Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-61-TR-2023/03 **July 2023**

Platform Integrity Department

Technical Report

Fabrication Data Elements to Inform Modeling and Simulation of Metal-based Welding and Additive Manufacturing Processes

by

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The Welding, Processing, and Nondestructive Evaluation (NDE) Branch (Code 611) at the Naval Surface Warfare Center, Carderock Division (NSWCCD) was tasked with identifying essential fabrication data elements associated with the experimental setup of metal-based welding and additive manufacturing processes to inform modeling and simulation (M&S) efforts across multiple length scales. This report is part of the Integrated Computational Materials Engineering (ICME)-enabling thrust to expand the use of computational simulations for design and fabrication.

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

The Welding, Processing, and Nondestructive Evaluation (NDE) Branch (Code 611) at the Naval Surface Warfare Center, Carderock Division (NSWCCD) was tasked with identifying essential fabrication data elements associated with the experimental setup of metal-based welding and additive manufacturing processes to inform modeling and simulation (M&S) efforts across multiple length scales. This report is part of the Integrated Computational Materials Engineering (ICME)-enabling thrust to expand the use of computational simulations for design and fabrication.

BACKGROUND

The purpose of this document is to communicate what fabrication data are needed from the laboratory setting to enable the modeling and simulation (M&S) of metal-based welding and additive manufacturing (AM) processes at various length scales. Processes of interest which have been included within this document are:

1. Conventional arc welding [*e.g.*, gas-metal, gas-tungsten, flux-cored, *etc.*]
2. Powder-bed fusion (PBF) [*e.g.*, laser and electron beam]
3. Directed energy deposition (DED) [*e.g.*, wire-arc AM, laser hot-wire AM, *etc.*]

As M&S efforts have become more commonplace to accelerate process parameter optimization and part qualification, it is critical to document certain aspects of fabrication to inform these efforts. **Figure 1** shows how information from welding and AM builds are used across different length scales in the M&S research community. Examples of M&S outputs include temperature history, microstructural evolution, defect formation, distortion, component performance, and many others. However, the high fidelity prediction of the aforementioned results must be thoroughly informed with the full array of process parameters and material properties listed in this document.

Additionally, this document describes the essential data elements from the fabrication and setup of metal-based welding and AM processes to inform corollary M&S efforts. While all of this information may not be needed for welds or AM builds that do not have accompanying M&S efforts, best practice for long term data storage would be to document in the case that M&S assistance is needed in the future.

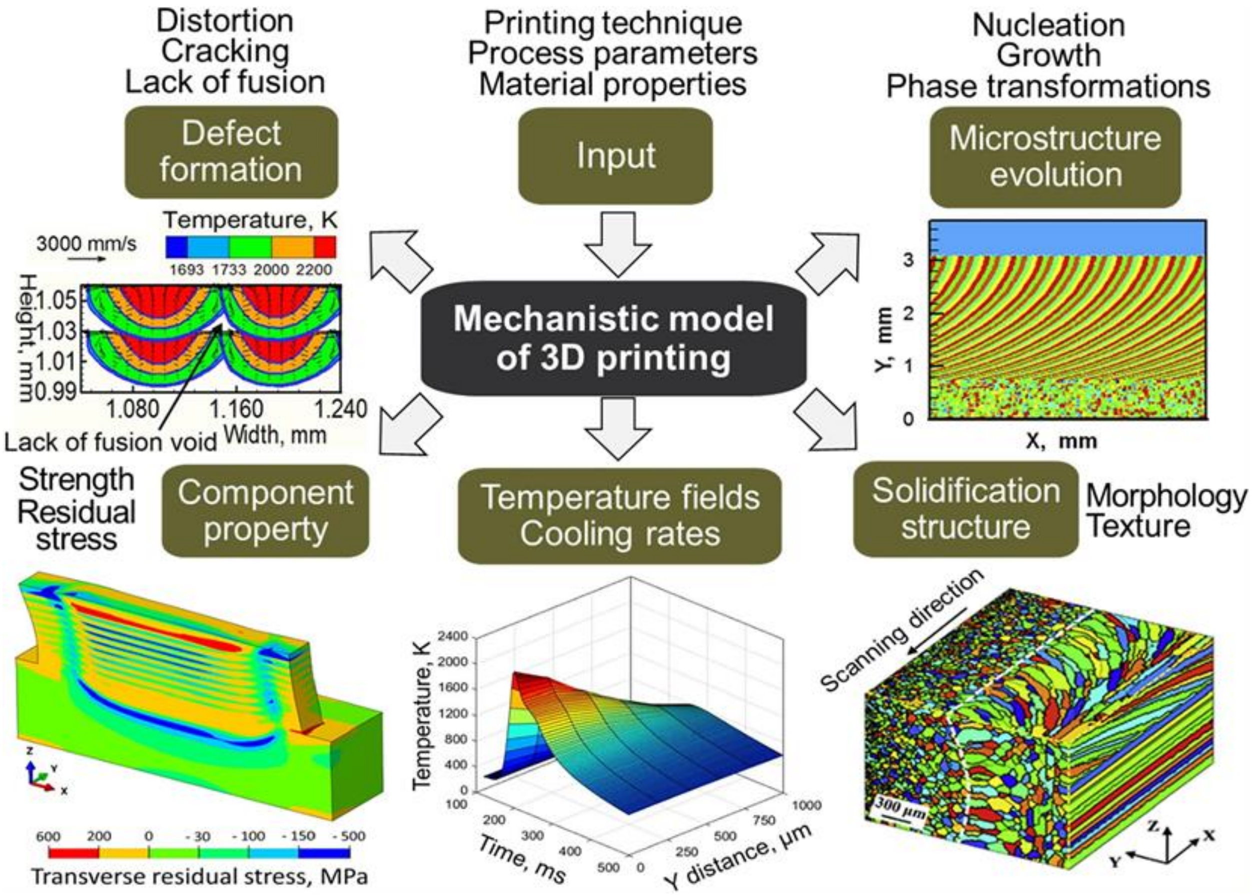

Figure 1. Schematic detailing the manner in which welding and metal AM processing parameters and material properties are used in M&S efforts at different length scales [1].

DISCUSSION

Material Data

Proper documentation of the alloys used in the AM build or weldment (*e.g.*, baseplates, powder, and filler metal), including material grade or specification, manufacturer, and as-received processing condition, is required to inform M&S efforts. Chemical composition, as reported from the supplier or internal testing, is needed to inform the thermodynamic models that can predict the thermal properties (*e.g.*, thermal conductivity, density, specific heat capacity, coefficient of thermal expansion) should actual data not be readily available. However, despite identical composition, different heat treatments or processing conditions can result in different material properties for a given material grade. Therefore, understanding the processing conditions of the material is desired to provide insight into the mechanical properties (*e.g.*, modulus of elasticity, yield strength, flow stress) for more accurate modeling results. Materials certification documentation from the manufacturer is a good resource for essential data, which typically includes alloy designation, specific chemistry, and room-temperature mechanical properties. Additional thermo-physical or thermo-mechanical property data from tests external to the manufacturer are also helpful. An overview of the desired material information is listed in **Table 1** and detailed in the tables in the **Appendix**.

Table 1. Important Material Data Elements for Welding and AM Simulations

Element	Description
Base Material	Material specification, chemistry, temper, and dimensions
Wire	Material specification, chemistry, and diameter
Powder	Material specification, chemistry, powder size distribution, and manufacturing process

Fabrication Setup

The deposition process and its associated AM or welding machine type is important information to inform M&S efforts (*e.g.*, gas-tungsten arc welding, laser hot-wire AM, *etc.*). First, the specific type of welding cell, robot, or AM machine is desired, as it can enable modelers to understand limitations associated with specific machines and help select the best M&S tool for the physical process. For example, the EOS M290 LPBF machine has a build platform that is 250 x 250 x 325 mm (9.85 x 9.85 x 12.8 in), which limits the size of component able to be fabricated. Further details of the heat source, particularly the type of heat source (*e.g.*, plasma arc, continuous wave laser, or electron beam) are essential elements. For example, in arc welding processes, the waveform of the applied current and voltage is used to inform the heat source model for thermal history prediction.

DED and Welding

Documentation of the metal deposition and clamping locations in reference to the baseplate orientation is important for thermo-mechanical M&S efforts. The dimensions of the baseplate(s) along with the size, location, and torque of each clamp are desired. Other build setup features of importance include documenting how the baseplate is situated on the table. For example, knowledge of whether there is a shim between the baseplate and the table or the degree of contact the part has with a heat sink is important to understand thermal flow characteristics. **Figure 2** provides an annotated schematic as an example for the required fabrication setup and includes features of importance such as labeled clamps, clamp dimensions, clamp spacing, bolt torque, and bolt torqueing order. However, **Figure 2** does not indicate where the weld begins which is desired for both DED and welding M&S efforts.

For welding and DED processes, clamping conditions can drive different distortion and residual stresses in both the baseplate and the weldment or AM build. **Figure 3** emphasizes how changes in clamping conditions can result in different distortion contours with significant differences shown on the right edges of the plate and the deposit. Case 5 in **Figure 3** was clamped only on the outer corners of the baseplate, while Case 7 was clamped in five locations on each side of wall. As a result, higher distortion is observed in the baseplate of Case 5, whereas higher distortion is observed in the build volume in Case 7. The clamping conditions and resultant post-build distortion and residual stress is important subsequent analysis using techniques such as profilometry, x-ray or neutron diffraction, or hole-drilling.

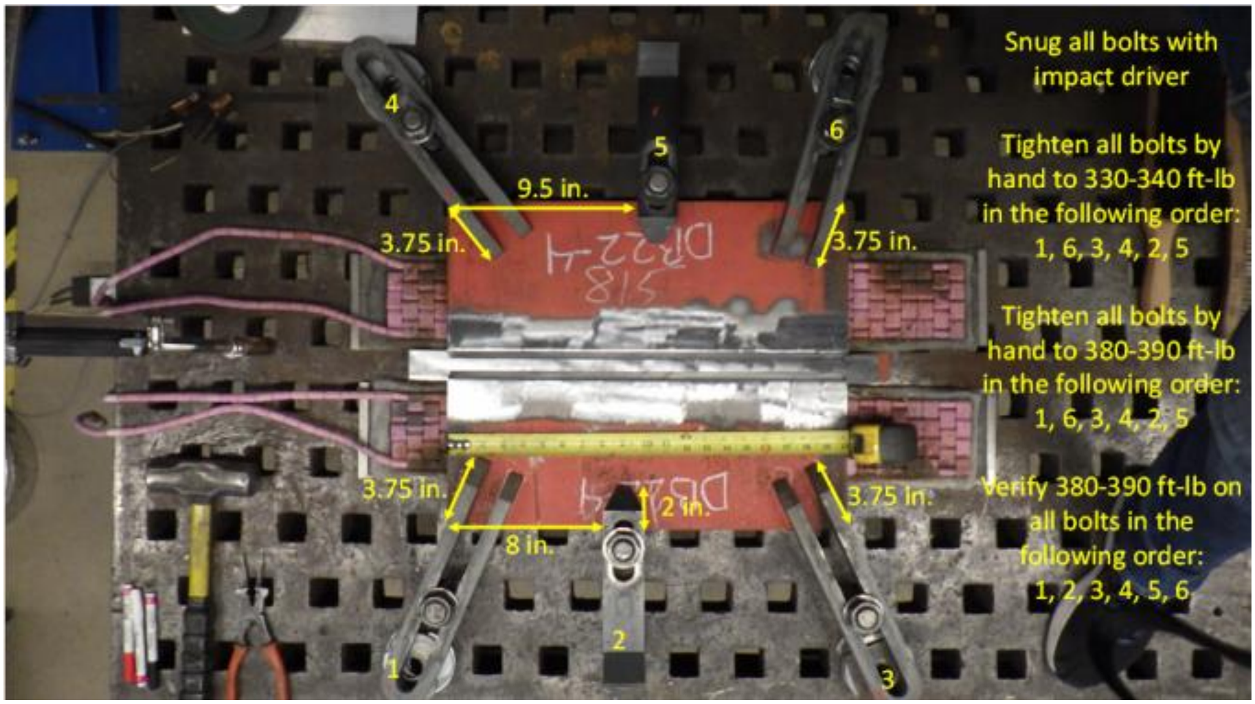

Figure 2. Schematic detailing the fabrication setup for a weld.

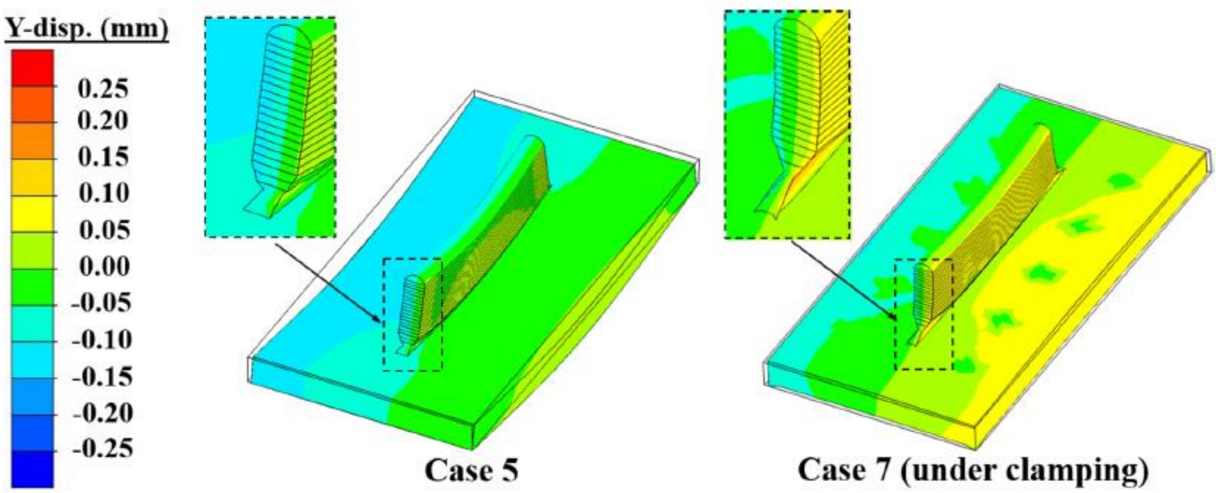

Figure 3. Effect of different clamping conditions on distortion [2]. Case 5 was clamped on each corner of the substrate. Case 7 was clamped in 10 locations (5 on each side of the wall).

An overview of the desired fabrication setup information for welding and DED processes is listed in **Table 2** and detailed in the tables in the **Appendix**.

Table 2. Important Setup Data Elements for Welding and DED Simulations

Element	Description
Process	Ex: wire-arc additive manufacturing
Arc-Metal Transfer Mode (or Laser Type)	Ex: cold metal transfer
Machine Make and Model	For welding power supply and, as applicable, wire feeder and, for SAW, weld head
Torch Make and Model	Ex: Lincoln Electric Magnum Pro
Clamping	Clamp type, material, number of clamps, clamp torque, order of clamping/unclamping, time in clamp
Runoff tabs	If runoff tabs were used, list the dimensions

PBF

In contrast to DED and conventional welding fabrication configurations, the substrate size and torque specification for PBF are typically dictated by the machine manufacturer and the associated build volume. Therefore, any deviations to the manufacturer substrate size or torque specification should be documented. This includes the use of a reduced build volume kit, which can affect both thermal and mechanical analyses in M&S.

An overview of the desired fabrication setup information for PBF processes is listed in **Table 3** and detailed in the tables in the **Appendix**.

Table 3. Important Setup Data Elements for PBF Simulations

Element	Description
Machine	Manufacturer, model, machine software version, build file processing software and version
Recoater	Material and type

Temperature Data

When applicable, preheat conditions should be reported in addition to the ambient temperature. This includes the method of preheating (*e.g.*, heating blanket, cartridge heater, flame torch, *etc.*), location at which the heat is applied, and the target preheating temperature. The timing of heating can also be important if the entire component was not heated and only a portion of the component was heated to a specific temperature. Furthermore, care should be taken to report whether or not baseplate pre-heating is maintained throughout the entire build or just a portion of the build.

If a forced cooling method is used, details such as location, size, and material of the heat sinks or cooling fans are desired in order to understand the differences in radiative and convective heat losses. Baseplate preheating and forced cooling can drive differences in temperature history, and thus, the final microstructure, distortion, and residual stresses of the fabricated part or weldment. **Figure 4** shows how a backing bar can shift the temperature history by up to a 20% difference on the baseplate by serving as a heat sink while **Figure 5** shows how forced cooling with a fan can also significantly change the temperature history. While these shifts in temperature may seem insignificant, for certain materials they can drive differences in as-built microstructure (*e.g.*, grain size, grain morphology, *etc*.), residual stresses, and distortion due to heat accumulation and/or changes in cooling rate. These differences can ultimately result in a premature failure or reduced mechanical performance.

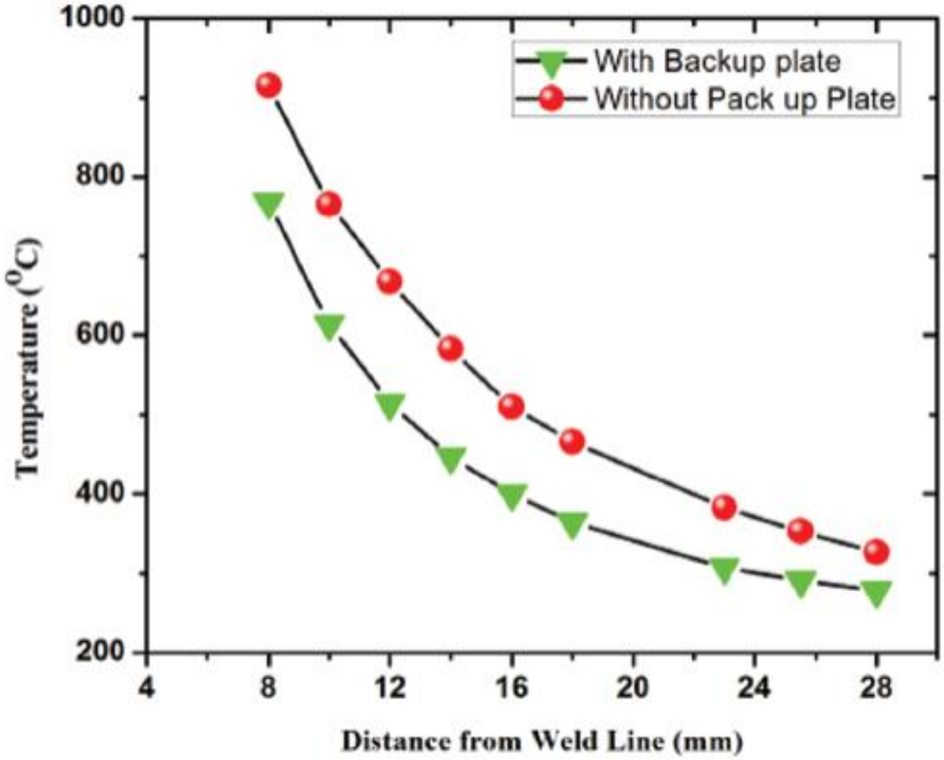

Figure 4. Effect of backup plate on temperature history at various distances from the fusion line [3].

If thermocouples or other in-situ temperature measurement techniques are not used, the time taken for the build or weldment to reach room temperature should be recorded. The final thermal boundary condition of interest for fabrication is the interpass temperature for welding and DED processes. Information of interest regarding this measurement is the target and actual temperature value along with the measurement location in relation to the build. In the case where material cools too rapidly to support a specific interpass temperature (as in the case of PBF), or where interpass temperature cannot be measured, the interlayer dwell time can be reported instead. Interpass temperature or interlayer dwell time can have significant, material-specific effects on the resultant distortion and residual stress, as shown in **Figure 6**.

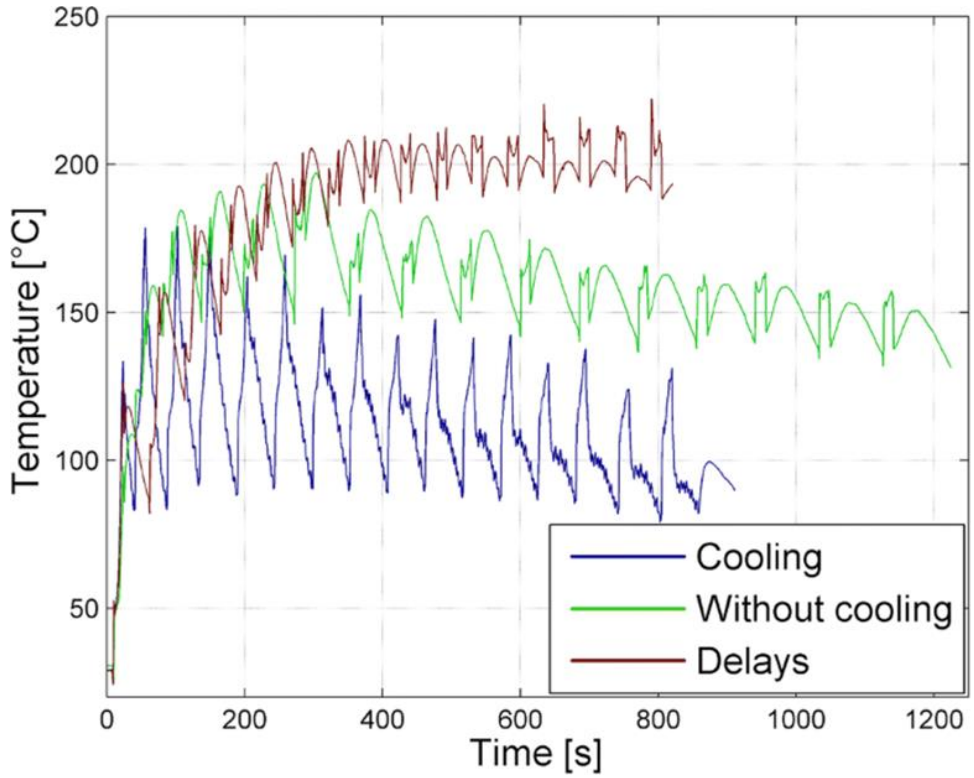

Figure 5. Effect of forced cooling via fan on temperature history at a single point on the baseplate of an AM build [4].

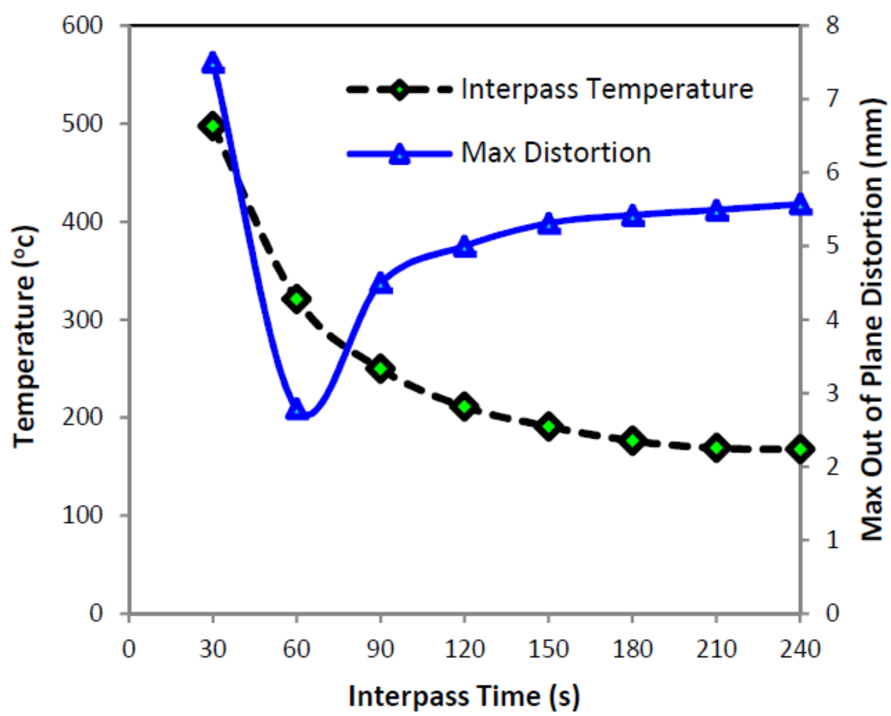

Figure 6. Effect of interpass temperature on maximum plate distortion [5].

An overview of the desired temperature data information is listed in **Table 4** and detailed in the tables in the **Appendix**.

Table 4. Important Temperature Data Elements for Welding and AM Simulations

Element	Description
Preheating	Temperature value, method of heating, and whether heating is maintained during entire process
Interpass	Temperature value and measurement method/location
Interlayer dwell time (if interpass temperature is not used)	Ex: 2 minutes
Ambient Temperature	Ex: 25° C
Forced Cooling/Heating	Fan location, fan setting, location noted in picture or figure; heating blanket details, *etc.*

In-situ Data Collection

Details involving the implementation and use of any in-situ sensor data collection is desired, including the brand name, model number, calibration technique, calibration date, and uncertainty of any instrument(s). Understanding the positioning and sampling frequency of the data collection instruments (such as thermocouples, microphones, thermal cameras, *etc.*) is essential to effectively use the measured data to validate the modeling predictions along with associated uncertainty quantification.

Interpass Gouging or Machining

Information of any gouging or machining dimensions (approximate measurements of the volume removed, depth of gouge, *etc.*) along the length of the plate or deposit is important for simulation of any back-gouging step during multi-pass welding or hybrid AM process. Such information can be captured with images, so long as scale bars (*e.g.*, adding a ruler to the image) are present. Additional information on the type of equipment used for gouging (*i.e.*, Dremel tool, angle grinder, *etc.*) can be useful to M&S efforts as different processes have different characteristics of performance.

Process Parameters

The process parameters used during fabrication are commonly reported, but typically reflect an acceptable range rather than ground truth values. Furthermore, these are reported in an inconsistent manner. Therefore, a well-established procedure for capturing and maintaining process data is recommended for all fabrication efforts, whether research in a government lab or production builds at an industrial partner. Commonly reported process parameters of interest to the M&S community are shown in **Figure 7**. The full range of desired process parameters are listed in the tables in the **Appendix**.

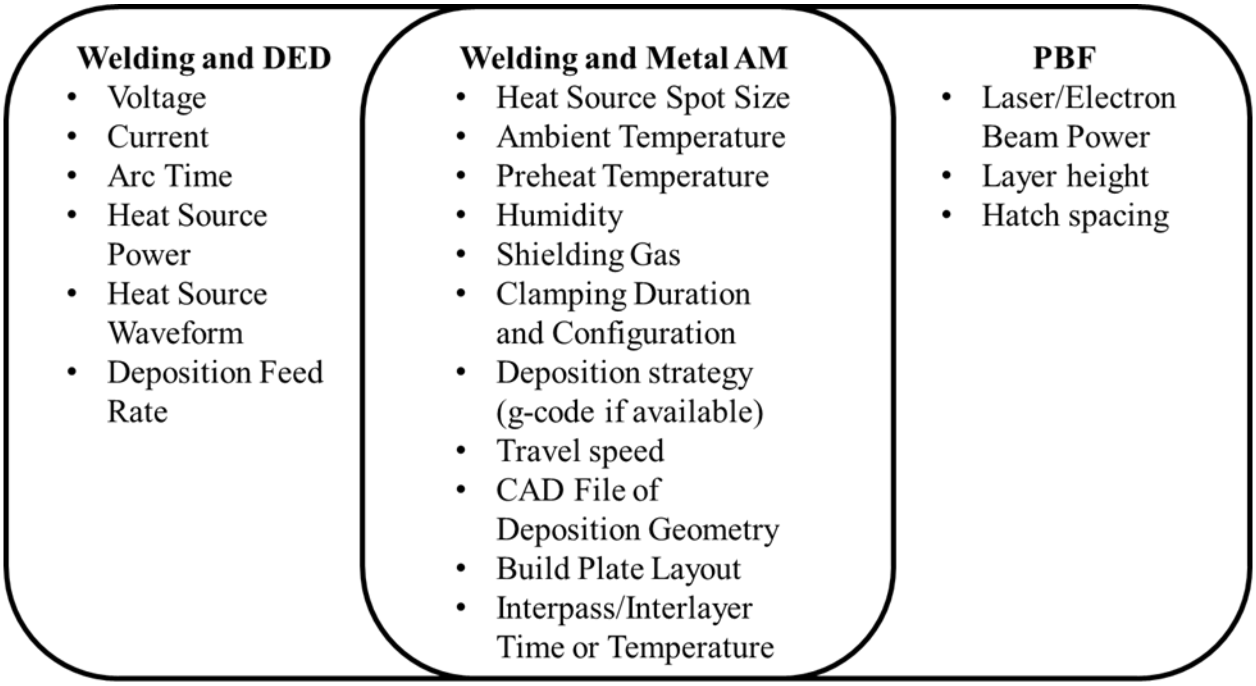

Figure 7. Commonly reported production data for welding, DED, and PBF processes.

Post-Fabrication Data Collection

Upon completion of the deposition process, measurements of the distortion and/or residual stress in the fabricated component might occur. If it does, then several details are desired to ensure proper validation against the predicted results. For distortion, data on the collection method (white light, photogrammetry, *etc.*) and locations of the measurements are essential. Additional information about how the measurement was taken, such as before and after clamping, timing of each measurement, the temperature at which the measurement was taken, and whether the component was placed on a flat surface or propped on other plates, are also desired for more accurate M&S.

Residual stress measurements might also be taken of the component, whether destructive (*e.g.*, hole drilling) or nondestructive (*e.g.*, high energy X-rays or neutron diffraction) in nature. As such, locations and orientations of the measurements are essential for model validation.

Additionally, if a cross-section of a spare component is available, the bead size and shape associated with the fabrication process can be used for model validation. In particular, etched micrographs with a scale bar for melt/weld pool sizing are beneficial to modeling calibration and validation efforts [6]. When a cross-section of the actual part is not available, the authors have found that using the process parameters to re-create a “dummy” specimen for a corollary cross-section works well. An overview of the desired in-situ and post fabrication data information is listed in **Table 5** and detailed in the tables in the **Appendix**.

Table 5. Important In-situ and Post Fabrication Data Elements for Welding and AM Simulations

Element	Description
Method of removal from build plate (if applicable)	Wire EDM, band saw, *etc.*
In-situ data collection	Describe make, model, measurement location, frequency, calibration date and uncertainty of any in-situ data collection instrumentation
Post-fabrication data collection	Describe make, model, measurement location, frequency, calibration date and uncertainty of any post-fabrication data collection instrumentation

Deposition Strategy

The deposition strategy along with its associated heat input is critical for thermo-mechanical M&S efforts because differing scanning strategies and heat inputs directly influence the temperature history and thus, the resultant residual stresses, distortion, and microstructure in the as-built part or weldment. Evidence of the effect of differing scanning strategies on distortion for a DED process is shown in **Figure 8**, with different strategies resulting in up to a 46% difference in distortion.

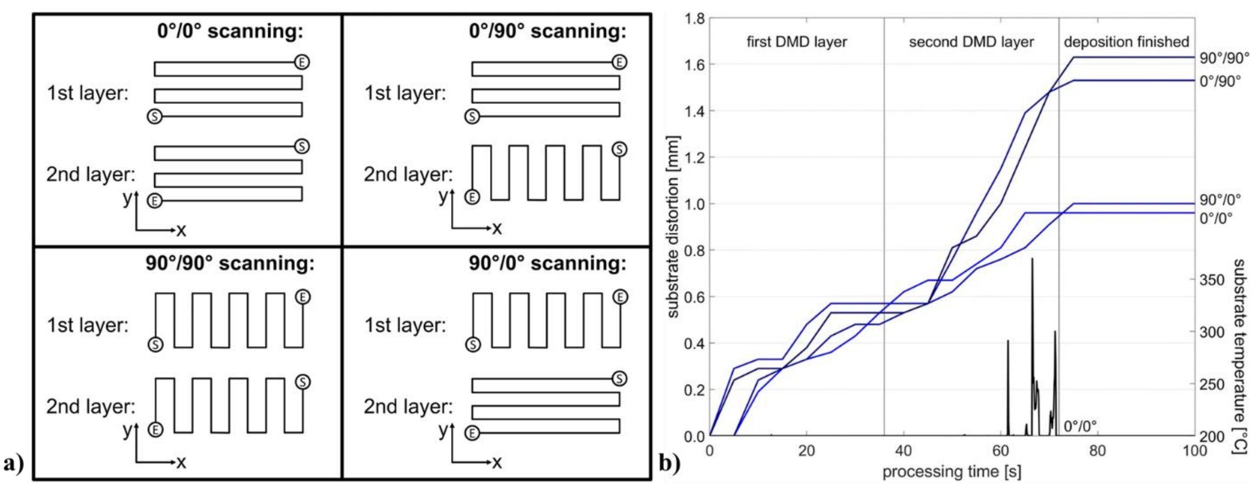

Figure 8. **(a)** Schematic detailing various deposition strategies and **(b)** effect of differing scanning strategies on plate distortion [7].

Although the deposition strategy for a majority of welds is fairly simple to document, the M&S of AM processes require the complete deposition strategy to accurately re-create the build in a simulation. For DED processes such as wire-arc AM, the g-code/machine code is required to reproduce the deposition path in addition to the orientation of the build. If the g-code/machine code is not available, then a .csv file containing the coordinates and heat source information (*e.g.,* laser/electron beam power or arc current and voltage) of the deposition head with respect to time is desired. If this information is not available for welding and DED, then the full thermal history cannot be recreated, and thus, any subsequent M&S efforts that are dependent on a thermal history cannot be used.

For PBF processes, the exact laser or electron beam scanning strategy may not be fully available, as some AM machine manufacturers limit the user from exporting this data. In cases such as this, information detailing the overall scanning strategy should be documented (*e.g.*, serpentine scanning strategy with a 60° rotation between layers) to inform the M&S. Because PBF is a much faster process in terms of heat source travel speed, many M&S efforts simply apply the heat flux for the full layer at one time rather than following the full deposition path (as typically used for DED processes). As a result, access to the full deposition strategy is not as critical for the M&S of PBF processes as it is for DED processes.

An overview of the desired deposition strategy and heat input information is listed in **Table 6** and detailed in the tables in the **Appendix**.

Table 6. Important Deposition Strategy and Heat Input Data Elements for Welding and AM Simulations

Element	**Description**
Digital Files	CAD files, slice files, and build files (g-code/machine code)
Deposition Method	Weave vs. stringer, max bead width
Oscillation	Amplitude, frequency, and dwell
Torch Position	Relative off-set from vertical centerline in horizontal-rolled position
Electrode Lead or Trail Angle	Wire feed angle
Gas Cup Size	Ex: 1/4 in.
Electrical Characteristics	Current, arc voltage range, and polarity; or laser power
Travel Speed	Ex: 12.7 mm/s

SUMMARY

This report emphasizes the need for documentation of essential processing parameters and relevant build information for metallic welding and AM builds to accelerate the M&S efforts at various length scales. For DED and welding processes, documentation of the build orientation in relation to the baseplate and clamps is of particular importance for distortion and residual stress prediction. Many of the details required for the M&S of traditional welding processes translate to DED and PBF processes, with some small additions regarding process specific process parameters such as deposition strategy.

The **Appendix** details all of the current important data elements desired to inform M&S efforts at various length scales of metal-based welding, DED, and PBF processes. Readers should note the levels of data are noted there to give an understanding of what is required now, useful to have, and best practices to maintain for the future.

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APPENDIX

Table A1 lists the important data elements for the modeling and simulation (M&S) of welding and directed energy deposition (DED) processes with example inputs and/or explanations. Data elements highlighted in **red with bold text** are critical; without those data serious assumptions will have to be made during M&S efforts that will jeopardize accuracy. Elements highlighted in blue with regular text are desirable; the more those data are included, the more accurate the M&S effort will be. Elements in *italics* may be applicable to future computational fluid dynamics (CFD) M&S efforts and therefore are helpful to include if readily available. Elements that are not highlighted are metadata for record keeping and are noted as best practices to maintain for unforeseen scenarios on future efforts.

Table lists the important data elements for the M&S of powder-bed fusion (PBF) processes with example inputs and/or explanations. Data elements highlighted in **red with bold text** are critical; without those data serious assumptions will have to be made during M&S efforts that will jeopardize accuracy. Elements highlighted in blue with regular text are desirable; the more those data are included, the more accurate the M&S effort will be. Elements in *italics* may be applicable to future computational fluid dynamics M&S efforts and therefore are helpful to include if readily available. Elements that are not highlighted are metadata for record keeping and are noted as best practices to maintain for unforeseen scenarios on future efforts.

Table A1. Essential Data Elements for Welding and DED Simulations

Element	Type	Description/Example
Base Material	**Critical**	Specification, chemistry, temper, and dimensions
Filler Material	**Critical**	Specification and type, diameter or powder size distribution, form (wire/strip/powder/insert), and manufacturing process
Flux (as applicable)	**Critical**	Specification, size, type
Process	**Critical**	Ex: wire-arc additive manufacturing
Arc Transfer Mode / Laser Type	**Critical**	Ex: cold metal transfer
Machine Make/ Model	Desirable	For welding power supply and, as applicable, wire feeder, and weld head
Applied Power	**Critical**	Current, arc voltage range, and polarity; or laser power
Travel Speed	**Critical**	Ex: 12.7 mm/s
Position	Desirable	Including progression vertical-up or -down
Torch Shielding Gases	*Future*	Type and flow rates
Purge Gases	*Future*	Type and flow rates
Post-heat treatments	Desirable	Hold times and temperatures; Ex: no heat treatment
Preheat Temp	**Critical**	Temperature value, method of heating, and whether heating is maintained during entire process
Interpass Temperature	**Critical**	Temperature value, and measurement method/location
Deposition Method	Desirable	Weave vs. stringer, max bead width
Oscillation	Desirable	Amplitude, frequency, and dwell
Torch Position	Desirable	Relative off-set from vertical centerline in horizontal-rolled position
Electrode Lead or Trail Angle	Desirable	Wire feed angle
Gas Cup Size	*Future*	Ex: 1/4 in.
Ambient Temperature	Desirable	Ex: 25 °C
Forced Cooling/Heating	Desirable	Fan location, fan setting, location noted in picture or figure; heating blanket details, *etc.*
Clamping	**Critical**	Clamp type, material, number of clamps, clamp torque, order of clamping/unclamping, time in clamp
In process grinding, machining, cleaning	Desirable	Describe amount and manner in which material is removed
Runoff tabs	Desirable	If runoff tabs were used, list the dimensions
Weld ID	Metadata	Ex: 10 Layer Wall #5
Weld Date	Metadata	Ex: 05/15/2021
Digital Files	**Critical**	CAD files, slice files, and build files (g-code)
Layer height	**Critical**	Ex: 2 mm
Interlayer dwell time / Interpass tem	**Critical**	Ex: 2 minutes or 120 °C
Method of removal from build plate	Desirable	Wire EDM, band saw, *etc.*
In-situ data collection	Desirable	Describe make, model, measurement location, frequency, calibration date and uncertainty of any in-situ data collection instrumentation
Post-fabrication data collection	Desirable	Describe make, model, measurement location, frequency, calibration date and uncertainty of any post-fabrication data collection instrumentation

Table A2. Important Data Elements for PBF Simulation

Element	Type	Description/Example
Powder material	**Critical**	Chemistry, size distribution and percent fines, morphology, shear testing, flowability, density, production process
Build plate material	**Critical**	Chemistry, temper, product form, size
Machine	**Critical**	Manufacturer, model, machine serial number, machine software version, build file processing software and version
Recoater	Desirable	Material and type
Build plate preheat temperature	**Critical**	Is this temperature maintained for the entire build?
Energy source parameters	**Critical**	Inclusive of programmed power, focus position, fiber diameter, pulse characteristics, current, beam offset
Digital files	**Critical**	CAD files, slice files, and build files
Purge shielding, in-process shielding	*Future*	Grade, dew point, flow rate, oxygen concentration, mixture
Post-build processing	Desirable	Heat treatment, hot isostatic pressing, chemical processing
Fill raster procedure	Desirable	Type (*e.g.*, hexagonal, collinear), overlap or width, speed
Edge raster procedure	Desirable	Type (*e.g.*, hexagonal, collinear), overlap or width, speed
Layer height	**Critical**	Ex: 40 µm
Build Chamber Temperature	Desirable	Ex: 25 °C
Build ID	Metadata	AM Bench Bridge #31
Build Date	Metadata	05/13/2021
Method of removal from build plate	Desirable	Wire EDM, band saw, *etc.*
Interlayer dwell time	**Critical**	Time between layers
In-situ data collection	Desirable	Describe make, model, measurement location, frequency, calibration date and uncertainty of any in-situ data collection instrumentation
Post-fabrication data collection	Desirable	Describe make, model, measurement location, frequency, calibration date and uncertainty of any post-fabrication data collection instrumentation

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