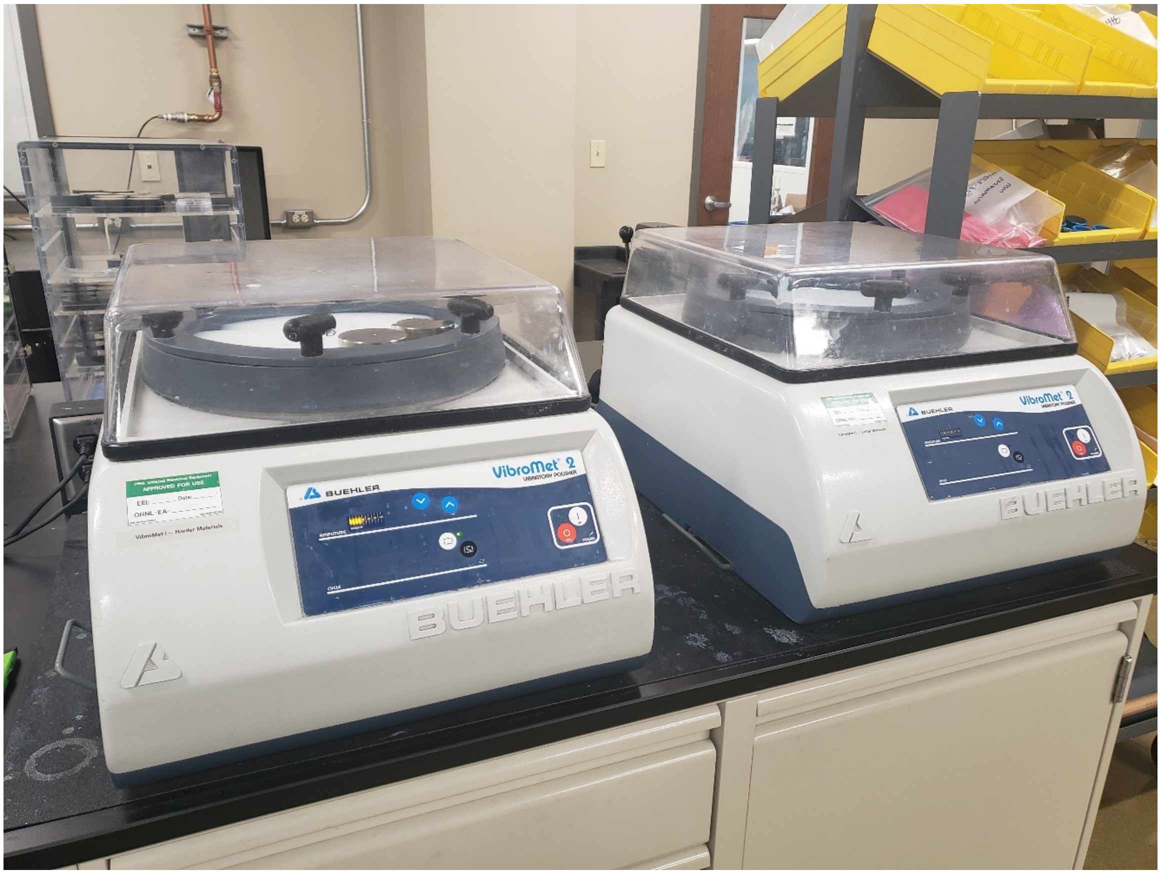

Figure 10. Buehler VibroMet Vibratory Polisher.

Category	Value
Approximate Data Volume per *Operation* (GB)	0
Approximate Number of *Operations* per Year	150+
Associated Software Tools	LabArchives, Damara Tern

3.2.4 Etching Equipment

3.2.4.1 Buehler Electromet 4 Polisher Etcher

The ElectroMet 4 is an electropolishing and etching system. The cathodes are interchangeable, and the system also has an etching cell. This instrument is beneficial because electrolytic sample preparation is efficient for final polishing and etching of metal alloys. The ElectroMet 4 electropolisher/etcher includes a polishing cell, an etching cell, and a specimen stand [12].

Figure 11. Buehler ElectroMet 4 Polisher Etcher.

Category	Value
Approximate Data Volume per *Operation* (GB)	0
Approximate Number of *Operations* per Year	25+
Associated Software Tools	LabArchives, Damara Tern

3.2.5 Optical Microscopy

3.2.5.1 Leica DM4000M

This microscope has a mechanical *Z*-drive and stage and has a coded six-position mechanical objective turret with M32 thread. The light intensity adjusts automatically to the objective in use, and brightness does not change when switching magnification [13].

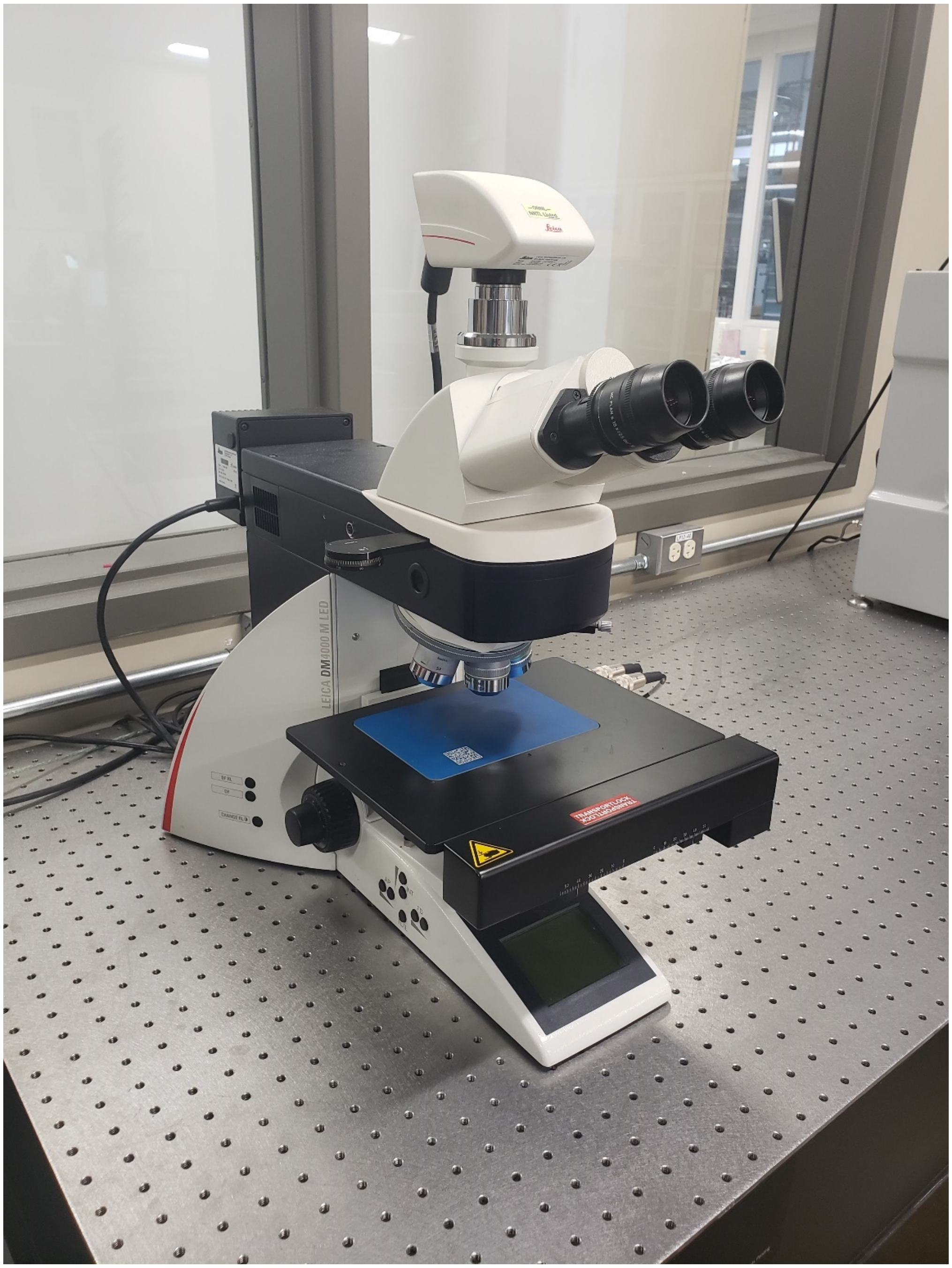

Figure 12. Leica DM4000M.

Category	Value
Approximate Data Volume per *Operation* (GB)	0.01–0.5
Approximate Number of *Operations* per Year	300+
Associated Software Tools	LAS 4.9, LabArchives, Damara Tern

Data Collection and Transfer

Currently, ex situ data are manually retrieved from the Leica DM4000M using an unencrypted hard drive. This hard drive is then hand-delivered to one or more desktop computers located inside or outside of the EC office space. Data are currently stored in an uncentralized manner by principal investigators. Metadata are currently not tracked but are available provided that OEM files are maintained.

Imaging

Objectives of 50–1,000× are installed on the microscope turret. Bright field, dark field, digital interference contrast, and polarized light microscopy can be performed. Microstructural features observable with this system include porosity, sample surface morphology, and grain boundaries.

Data Visualization and Analysis

Vendor software facilitates quantifying data and exporting to nonproprietary formats, as well as visualizing raw and quantified data to a limited extent. Principle investigators are typically provided with raw data to parse with a variety of software tools or scripting languages.

3.2.6 Scanning Electron Microscopy

3.2.6.1 ZEISS EVO 15

The EVO 15 is a multidetector scanning electron microscope. This additive manufacturing operation acts on feedstock (powder or wire) and parts [14].

Figure 13. ZEISS EVO 15.

Category	Value
Approximate Data Volume per *Operation* (GB)	10
Approximate Number of *Operations* per Year	300
Associated Software Tools	Zeiss SmartSEM, EDAX

Data Collection and Transfer

Currently, ex situ data are manually retrieved from the EVO 15 using an unencrypted hard drive. This hard drive is then hand-delivered to one or more desktop computers located inside or outside of the EC office space. Data are currently stored in an uncentralized manner by principal investigators. Metadata are currently not tracked but are available provided that OEM files are maintained.

Imaging

Detectors were installed and are maintained by ZEISS. Microstructural features observable with this system includes porosity, oxide and carbide inclusions, grain phases, elemental composition, sample surface morphology, and grain boundaries.

Data Visualization and Analysis

Vendor software facilitates quantifying data and exporting to nonproprietary formats, as well as visualizing raw and quantified data to a limited extent.

3.2.6.2 ZEISS Gemini 450

The Gemini 450 field emission SEM performs advanced analytical measurements using ultrahigh-resolution imaging [15].

Figure 14. ZEISS Gemini 450.

Category	Value
Approximate Data Volume per *Operation* (GB)	10
Approximate Number of *Operations* per Year	300
Associated Software Tools	Zeiss SmartSEM, Bruker

Data Collection and Transfer

Currently, ex situ data are manually retrieved from the GEMINI 450 using an unencrypted hard drive. This hard drive is then hand-delivered to one or more desktop computers located inside or outside of the EC office space. Data are currently stored in an uncentralized manner by principal investigators. Metadata are currently not tracked but are available provided that OEM files are maintained.

Imaging

Detectors were installed and are maintained by Zeiss. Microstructural features observable with this system include porosity, oxide and carbide inclusions, grain phases, elemental composition, sample surface morphology, and grain boundaries.

Data Visualization and Analysis

Vendor software facilitates quantifying data and exporting to nonproprietary formats, as well as visualizing raw and quantified data to a limited extent.

3.2.7 Hardness Testers

3.2.7.1 LECO AMH55 Automatic Hardness Tester—LM110 Series

The LECO AMH55 performs micro indentation and macro and Vickers hardness testing to measure impressions on various surfaces. The instrument has "lite," semiautomatic, and fully automatic configurations to customize results based on the material being tested and the testing being done. The AMH55 uses LECO's Cornerstone software [16].

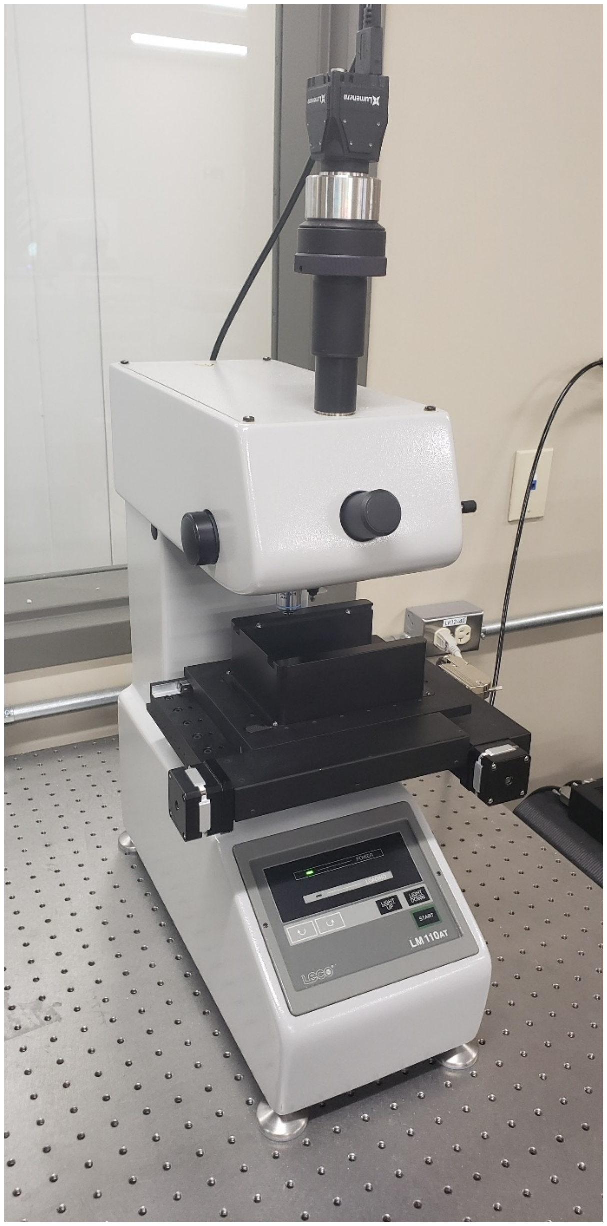

Figure 15. LECO AMH55.

Category	Value
Approximate Data Volume per *Operation* (GB)	1
Approximate Number of *Operations* per Year	150+
Associated Software Tools	CornerStone, LabArchives, Damara Tern

Data Collection and Transfer

Currently, ex situ data are manually retrieved from the LECO AMH55 using an unencrypted hard drive. This hard drive is then hand-delivered to one or more desktop computers located inside or outside of the

EC office space. Data are currently stored in a decentralized manner by principal investigators. Metadata are currently not tracked but are available provided that OEM files are maintained.

Imaging

Basic imaging capabilities are available but not used frequently with this system.

Data Visualization and Analysis

Vendor software facilitates quantifying data and exporting to nonproprietary formats, as well as visualizing raw and quantified data to a limited extent. Principle investigators are typically provided with raw data to parse with a variety of software tools or scripting languages.

6.2.7.2 KLA iMicro Nanoindenter

The iMicro Nanoindenter performs mechanical tests, such as nanoindentation, hardness, scratch, and universal nanoscale, on both soft and hard materials, including small volumes and thin films. The instrument has material property maps (including NanoBlitz3D/4D), frequency-specific testing, scratch and wear testing, and high-temperature testing. Sample heating can go up to 400°C, and a variety of forces and displacements are possible. The iMicro Nanoindenter can also perform stiffness measurements, tribology, and other two-axis measurements using the Gemini 2D force transducer [17].

Figure 16. KLA iMicro Nanoindenter.

Category	Value
Approximate Data Volume per *Operation* (GB)	0.5–1
Approximate Number of *Operations* per Year	25+
Associated Software Tools	InView, LabArchives, Damara Tern

Data Collection and Transfer

Currently, ex situ data are manually retrieved from the iMicro Nanoindenter using an unencrypted hard drive. This hard drive is then hand-delivered to one or more desktop computers located inside or outside of the EC office space. Data are currently stored in a decentralized manner by principal investigators. Metadata are currently not tracked but are available provided that OEM files are maintained.

Imaging

Basic imaging capabilities are available but not used frequently with this system.

Data Visualization and Analysis

Vendor software facilitates quantifying data and exporting to nonproprietary formats, as well as visualizing raw and quantified data to a limited extent. Principle investigators are typically provided with raw data to parse with a variety of software tools or scripting languages.

3.2.8 Miscellaneous Characterization Tools

3.2.8.1 AccuPyc II 1340 Helium Pycnometer

The AccuPycII 1340 is a pycnometer that quickly measures volume and density for a variety of solid materials, including powders and slurries. The volume range is 0.01 to 350 cm^3 [18].

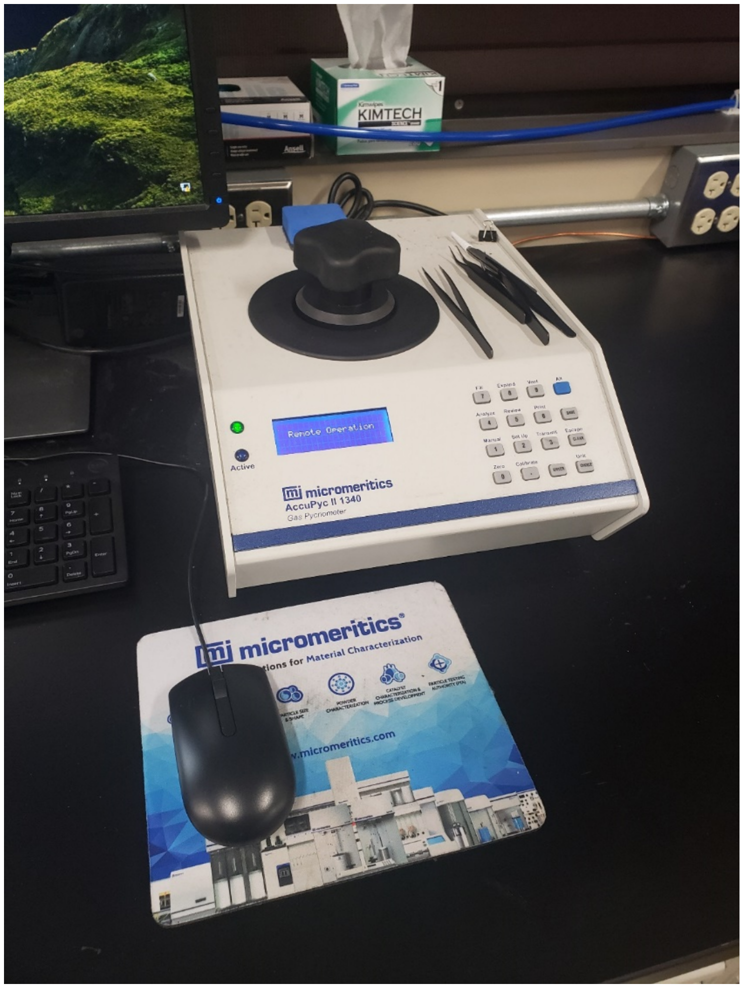

Figure 17. AccuPyc II 1340 Helium Pycnometer.

Category	**Value**
Approximate Data Volume per *Operation* (GB)	0.01–0.1
Approximate Number of *Operations* per Year	50+
Associated Software Tools	MicroMeritics, LabArchives, Damara Tern

Data Collection and Transfer

Currently, ex situ data are manually retrieved from the AccuPyc pycnometer using an unencrypted hard drive. This hard drive is then hand-delivered to one or more desktop computers located inside or outside of the EC office space. Data are currently stored in a decentralized manner by principal investigators. Metadata are currently not tracked but are available provided that OEM files are maintained.

Data Visualization and Analysis

Vendor software facilitates quantifying data and exporting to nonproprietary formats, as well as visualizing raw and quantified data to a limited extent. Principle investigators are typically provided with raw data to parse with a variety of software tools or scripting languages.

3.2.8.2 Microtrac MRB SYNC Laser Diffraction Analyzer

This laser diffraction analyzer measures particle size, particle size distribution, and other morphological particle parameters. Materials from 0.01 to 4,000 µm can be examined using Microtrac's BLEND routine [19].

Figure 18. Microtrac MRB SYNC Laser Diffraction Analyzer.

Category	Value
Approximate Data Volume per *Operation* (GB)	0.01–0.1
Approximate Number of *Operations* per Year	50
Associated Software Tools	FLOWSYNC, LabArchives, Damara Tern

Data Collection and Transfer

Currently, ex situ data are manually retrieved from the Microtrac instrument using an unencrypted hard drive. This hard drive is then hand-delivered to one or more desktop computers located inside or outside of the EC office space. Data are currently stored in a decentralized manner by principal investigators. Metadata are currently not tracked but are available provided that OEM files are maintained.

Imaging

Basic imaging capabilities are available but not used frequently with this system.

Data Visualization and Analysis

Vendor software facilitates quantifying data and exporting to nonproprietary formats, as well as visualizing raw and quantified data to a limited extent. Principle investigators are typically provided with summarized results or raw data to parse with a variety of software tools or scripting languages.

4. METALLOGRAPHY DATA INTEGRATION WITHIN THE DIGITAL THREAD

In FY2024, the MDF Digital Tool underwent a significant overhaul to better support the AMMT program, resulting in the development of the Damara Tern framework. This new platform enhances the digital infrastructure by organizing and structuring metadata around two core concepts: *operations* and *trackables*. Operations include actions performed by machines (e.g., printing, testing, curing) or human interactions (e.g., procurement, annotation), and trackables refer to any physical or digital components (e.g., parts, builds, materials, or digital twins) involved in the manufacturing process. A primary objective of this overhaul was to enable greater flexibility, extensibility, and automation, accommodating a broad range of operations, machines, and technologies. Thanks to its generic structure, Damara Tern seamlessly integrates processes such as metallography operations, making them distinct, searchable elements within the digital thread—each with its own contextual metadata and data files.

4.1 METALLOGRAPHY OPERATION TYPES AND GRANULARITY

In the context of the metallography laboratory, the metadata collected must not only capture the results from each sample characterization but also must track the material and sample preparation methods, as described in Section 3.2. Although an operation can be defined as any action performed, the sample preparation process itself could be divided into multiple operations based on the machines involved. However, for the purpose of metallography characterization, breaking down each step into separate operations would result in a series of microtasks not individually contributing to the data collection and would create an overly complex process for operators. Instead, in conjunction with domain specialists, the decision was made to implement a single "metallography characterization" operation type to encapsulate the characterization process's metadata. At this time, these metallography laboratory processes can be recorded within the Damara Tern interface as operations falling under the umbrella of Metallography characterization and x-ray CT operation types.

4.2 DATA REGISTRATION, ACCESS, AND REPRESENTATION

Within the Damara Tern interface, each operation and trackable can be created, edited, searched for, and displayed. The creation process is powered by dynamic forms that build the underlying database structure. To ensure flexibility, these structures consist of only a few key fields, and specific details are stored in a flexible JavaScript Object Notation (JSON) format. However, entering detailed metadata directly into JSON fields can be challenging. To simplify this task, Damara Tern automatically converts JSON entries into schema-based forms tailored to each operation type. Illustrated in Figure, when creating a metallography characterization operation, the interface presents a custom form specifically designed to capture metadata related to sample preparation and is aligned with the equipment and procedures of the metallography laboratory.

For each operation, trackables can be selected or newly created and assigned as inputs or outputs of the operation. The framework maintains these trackable–operation relationships to reconstruct the digital thread for each trackable, enabling the recreation of the complete contextual history of a component's manufacturing and testing process.

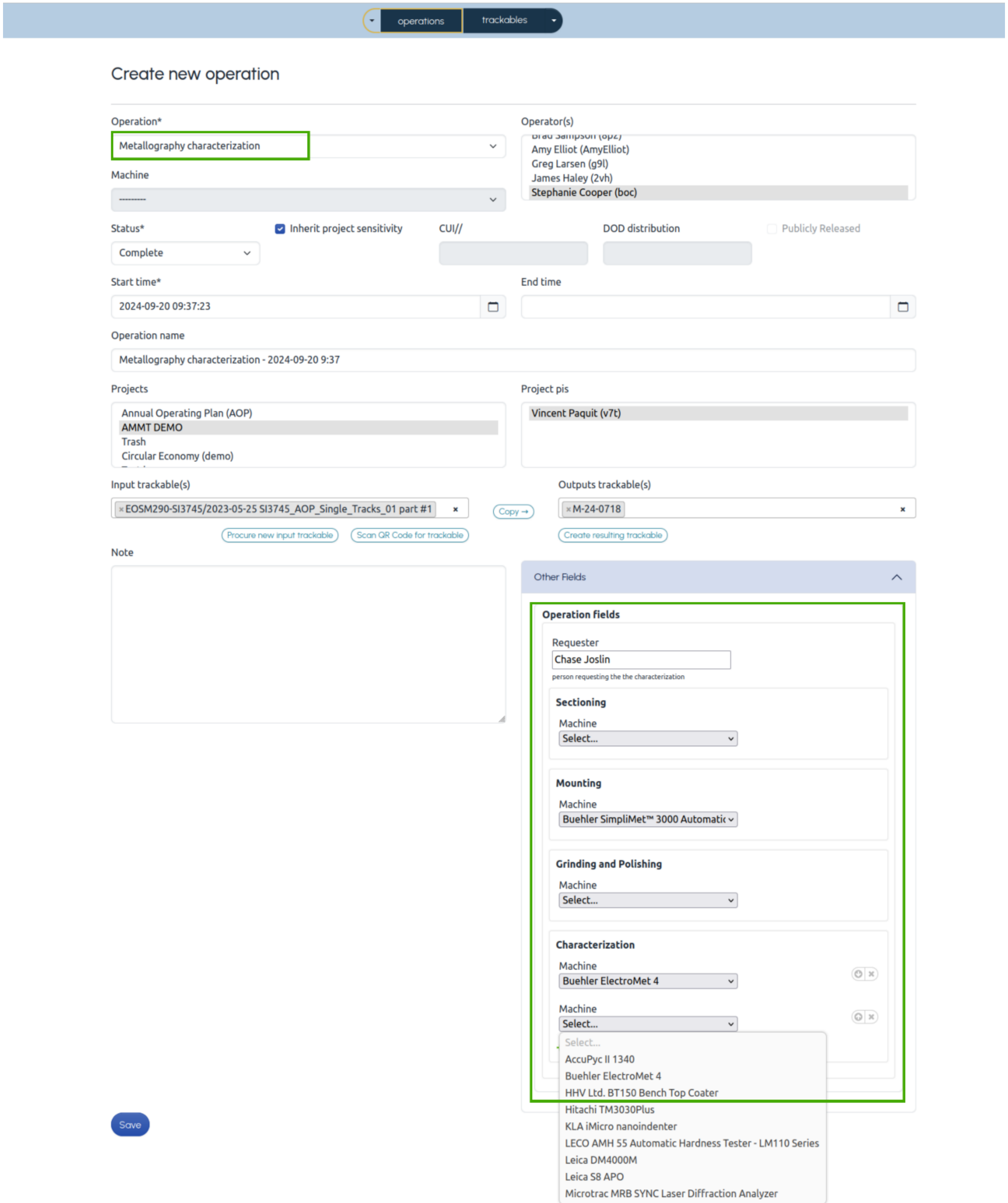

Figure 19. Operation creation form in the Damara Tern Interface. When "Metallography characterization" is selected as the operation, the default JSON entry field is dynamically updated with a detail form tailored to the metallography laboratory equipment, both of which are highlighted in green.

The interface provides dedicated views to consult both trackable and operation data and metadata. The operation views, as shown in Figure**Error! Reference source not found.**, display the operation's metadata (i.e., specificities or context), the list of trackables used as inputs or produced as outputs, and related data files or links. Data files can be uploaded, downloaded, or viewed directly from the operation page. Information for the trackables listed as inputs or outputs is accessible through direct links to their respective trackable pages.

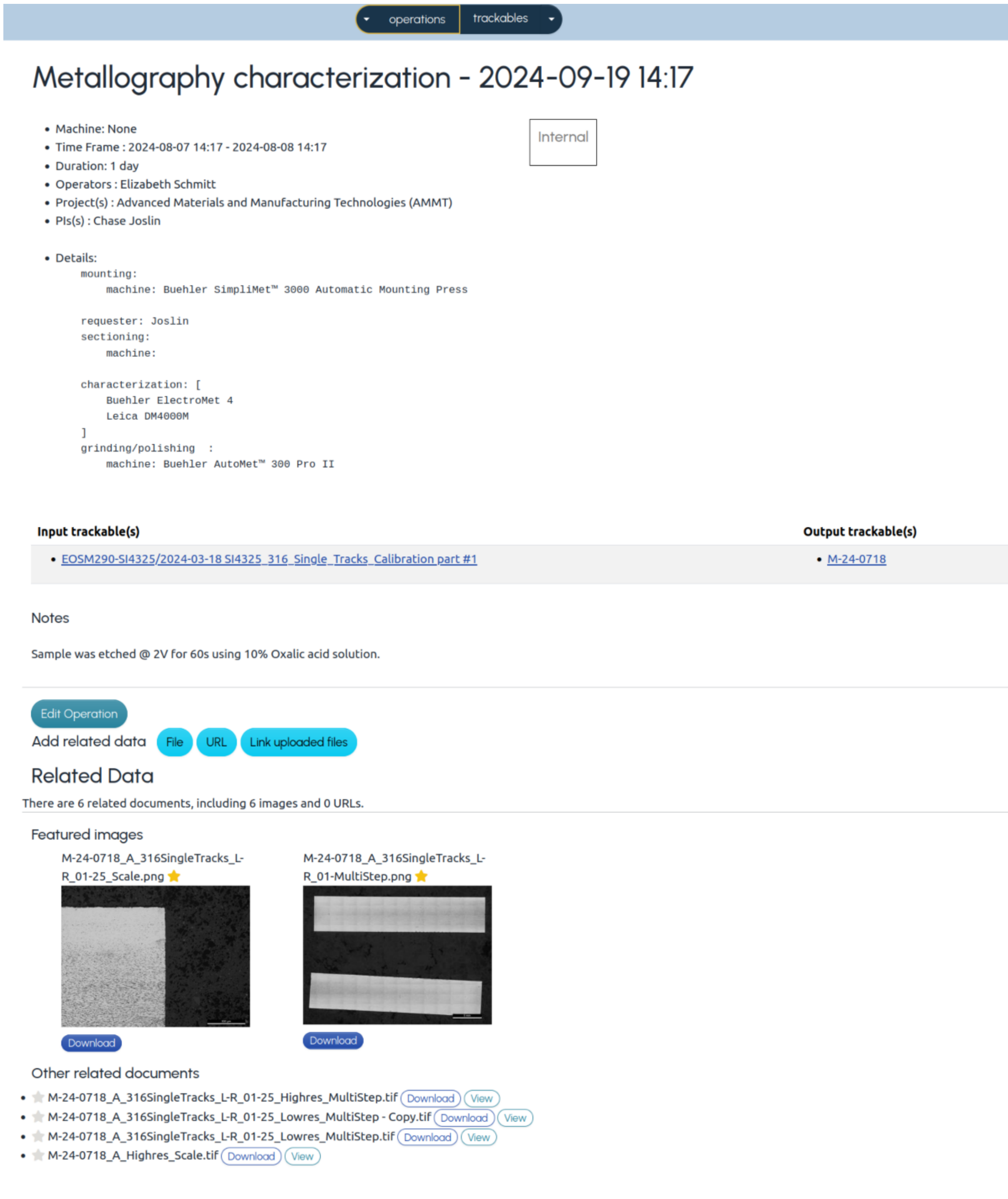

Figure 20. Metallography characterization operation in the Damara Tern interface. From top to bottom, the operation view displays the operation details/metadata, related trackables (input and output), edit and data upload/link buttons, and a list of data files associated with the operation, along with their highlight, download, and visualization access buttons. Sensitivity information is boxed and displayed at the top right of the page beneath the operation name.

The trackable views focus on the trackable's creation context and history. As illustrated in Figure 6, each trackable page summarizes the initial operation responsible for its creation or procurement and provides a history of all operations it has undergone. The view also includes a visual representation of the digital thread for the consulted trackable. Each element within the visualization, along with buttons for operations and links to parent trackables, is interactive, allowing users to navigate through the operations and trackables involved in the digital thread.

Figure 6. Trackable detail page in the Damara Tern interface. The trackable name is followed by a summary of its initial operation and basic information, including the QR code, status, and any applicable sensitivity labels. The digital thread for the trackable is presented as an expandable list of operations and parent trackables, accompanied by an interactive diagram.

4.3 DATA MIGRATION AND CONSOLIDATION

Although adding new metallography operations and trackables within the Damara Tern interface is possible, the metallography laboratory has been relying on a dedicated database entry tool for years. To fully transition to the new system, legacy data must be migrated to the Damara Tern database. Although the existing database structure is simple enough for an easy migration script to transfer its contents to the new system, the challenge lies in recreating the associations between the metallography laboratory trackables and the MDF trackables. Many samples tracked within the metallography laboratory were produced and registered in the MDF, meaning that they already exist in the Damara Tern database but with different identifiers than those used in the metallography lab system. As a result, blindly migrating the metallography laboratory data without addressing these associations would create duplicate trackables with different identifiers, preventing proper reconstruction of the digital thread. To avoid losing any data during the transition, Damara Tern has been extended to store multiple identifiers for each trackable, allowing legacy data to be registered or located using any of these identifiers. However, the challenge lies in developing an effective strategy to track and reconstruct the associations between the metallography laboratory and the MDF identifiers, which will require significant manual effort.

5. CONCLUSION

This report provided an inventory of the material characterization equipment available at the ORNL MDF, which will be integrated within the Damara Tern platform. The data produced by these pieces of equipment will be made available to the AMMT program team and will be leveraged by the MDDC framework when fully integrated. The report included a general description of the equipment, along with a description of the type of data, software, and storage requirements.

Moving forward, this project intends to convert this report into a Wiki document made available online to let interested reader access the latest development in the integration of this equipment to this project's data management platform, including data registration and linkage across operations and trackables. Additional information related to the Damara Tern integration will also be released to provide a broader adoption of the digital discipline strategy that is being put in place.

This report marks the completion of FY 2024 milestone M4CT-24OR1305053: Deliver Whitepaper of Data Management Infrastructure Progress.

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