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Standard Guide for Additive Manufacturing of Metals — Data — File Structure for In-Process Monitoring of Powder Bed Fusion (PBF)[1]

This standard is issued under the fixed designation F3605; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide provides standardized procedures and requirements for converting acquired in-process monitoring data into one file representing the printing process of powder bed fusion (PBF) for quality evaluation.

1.2 Many of the operational descriptions included in this guide are intended as general overviews. They may not present the detailed information required.

1.3 This guide covers:

1.3.1 Data registration,

1.3.2 Extraction of in-process data, and

1.3.3 File conversion and visualization.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ISO/ASTM Standards:*[2]

ISO/ASTM 52900:2015 Standard Terminology for Additive Manufacturing — General Principles — Terminology

ISO/ASTM 52915:2020 Specification for Additive Manufacturing File Format (AMF) Version 1.2

ISO/ASTM 52921:2013 Standard Terminology for Additive Manufacturing — Coordinate Systems and Test Methodologies

3. Terminology

3.1 *Definitions*—For the purpose of this guide, refer to the terms and definitions in ISO/ASTM 52900:2015 and ISO/ASTM 52915:2020.

4. Summary of Guide

4.1 The raw data could be obtained from various in-process monitoring systems. This guide does not involve specific details of these systems, such as sensors and controllers. It is assumed that the user has completed the system setup and calibration and can successfully collect the in process monitoring data.

4.2 The user shall provide the details of the data-processing method and choose the information embedded into the final converted file to satisfy their special requirements. They shall be fully aware of the effect of data processing to avoid extracting misleading information and erroneous interpretation.

NOTE 1—Any data processing is recommended to be applied only to a working copy of the data with the raw data preserved.

4.3 The focus of this guide is on extracting and demonstrating the information from the printing process and leaves the part quality to the user to draw their own conclusion.

5. Significance and Use

5.1 The converted file will be organized in a specific structure to reflect the relationship between the in-process monitoring data with the quality of the printing process.

5.2 This standard file structure will help ensure the data compatibility across various printing systems, analyses, and illustration software. It aims to be self-explaining and easy to use to accommodate data sharing in a large base of users.

5.3 The converted file can be used for the evaluation of printing quality and the detections of defects and anomalies.

6. Data Registration

6.1 This necessary procedure aims to transform different sets of geometrically or temporally related in-process data into a single and global coordinate system before converting them into one file.

[1] This guide is under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.08 on Data.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

6.2 The in-process data include all the information acquired from the layer-wise raw data captured by monitoring sensors in the powder bed fusion (PBF) process.

NOTE 2—The layer-wise raw data refers to all the raw data that are acquired during the printing process of each layer (or each build cycle).

NOTE 3—Different sensors generate various layer-wise data types (for example, temperature sequence at a certain point or line, optical or infrared image, topography data by three dimensional (3D) camera). The raw data for each layer are a time series of data (for example, images, videos). In the PBF process, all data can be processed and transformed into a static (non-temporal) representation for each layer.

6.3 The registration method depends on the data acquisition method.

6.3.1 The in-process data captured by various sensors with different characteristics usually have different resolutions, sampling frequencies, and so forth. Data registration could be based on the characteristic parameters of lower-resolution or higher-resolution sensors. Data interpolation or omission may be applied to match all the data from different-performance sensors during registration.

6.3.2 For the synchronously acquired data, the spatial coordinate is aligned during data registration. In Fig. 1, data registration of the synchronously acquired layer-wise images from different sensors is presented.

NOTE 4—Synchronously acquired data refer to data that are acquired by various sensors, in which all data points from one sensor can be matched or referenced to any data point of the other sensor.

6.3.3 For the asynchronously acquired data, both the spatial and temporal coordinates are aligned during data registration.

NOTE 5—Asynchronously acquired data refer to data that are acquired by various sensors and have different starting times or sample frequencies.

6.3.4 Data interpolation or omission during the spatial and temporal alignment may affect data accuracy and introduce errors.

7. Extraction of In-Process Data

7.1 The sensors in the PBF process capture a larger amount of layer-wise raw data. The user may not be interested in all of them. Extraction of in-process data is intended to extract data from the registered layer-wise data based on the user's special requirements, for example, data of a certain type or data from region of interest (ROI).

7.2 *Extraction Processes:*

7.2.1 Pre-process the registered data for each layer.

7.2.2 Choose the representative layer-wise data at a designated time of each build cycle according to the user's requirements (for example, after laser scanning or after powder coating) and transform the layer-wise registered data into a static (non-temporal) representation for each layer and so the layer number coincides with the *z* axis.

NOTE 6—In the PBF process, the data of each layer (or build cycle) usually have the same *z* coordinate calculated by multiplying layer number and height. If the representative layer-wise data is not chosen at a designated time for each layer (or build cycle), a time series of data (for example, images, videos) yield multiple data points at the same *x*, *y*, and *z* coordinates and the converted 3D file will fail to be read and visualized by the visualization tools.

7.2.3 Determine the sampling points and their space coordinates for the extracted data of each layer.

7.2.3.1 All the sampling points in the extracted data are defined by *x*, *y*, and *z* coordinates; the time axis follows the *z* axis in the PBF process.

7.2.3.2 Considering the different characteristics of various sensors, file size, data accuracy, data processing time, and so forth, a compromise should be made when determining the sample size.

7.2.4 Extract the in-process information of all sampling points for each layer.

7.2.4.1 The basic in-process information that will be embedded into the final file is directly extracted from the layer-wise data, such as temperature values from thermocouple or infrared (IR) images, or gray values from optical images.

NOTE 7—In the *i*th layer (having the same *z* coordinates expressed as z_i), the point extracted data have fixed *x* and *y* coordinates [for example, $S_i = f(x_0,y_0,z_i)$]; the 1D extracted data have varing *x* or *y* coordinates [for example, $S_i = f(x,y_0,z_i)$]; the 2D extracted data have varying *x* and *y*

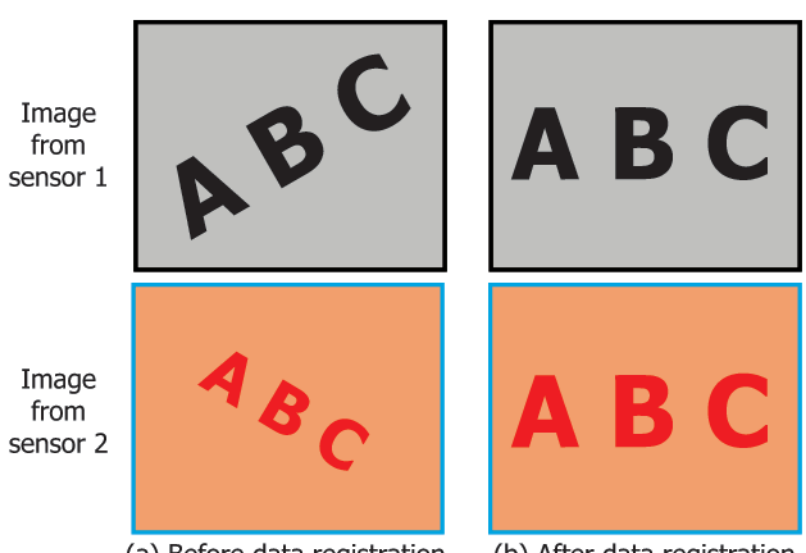

FIG. 1 Layer-Wise Images from Different Sensors (a) Before and (b) After Data Registration

(1) **File header**: briefly introducing the file structure

(2) **Data title**: describing the content of data file.

(3) **Data type**: ASCII or BINARY

(4) **Geometry or topology**: defining the geometric coordinates of each data point

(5) **Dataset attributes**: storing the data information of each point.

(6) **Custom labels**: including other notes according to user's requirements.

FIG. 2 An Example of Commonly Used File Structure

coordinates [for example, $S_i = f(x,y,z_i)$].

NOTE 8—It may be hard to directly embed the topography data by 3D camera [expressed as $z = f(x,y,z_i)$] into the final converted 3D file. However, it is possible to transform the 3D topography of each layer into one 2D gray or colorful image with the gray or RGB value representing the topography information (for example, roughness expressed as $S_i = f(x,y,z_i)$). Then, all the 2D image data could be easily converted into single 3D file [expressed as $S = f(x,y,z)$]. Using this file, the visualization tools can quickly rebuild the 3D topography for each layer.

7.2.4.2 Special complex processing of the layer-wise registered data is needed to extract other derived information (such as temperature gradient, cooling rate, features related to possible defects, data in the ROI) for further analysis according to the user's requirements.

7.2.4.3 Some derived information (such as temperature gradient, data in the ROI) may be obtained from the visualization results of the final converted file.

7.2.4.4 Data processing may introduce some misleading information and erroneous interpretation.

8. File Conversion and Visualization

8.1 File conversion is to embed the extracted in-process data into one file and organize it in specific structure and data format. File visualization is to visualize the final converted file with suitable tools.

8.2 *Conversion of In-Process Data into One File:*

8.2.1 Choose the file structure and data format.

8.2.1.1 The file structure and data format are in accordance with the commonly used third party software products chosen by the user, including commercial (for example, Tecplot[3,4]), developed inhouse, and open-source (for example, ParaView[5,4]) tools.

NOTE 9—The file format with efficient compression and retrieval may be preferred for large volumes of data. For example, use of HDF[6,4], netCDF[7,4], or FITS[8,4] file types. Parsers may need to be written to allow visualization tools to view, for example, XDMF.[9,4]

NOTE 10—The AMF file format defined in ISO/ASTM 52915:2020 is encouraged if possible. Otherwise, XML 1.0 is recommended to be used to output and store the data, which is easy to implement since there is a standardized open data interchange format used by any third party software and is also compatible with ISO/ASTM 52915:2020.

NOTE 11—It is recommended to review and follow the FAIR data principles (Findability, Accessibility, Interoperability, and Reuse of digital assets) when storing or sharing data.[10]

8.2.1.2 In Fig. 2, an example of commonly used file structure is shown. The file generally includes five parts: file header, data title, data type, geometry or topology, dataset attributes, and custom labels.[3,5,11]

8.2.2 Follow the special instructions on the chosen file structure and data format, then embed all the in-process data into one file.

8.2.2.1 The in-process data include the coordinates and all extracted information of all sampling points.

8.2.2.2 Different layer-wise extracted data generate different data in the final converted files. The final converted file of point extracted data contains 1D data [for example, $S = f(x_0,y_0,z)$]; the converted file of 1D extracted data contains 2D data [for example, $S = f(x,y_0,z)$]; the converted file of 2D extracted data contains 3D data [for example, $S = f(x,y,z)$].

8.2.3 Store the final converted file.

8.2.3.1 The converted file could be stored in plain text or compressed.

8.2.3.2 The compression could be completed by the user via compression software or done by using compression libraries when building the converted file.

NOTE 12—The compression rate of a ZIP archive format is tested to be approximately 10 %.

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[3] The sole source of supply of the product (Tecplot 360 2020 R2) known to the committee at this time is Tecplot, Inc., 2020, https://www.tecplot.com.

[4] If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.

[5] The sole source of supply of the product (ParaView 5.9.0) known to the committee at this time is Kitware Inc., 2020, https://www.paraview.org.

[6] The sole source of supply of the product known to the committee at this time is The HDF Group, 2006, https://www.hdfgroup.org.

[7] The sole source of supply of the product known to the committee at this time is Network Common Data Form (NetCDF), https://www.unidata.ucar.edu/software/netcdf.

[8] The sole source of supply of the product (a Primer on the FITS Data Format) known to the committee at this time is The HEASARC (High Energy Astrophysics Science Archive Research Center), https://fits.gsfc.nasa.gov/fits_primer.html.

[9] The sole source of supply of the product (eXtensible Data Model and Format) known to the committee at this time is https://www.xdmf.org/index.php/Main_Page.

[10] FAIR Principles, https://www.go-fair.org/fair-principles.

[11] The VTK User's Guide, 11th ed.,, Kitware Inc., 2010, https://www.kitware.com/products/books/VTKUsersGuide.pdf.

8.3 *File Visualization:*

8.3.1 Read the converted file using visualization tools and visualize the data.

8.3.1.1 Decompress the file if compressed.

8.3.1.2 The visualization outcomes are dependent on the data types. For the layer-wise point, 1D, and 2D extracted data (corresponding to 1D, 2D, and 3D data in converted file), the visualization outcomes are a 1D line, a 2D surface, and a 3D body, respectively.

8.3.1.3 In Fig. 3, the reconstructed 3D body from the in-process 2D image data in Fig. 1 is presented.

8.3.2 Customize and analyze the visualization results.

NOTE 13—If necessary, the user could utilize the functions in the visualization tools to analyze further the data qualitatively and quantitatively. These functions could calculate the gradient, curvature, and so forth to satisfy the user's requirements.

8.3.3 Export the customized results or processed data if needed. The exported file could be a multimedia file for presentation or temporary data for future use.

9. Guidelines for Converting In-Process Data into One File

9.1 Standard procedures should be developed and followed to complete the data processing and convert the acquired in-process data into one file (Fig. 4).

9.2 *Apparatus*—The user shall define required hardware and software for data acquisition, storage, management and processing, and file conversion and visualization including, but not limited to:

9.2.1 *Hardware:*

9.2.1.1 Sensor devices,

9.2.1.2 Sensor data acquisition devices,

9.2.1.3 Storage, and

9.2.1.4 Data management, processing, and extraction system.

9.2.2 *Software:*

9.2.2.1 Data management,

9.2.2.2 Data processing and extraction, and

9.2.2.3 File conversion and visualization.

9.3 *Procedures*—The user shall establish specific step-by-step procedures according to published guidelines that will satisfy their requirements and interests. The procedure should address the following at a minimum:

9.3.1 Capture,

9.3.2 Storage,

9.3.3 Data management,

9.3.4 Data processing and extraction,

9.3.5 File conversion,

9.3.6 Data security, and

9.3.7 Output.

9.4 *Limitations*—The user shall document the limitations of their data-processing method and equipment as well as the accuracy of the converted file.

9.5 *Safety*—The user shall establish specific safety procedures to satisfy their needs.

9.6 *References*—The user shall maintain their specific documents, manufacturers' manuals, and published guidelines.

10. Keywords

10.1 data alignment; data processing; data registration; file conversion; in-process monitoring; visualization

FIG. 3 Reconstructed 3D Body from the in-process 2D image data in Fig. 1

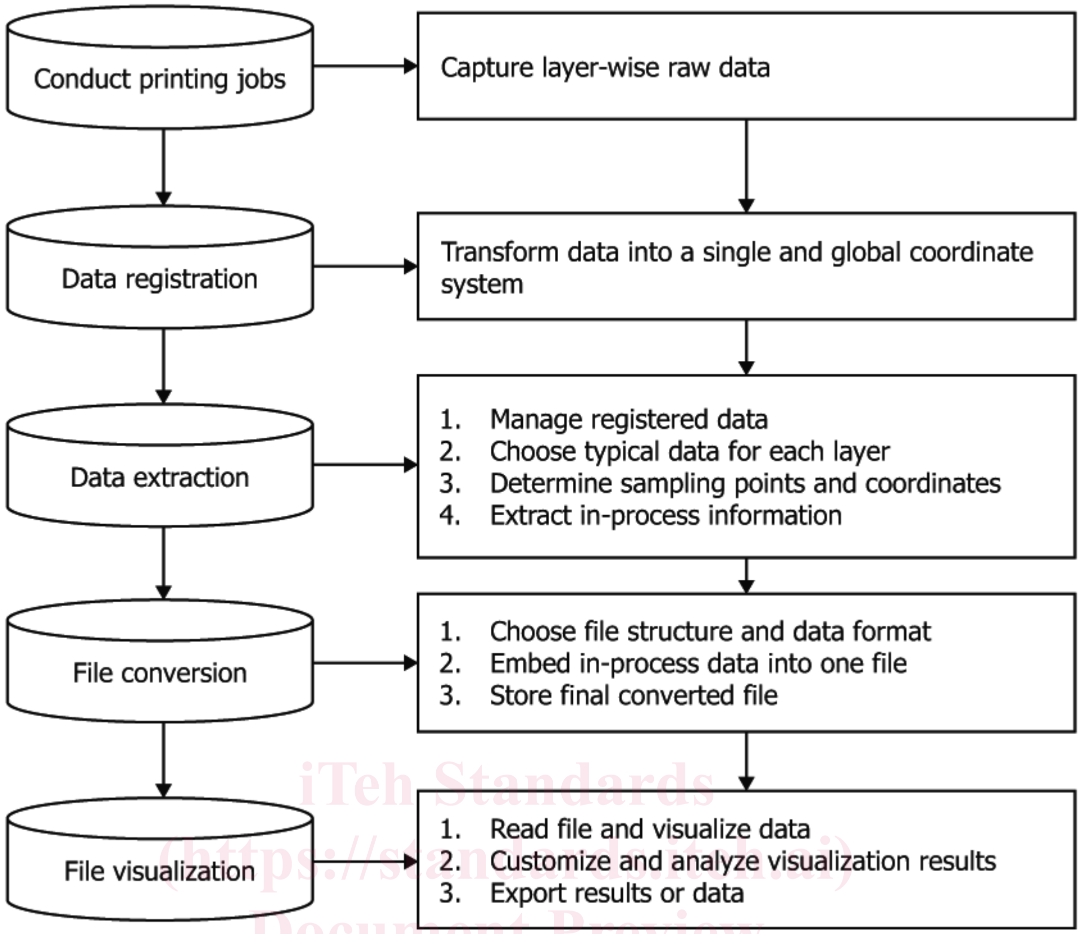

FIG. 4 Flow Diagram for Converting In-Process Layer-Wise Data into One File

APPENDIX

(Nonmandatory Information)

X1. CONVERSION OF LAYER-WISE OPTICAL AND THERMAL DATA INTO SINGLE 3D FILE

INTRODUCTION

This appendix introduces an application case of following the procedures provided in this standard to convert the in-process monitoring data into a single 3D file in Powder Bed Fusion. Here, the in-process layer-wise optical and thermal images are captured synchronously by optical and infrared cameras in an in-process monitoring system for each layer when conducting the printing jobs, as shown in Fig. X1.1(a).

X1.1 Data Registration

X1.1.1 Since the synchronously acquired optical and thermal images automatically have the same temporal coordinates, we could only align their spatial coordinates during data registration. Any data anomalies should be removed prior to data registration. Using a checkerboard, both affine transformation matrices for aligning layer-wise optical and thermal images are determined with the help of the checkerboard detection function in commercially available software (for example, MATLAB[12,4]) or open-source image processing tools (for example, OpenCV[13,4]), which are related to the extrinsic parameters of the in-process monitoring system. In Fig. X1.1, the layer-wise optical and infrared images before and after data registration are presented.

[12] The sole source of supply of the product (MATLAB R2020b) known to the committee at this time is MathWorks, Inc., 2020, https://www.mathworks.com.

[13] The sole source of supply of the product (OpenCV 4.5.1) known to the committee at this time is OpenCV team, 2020, https://opencv.org.