Designation: F3187 – 16

Standard Guide for
Directed Energy Deposition of Metals[1]

This standard is issued under the fixed designation F3187; 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 Directed Energy Deposition (DED) is used for repair, rapid prototyping and low volume part fabrication. This document is intended to serve as a guide for defining the technology application space and limits, DED system set-up considerations, machine operation, process documentation, work practices, and available system and process monitoring technologies.

1.2 DED is an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

1.3 DED Systems comprise multiple categories of machines using laser beam (LB), electron beam (EB), or arc plasma energy sources. Feedstock typically comprises either powder or wire. Deposition typically occurs either under inert gas (arc systems or laser) or in vacuum (EB systems). Although these are the predominant methods employed in practice, the use of other energy sources, feedstocks and atmospheres may also fall into this category.

1.4 The values stated in SI units are to be regarded as standard. All units of measure included in this guide are accepted for use with the SI.

1.5 *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 and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 The latest version of the specifications referenced below should be used, unless specifically referenced otherwise in the main document.

2.2 *ASTM Standards:*[2]

B214 Test Method for Sieve Analysis of Metal Powders
C1145 Terminology of Advanced Ceramics
D6128 Test Method for Shear Testing of Bulk Solids Using the Jenike Shear Tester
E11 Specification for Woven Wire Test Sieve Cloth and Test Sieves
E1316 Terminology for Nondestructive Examinations
E1515 Test Method for Minimum Explosible Concentration of Combustible Dusts
F327 Practice for Sampling Gas Blow Down Systems and Components for Particulate Contamination by Automatic Particle Monitor Method
F2971 Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing

2.3 *ISO/ASTM Standards:*[3]

52900 Additive Manufacturing—General Principles—Terminology
52921 Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies

2.4 *ASQ Standard*[4]

ASQ C-1 Specification of General Requirement For A Quality Program

2.5 *AWS Standards:*[5]

A3.0/A3.0M Standard Welding Terms and Definitions
A5.01/A5.01M Procurement Guidelines for Consumables—Welding and Allied Processes
A5.02/A5.02M Specification for Filler Metal—Standard Sizes Packaging and Physical Attributes
A5.14/A5.14M Specification for Nickel and Nickel-Alloy Bare Welding Electrodes and Rods
A5.16/A5.16M Specification for Titanium and Titanium-Alloy Welding Electrodes and Rods

2.6 *DIN Standard:*

DIN 4188 Screening Surfaces; Wire Screens for Test Sieves, Dimensions

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[1] This test method is under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.05 on Materials and Processes.

Current edition approved Sept. 1, 2016. Published November 2016. DOI: 10.1520/F3187–16.

[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.

[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

[4] Available from American Society for Quality, P.O. Box 3005, Milwaukee, WI 53201-3005.

[5] Available from American Welding Society (AWS), 8669 NW 36 St., #130, Miami, FL 33166-6672, http://www.aws.org.

2.7 *ISO Standards:*[6]

ISO 9001 Quality Management Systems: Requirements

ISO 6983-2 Numerical control of machines – Program format and definition of address words – Part 1: Data format for positioning, line motion and contouring control systems

ISO 565:1990 Test sieves – Metal wire cloth, perforated metal plate and electroformed sheet -- Nominal sizes of openings

2.8 *NFPA Standard:*[7]

NFPA 484 Standard for Combustible Metals

2.9 *OSHA Standards:*[8]

CFR Title 29, Chapter XVII, Part 1910 Occupational Safety and Health Standards

OSHA Standards Checklist: Volume 15 Welding, Cutting and Brazing

3. Terminology

3.1 DED Technology draws its terminology from several sources, particularly from the 3D printing and welding industries. Section 3.2 lists the terminology used in this guide, with many definitions referring simply to other standards issued by ASTM, ISO or AWS. Section 3.3 is then provided for the reader's convenience, re-listing some of the definitions most important to an understanding of DED so the reader of this guide does not have to cross-reference numerous other sources of information simply be able to read this guide. Please note, however, that the definitions given in 3.3 are NOT kept up-to-date as the official definitions of these terms. The reader needing the most up-to-date definition should reference the other sources listed.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *active gases, n*—gases, including those containing carbon dioxide, oxygen, hydrogen and, in some cases, nitrogen. Most of these gases, which in large quantities, would damage the deposit, when used in small, controlled quantities, can improve deposit characteristics.

3.2.2 *agglomerates, n*—cluster of primary particles held together by weak physical interactions.

3.2.3 *alloy, n*—see alloy, AWS A3.0/A3.0M.

3.2.4 *arc plasma, n*—an ionized gas, used in all arc welding process, through which an electric current flows.

3.2.4.1 *Discussion*—Arc processes suitable for DED are based ostensibly on the gas shielded processes, namely GTA, PA, PTA, and GMA, and variants thereof.

3.2.5 *as built, adj*—see *as built*, ISO 52900, and 3.3.

3.2.6 *build platform, n*—see *build platform*. **ISO/ASTM 52900**

3.2.6.1 *Discussion*—In ISO/ASTM 52900, the build platform of a machine is defined as the base which provides a surface upon which the building of the part/s is started and supported throughout the build process. In DED, the build platform can also be a component that is to be repaired, and may also be non-planar.

3.2.7 *capture efficiency, n*—fraction of powder ejected from the deposition head that is incorporated into the built structure. Usually expressed in percent.

3.2.8 *carrier gas, n*—gas, typically inert, used to transport the powder from the deposition head to the melt pool and also in some systems to assist the transport of powder from the storage system to the deposition head.

3.2.9 *cast, n—of a wire*, diameter of the circle formed by a length of wire thrown loosely on the floor.

3.2.10 *cladding, n*—see cladding, AWS A3.0/A3.0M.

3.2.11 *cross stream, n*—flow, normally of inert gas, directed perpendicular to the optical axis of the lens being protected.

3.2.12 *cycle, n*—single cycle in which one or more components, features or repairs are built up in layers in the build space of the machine. **ISO/ASTM 52900**

3.2.12.1 *Discussion*—DED is well suited to repair, feature addition and remanufacturing applications. Throughout this guide, the use of the terms "DED Build Cycle" and "DED Deposition Cycle" are synonymous, irrespective of whether a complete part is built, or a portion thereof, or a repair.

3.2.13 *defect, n*—see *defect*, Terminology E1316.

3.2.14 *deposition head, n*—the device that delivers the energy and feedstock to the melt pool.

3.2.15 *deposition rate, n*—see deposition rate, AWS A3.0/A3.0M.

3.2.16 *directed energy deposition (DED), n*—see ISO/ASTM 52900 and 3.3.

3.2.17 *feed, n*—a mechanism which delivers material, in the form of wire or powder, to the melt pool.

3.2.18 *filler metal, n*—see filler metal, AWS A3.0/A3.0M.

3.2.19 *flaw, n*—see *flaw*, Terminology E1316.

3.2.20 *focal spot, n*—see focal spot, AWS A3.0/A3.0M.

3.2.21 *functionally graded material, n*—depostied material that varies spatially in composition or structure, or both, resulting in corresponding changes in the properties of the material.

3.2.22 *gas metal arc (GMA), n*—see gas metal arc welding (GMAW), AWS A3.0/A3.0M.

3.2.22.1 *Discussion*—The word "welding" in the AWS definition conveys the joining of two or more pieces of material. As this is not the case for DED, the word "welding" is dropped. The remaining term characterizes the arc physics.

3.2.23 *gas porosity, n*—property, presence of small voids in a part making it less than fully dense.

3.2.23.1 *Discussion*—gas-filled flaws can form during the DED process or subsequent post-processing that remain in the metal after it has cooled. This occurs because most liquid materials can hold a large amount of dissolved gas, but the solid form of the same material cannot, so the gas forms flaws

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[6] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

[7] Available from National Fire Protection Association (NFPA), 1 Batterymarch Park, Quincy, MA 02169-7471, http://www.nfpa.org.

[8] Available from National Safety Council (NSC), 1121 Spring Lake Dr., Itasca, IL 60143-3201, http://www.nsc.org.

within the material as it cools. Gas porosity may present itself on the surface of the DED deposit or the flaw may be trapped inside the metal, which reduces strength in that vicinity.

3.2.24 *gas tungsten arc (GTA), n*—see gas tungsten arc welding (GTAW), AWS A3.0/A3.0M.

3.2.24.1 *Discussion*—See Discussion in 3.2.22.

3.2.25 *glovebox, n*—typically a hermetically-sealed build space or chamber, normally filled with an inert gas, within which material processing may occur. The chamber usually includes gloves, through which an operator may reach to manipulate components within the chamber without breaking the seal, hence the name.

3.2.26 *hatch spacing, n*—the lateral distance between subsequent, adjacent passes of the deposition head whilst depositing a layer.

3.2.27 *heat, n*—see definition for powder lot per ISO/ASTM 52900.

3.2.28 *helix, n—of a wire*, the vertical distance between one end of a wire and the other end formed by a length of spooled wire thrown loosely on the floor. Helix can also be referred to as "pitch".

3.2.29 *hopper, n*—the converging portion of a bin. **D6128**

3.2.30 *inert gas, n*—see inert gas AWS, A3.0/A3.0M.

3.2.31 *intermetallic phases, n*—compounds, or intermediate solid solutions, containing two or more elements, which usually have characteristic properties and crystal structures different from those of the pure metals or the terminal solid solutions. **E7**

3.2.32 *interpass temperature, n*—see interpass temperature, AWS A3.0/A3.0M.

3.2.33 *interpass time, n*—the length of time between ending a particular layer and starting the next layer, or the length of time between individual beads.

3.2.33.1 *Discussion*—Further to the AWS definition, in DED a common practice is to deposit multiple adjacent deposition beads in succession (as when following a hatch pattern on a layer), and then allow the entire layer to cool before commencing the next layer. When this term is used in DED, it should be specified whether it refers to a dwell between the deposition of individual beads or entire layers.

3.2.34 *lack of fusion, n*—flaws caused by incomplete fusion between the deposited metal and previously-deposited metal.

3.2.35 *layer thickness, n*—programmed distance between one layer of the deposited material and the subsequent layer.

3.2.35.1 *Discussion*—The programmed layer thickness may differ from the actual layer thickness obtained. The actual layer thickness is determined by factors such as the power, feedstock feed rate and travel speed.

3.2.36 *manufacturing lot, n*—see ISO/ASTM 52900.

3.2.37 *manufacturing plan, n*—a document that the purchaser may require in order to control the quality and repeatability of a deposition. A plan includes, but is not limited to the production sequence, machine parameters, manufacturing control system used in the production run, and quality checks.

3.2.37.1 *Discussion*—Manufacturing plans are typically required under a quality management system such as ISO-9001 and ASQ C-1.

3.2.38 *melt pool, n*—the region of material melted by the heat source.

3.2.39 *minimum explosible concentration (MEC), n*—the minimum concentration of a combustible dust cloud that is capable of propagating a deflagration through a well dispersed mixture of the dust and air under the specified conditions of test. **E1515**

3.2.40 *mixed powder, n*—powder composed of two or more constituent powders of different compositions.

3.2.40.1 *Discussion*—The DED process allows both the use of powders mixed prior to the start of the deposition and also mixing of powders enroute to the deposition head during the deposition.

3.2.41 *near net shape, n*—condition where the components require little post processing to meet dimensional tolerance.

3.2.42 *plasma arc (PA), n*—see plasma arc welding (PAW), AWS A3.0/A3.0M.

3.2.42.1 *Discussion*—See Discussion in 3.2.22.

3.2.43 *plasma transferred arc (PTA), n*—Plasma Transferred Arc (PTA) is a constricted arc process similar to Plasma Arc Welding (PAW) in most respects. The arc is constricted using a water-cooled small diameter nozzle which reduces the arc diameter and increases its power density. PTA differs from PAW inasmuch as it is used predominantly as a surfacing process rather than a joining process. PTA also usually uses powder feed delivery (through powder ports in the nozzle or an annular feed around the nozzle) so is more flexible in terms of the alloys that can be deposited, since more alloys tend to be commercially available in powder form than in wire form.

3.2.44 *powder blend, n*—quantity of powder made by thoroughly intermingling powders originating from one or several powder lots of the same nominal composition.

3.2.44.1 *Discussion*—A common type of powder blend consists of a combination of virgin and used powder. The specific requirements for a powder blend are typically determined by the application, or by agreement between the supplier and end-user.

3.2.44.2 *Discussion*—In traditional powder metallurgy, a distinction is made between blended powders and mixed powders, in which case blended powders start with nominally identical composition and particle morphology, whereas mixed powders are composed of powders of different compositions. See definition for *mixed powder*.

3.2.44.3 *Discussion*—If combined during the deposition process, for example by loading different powders into different feeders and combining at the point of deposition, the correct term is "mix".

3.2.45 *powder feeder, n*—see powder feeder, AWS A3.0/A3.0M.

3.2.46 *powder lot, n*—see powder lot, ISO/ASTM 52900.

3.2.47 *pre-heat temperature, n*—see pre-heat temperature, AWS A3.0/A3.0M.

3.2.48 *pre-run step(s), n*—controlled process steps to be completed prior to commencing DED material deposition.

3.2.49 *production run, n*—See ISO/ASTM 52900.

3.2.50 *purge, v*—to flush a gas supply system or component with a regulated flow of gas **F327**

3.2.51 *repair lot, n*—repaired components having commonality between feedstock lot, production run, machine, and post-processing steps (if required) as reported in single repair work order.

3.2.52 *residual stress, n*—see residual stress, AWS A3.0/A3.0M.

3.2.53 *reused powder, n*—see ISO/ASTM .

3.2.54 *screed, v*—to remove excess material using a straight edge to leave a uniform layer of powder on the build platform.

3.2.55 *secondary processing, n*—manufacturing steps required to achieve a finished form that take place after the DED process is complete. Often also referred to as post-processing.

3.2.56 *shielding gas, n*—see shielding gas, AWS A3.0/A3.0M.

3.2.57 *sieve analysis, n*—the particle size distribution of a particulate or granular solid or sample thereof, when determined by passage through and retention on a graded set of sieves. **C1145**

3.2.58 *substrate, n*—the material, work piece, part, component or substance which provides the area on which the material is deposited.

3.2.59 *trailing shield, n*—inert shielding gas applied to material trailing behind the melt pool, or a mechanical device or structure that helps contain inert shielding gas around material trailing the melt pool.

3.2.60 *virgin powder, n*—see ISO/ASTM 52900.

3.2.61 *voids, n*—flaws created during the build process that are empty or filled with partially or wholly unsintered or un-fused powder or wire creating pockets. Voids are distinct from gas porosity, and are the result of lack of fusion and skipped layers parallel or perpendicular to the build direction. Voids are also distinct from intentionally added open cells that reduce weight. Like gas porosity, voids cause a part to be less than fully dense.

3.3 *Definitions:*

3.3.1 *as built, adj*—refers to the state of components made by DED before any post-processing, except where removal from a base plate is necessary, or powder removal or support removal is required. **ISO/ASTM 52900**

3.3.2 *directed energy deposition (DED), n*—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. **ISO/ASTM 52900**

3.3.2.1 *Discussion*—Focused thermal energy means that an energy source (for example, laser electron beam, or plasma arc) is focused to melt the materials being deposited.

3.3.2.2 *Discussion*—In contrast, "powder bed" processes lay powder material out in a layer in a first step, and then direct thermal energy to melt the material as a second, subsequent step. In directed energy deposition, the provision of feedstock occurs at the same time as the provision of the focused thermal energy.

3.4 Terminology relating to additive manufacturing in ISO/ASTM 52900 shall apply.

4. Summary of Guide

4.1 This guide is intended to provide users of directed energy deposition technology information useful for the specification or use of the technology, including technology application and limits, DED system set-up, machine operation, documentation, work practices, and system and process monitoring.

4.2 This guide is arranged as follows:

4.2.1 Section 5 contains a high-level description of the features and benefits of DED, and makes some comparisons between DED and other metal 3D printing technologies.

4.2.2 Section 6 describes the machines used to perform DED. Since the DED process can take several forms, the reader should be careful to understand the different types of DED (laser/powder, electron beam/wire, arc/wire, etc.) and note which pieces of equipment are normally required for each process.

4.2.3 Section 7 discusses atmosphere control, which is an important part of all DED processes. All materials and processes, to some extent, require the removal of air and perhaps the addition of some inert gas to prevent oxidation.

4.2.4 Section 8 concerns the feedback used for DED, principally metal powder or metal wire. The features of each are discussed, and the importance of proper cleanliness and safety practices discussed.

4.2.5 Section 9 details the DED process itself, particularly how to define, measure and control the key process variables.

4.2.6 Section 10 defines how to set-up, calibrate and maintain a DED machine, so that the user can be sure that the DED process is operated in a reliable, repeatable manner in production.

4.2.7 Section 11 is concerned with post-processing of DED-produced material. A description of common inspection techniques, heat-treatments, and surface finishing processes is provided.

4.2.8 Section 12 provides an overview of safety concerns to be aware of when using DED. Note that this safety section provides an overview only, and does not provide complete safety practices to be employed.

4.2.9 Section 13 describes how to put together a manufacturing plan that could be used to implement DED in a production setting.

4.2.10 Finally, Section 14 describes how to specify a DED process. This can be used to assist in communication between suppliers, buyers, and users of DED technology to make sure all important details are communicated, recorded, and implemented.

5. Significance and Use

5.1 This guide applies to directed energy deposition (DED) systems and processes, including electron beam, laser beam, and arc plasma based systems, as well as applicable material systems.

5.2 Directed energy deposition (DED) systems have the following general collection of characteristics: ability to process large build volumes (>1000 mm^3), ability to process at relatively high deposition rates, use of articulated energy sources, efficient energy utilization (electron beam and arc plasma), strong energy coupling to feedstock (electron beam and arc plasma), feedstock delivered directly to the melt pool, ability to deposit directly onto existing components, and potential to change chemical composition within a build to produce functionally graded materials. Feedstock for DED is delivered to the melt pool in coordination with the energy source, and the deposition head (typically) indexes up from the build surface with each successive layer.

5.3 Although DED systems can be used to apply a surface cladding, such use does not fit the current definition of AM. Cladding consists of applying a uniform buildup of material on a surface. To be considered AM, a computer aided design (CAD) file of the build features is converted into section cuts representing each layer of material to be deposited. The DED machine then builds up material, layer-by-layer, so material is only applied where required to produce a part, add a feature or make a repair.

5.4 DED has the ability to produce relatively large parts requiring minimal tooling and relatively little secondary processing. In addition, DED processes can be used to produce components with composition gradients, or hybrid structures consisting of multiple materials having different compositions and structures. DED processes are also commonly used for component repair and feature addition.

5.5 Fig. 1 gives a general guide as to the relative capabilities of the main DED processes compared to others currently used for metal additive manufacturing. The figure does not include all process selection criteria, and it is not intended to be used as a process selection method.

6. Machine

6.1 The machine is defined in ISO/ASTM 52900 as the section of the additive manufacturing system including hardware, machine control software, required set-up software and peripheral accessories necessary to complete a build cycle for producing parts. The DED machine often includes hardware and software of differing natures to other 3D printing equipment, and even differing substantially among the various types of DED.

Process	Build Volume	Detail Resolution	Deposition Rate	Coupling Efficiency	Potential for Contamination
Laser Directed Energy Deposition	◕	◑	◑	◔	◕
Electron Beam Directed Energy Deposition	●	◔	◕	●	●
Arc Plasma Directed Energy Deposition	◕	◔	◕	●	◑
Lower	◔	◑	◕	●	**Higher**
This table is intended as a general guide. Variations in individual systems and process advancements may affect the characteristics of each process.					

FIG. 1 Comparison of Various Metal Additive Manufacturing Processes

NOTE 1—In this figure, Build Volume refers to the relative size of components that can be processed by the subject process. Detail Resolution refers to the ability of the process to create small features. Deposition Rate refers to the rate at which a given mass of product can be produced. Coupling Efficiency refers to the efficiency of energy transfer from the energy source to the substrate, and Potential for Contamination refers to the potential to entrain dirt, gas, and other possible contaminants within the part.

6.2 A DED system comprises four fundamental subcomponents: heat source, positioner, feedstock feed mechanism, and a computer control system. DED systems come in many shapes, sizes, and types, and commonly use laser, electron beam, or arc plasma heat sources. In all systems, the feedstock is fed directly to the junction of the heat source and the work piece. From there, the advantages of the different heat sources begin to assert themselves. Laser and electron beam (EB) have significant standoff capability and have very high energy density at the work piece compared to arc sources. On the other hand, an arc system can be less costly. Thus, each system, distinguished by its heat source and feedstock, brings certain capabilities to 3D building and repair. Those capabilities are briefly elaborated upon below and should be kept in mind when procuring or using a system. The parts of the system are as follows:

6.3 *Directed Energy Deposition (DED) Heat Source:*

6.3.1 Common heat sources include a laser (CO_2, Nd:YAG, fiber, disk or direct diode), electron beam, or arc plasma (typically GTA, GMA, PTA). Heat sources can range in power from less than 1 kW to 60 kW or more depending on the size, shape and function of the intended part, and the desired metallurgical structure for the particular application.

6.3.1.1 Laser-based DED systems utilize laser beams, with beam delivery or fiber delivery, or both, and focusing optics, to provide highly controllable energy to localized regions of the substrate. Feedstock can take the form of powder or wire. Laser electrical efficiency can be as high as 30 %, and coupling efficiency (that is, energy absorption by substrate) ranges from 5–40 % or higher depending on laser wavelength and feedstock/substrate material. Optics can be varied to produce spots as small as 50 microns diameter to produce small features, or lines up to 25 mm wide or more for large depositions. Typical laser powers for production AM systems currently range from 400–4,000 W, although higher power systems exist. Like arc-based systems, they can be operated in non-vacuum environments and thus have potential for large volume builds (in certain materials) or for deposition in the field.

6.3.1.2 DED electron beam systems are capable of providing relatively high power compared to lasers, and consequent high deposition rates with reasonable electrical power efficiency. Generally, the energy density is very high compared to lasers. However, the average energy density is easily varied through rapid beam manipulation to allow for large bead sizes. One feature of this process is the large standoff distance from the gun to the work piece that can be employed, which can be over 300 mm. In contrast, the working distance for arc processes is typically less than 25 mm. This large standoff can provide room for sensors or other ancillary equipment, and can help avoid collisions with the part, especially with non-planar substrates. The vacuum in which the electron beam typically operates can result in marked evaporation of volatile alloying elements; hence feedstock chemistry may require modification to achieve acceptable final chemistry.

6.3.1.3 Arc-based DED systems can function with a wide range of power densities and deposition rates, with high electrical power efficiency. Arc energy sources can provide a low cost heat source that enables intermediate energy density. The arc can be manipulated to deliver the heat in a variety of ways including pulsing with a variety of waveforms and frequency. This may help reduce overall heat input to the work piece. Since arc welding power sources are readily available, they can be converted to a 3D build system by combining the power source with an adequate controller and a multi-axis positioner. Today's computer control systems easily control the power source and positioner. System maintenance is often straightforward since many organizations already have capability to maintain welding power sources. Arc sources are particularly useful for performing repair. This is true of all DED systems but particularly so for arcs due to their low cost and flexibility of implementation.

6.4 *Motion Device to Manipulate the Heat Source, the Substrate, or Both:*

6.4.1 Motion is achieved either by moving the heat source relative to a stationary component, or moving the component relative to a stationary heat source, or a combination of these methods. Motion is typically provided in at least three orthogonal axes. Linear motion elements may be ball screw, toothed belt, rack and pinion, or other types. In addition, rotary axes may be employed to rotate or tip and tilt the part, to tip and tilt the end effector, or both. The molten pool can be affected by gravity, placing a limit on the substrate angle. For certain part geometries, therefore, it may be desirable to tip and tilt the part. Integrated motion of auxiliary axes (rotary, tilt axes), working with the main motion control axis (Cartesian gantry or 6-axis robotic arm), are typically used. Such systems provide for a wide array of working envelopes and thus the ability to build large or small parts, as desired, based on the motion system design and working envelope.

6.5 *Device to Feed the Powder or Wire Feedstock:*

6.5.1 *Powder Feeder:*

6.5.1.1 The purpose of the powder feeder is to deliver powder feedstock to the interaction zone in a robust and consistent manner. Powder feed systems typically include a powder hopper that serves as a reservoir for the powder, plumbing to link the hopper to the nozzles, carrier gas, and a computer controlled feeding mechanism. Some require gravity to aid in powder delivery, and others do not. If high pressure carrier gas is employed, a pressure relief valve is incorporated into the line to prevent blow-out in case of a clogged nozzle or obstruction in the line. Powder capture efficiencies can vary widely (5–95 %), with 40–80 % being typical. Powder mass flow rates fall typically between 1 and 50 g/min.

6.5.1.2 Powder feedstock works more reliably when applied in a "down-hand" orientation; in other words, gravity assists powder transport from the deposition head to the melt pool. The powder enhances absorption, leading to robust production of low heat and low dilution depositions. Generally, not all powder feedstock is melted and incorporated into the melt pool. Though reuse of powder is possible in many cases, accidental powder contamination (for example from dirt, lubricants, powder agglomerates, unfused powder exposed to high temperatures and thus oxidized, etc.) may yield undesirable material properties, and in some cases excess powder may not be able to be reused, and thus is wasted (unless it is fully recycled via remelting by the powder supplier). Powder can be fed from the side of, or co-axial to, the energy source. Coaxial feedstock delivery simplifies multi-directional depositions, and can simplify motion programming. Powders can be mixed during delivery to produce unique alloy compositions or to grade materials to ensure material compatibility, for example, from a low-cost substrate to a wear or corrosion-resistant layer, or both.

6.5.1.3 There are a variety of commercially available powder feed technologies that can fulfill this need. Many accessories, such as vibrators to reduce clogging, heaters to preheat the powder, and mixers to enable creation of unique alloys or grading of materials to achieve locally engineered properties, are common to the different powder feed options. Mass-based closed loop feedback control may also be available.

6.5.1.4 Powder feeders that utilize a worm gear or screw to feed powder consistently have been used for many years for high mass flow rate processes such as plasma arc deposition and cold spray. They employ a carrier gas to feed the powder and are not gravity fed. They can operate with non-spherical powders (which are not optimal for delivery methods requiring flowability) between 5 and 150 microns in size. If the powder hopper is located below the delivery area such that gravity is not aiding powder flow, then high carrier gas flow rates may be necessary, which can result in turbulence that is detrimental to the deposition process.

6.5.1.5 Gravity fed systems have also been developed, and come in two basic categories; mechanical wheel or disk-based systems and gas fluidized systems. Systems in the first category typically utilize wheels or disks that are fashioned with "cups" that apportion a specific amount of powder each revolution, and whose speed is controlled by the operator to set powder mass flow rate. Utilizing highly flowable, spherical powders is more important with these systems, and very small powder sizes can result in clogging within powder lines.

6.5.1.6 The second category of gravity-fed powder feeders uses gas coupled with vibrators to fluidize powder within the hopper, and another gas stream to feed the powder to the processing region. Due to the fluidizing action, these systems can flow smaller diameter powders, in the range of 2–200 microns, at 5–300 g/min.

6.5.1.7 For powder fed systems it is usual to employ a powder feed configuration with a feed hopper and carrier gas. For precision feed, an auger-type feeder is usually employed, with argon carrier gas to deliver the powder from the hopper to the deposition head. Powder feed ports are typically single, triple (120 degrees apart), quad (90 degrees apart), or concentric annular arrangements around the nozzle. Such systems usually have integrated feed tubes and nozzles such that the powder can be accurately fed in the correct relationship to the melt pool to maximize powder capture and deposition efficiencies. Dual powder feeders can be employed to feed different powders and allow a metallurgically and functionally graded composition to be produced by varying the feed rate of each powder separately.

6.5.2 *Wire Feeder:*

6.5.2.1 Wire feeder selection is dependent on the type of wire to be fed, the diameter of wire to be fed and other process considerations, for example, pulsing or hot wire capability. Wire feeder systems generally utilize either two or four drive rollers. Systems utilizing two drive rollers are usually used in compact systems for feeding small diameter wire. Systems utilizing four drive rollers are usually used in large systems for feeding large diameter wire at high rates or longer distances, or both. The system may also include a wire straightener to remove the cast and helix resulting from winding the wire on a spool. Drive roller selection is an important consideration and must be matched to wire type and diameter. Soft wires, such as aluminum, typically use a U-groove to avoid flattening the wire. Harder wires, such as titanium or steel alloys, typically use either a V-groove or textured surface to avoid slippage. In order to avoid buckling, or "birdnesting", it is important to provide support for the wire from the output of the drive rollers to the delivery point. This becomes more important with softer wires such as aluminum alloys.

6.5.2.2 Due to a large arc welding market, wire feedstock is readily available from a variety of sources in a wide range of weldable alloys. Additionally, most of the feedstock is consumed during the process, so wasted material, process waste stream, and any need to reuse or recycle feedstock are minimized. Readily available wire diameters range from 0.75 to 3 mm or greater for many materials. Smaller and larger diameters can be custom made. Smaller diameter wires can provide a higher level of detail in the deposit, but at a reduced deposition rate. Larger diameters can help dramatically increase deposition rate, as the deposition rate is proportional to the square of the diameter, with an appropriate increase in the energy input. However, this increase in deposition rate comes at the cost of reduced level of detail in the deposit.

6.5.2.3 Modern wire feeders provide the capability to pulse, where the wire feed rate is pulsed in the range of tens or hundreds of Hz, in synch with the heat source. This enables an efficient use of energy during deposition, that is the maximum wire feed rate is used when the maximum heat pulse is employed. This can assist in minimizing total heat input. Wire pulsing is limited by the capability of the electro-mechanical system to actually match the frequency of the heat pulse. Finally, the pulsing of the wire can give a relatively fine surface finish when used properly. Typically, finer surface finishes result from higher frequencies.

6.5.2.4 In a hot wire feed system the wire is heated prior to entering the melt pool. This may improve deposition rate for a given heat source power, as less heat is required to melt the wire. It may also improve the level of detail and surface appearance, as a smaller melt pool may be used. This approach may currently be used with laser, arc or electron beam heat sources.

6.5.3 *Deposition Head:*

6.5.3.1 The Deposition head, also sometimes known simply as the "head", or the "end effector", is the device that delivers the energy and feedstock to the melt pool. The deposition head is often only centimeters from the melt pool, and if so, must be designed to be durable to withstand the heat and reflected energy from the melt pool.

6.5.3.2 *Common Features*—Laser powder deposition head.

(1) A deposition head used for laser powder deposition may have the following common features:

(a) Laser Collimator—The laser is often delivered to the deposition head through a fiber, or direct from the laser in the case of CO_2 lasers. If fiber delivered, the end of the deposition head furthest from the melt pool often consists of the laser fiber, and a collimator. The collimator's purpose is to expand the laser beam and collimate it so that it moves straight through the deposition head to the focusing lens. Collimators are often provided by the laser manufacturer or specialty laser optics providers.

(b) Beam Shapers/Redirection—After the collimator, the deposition head may contain other laser optical elements to serve specific purposes. For example, the laser beam may be converted to a rectangular shape rather than a round beam, or it may be turned by 90 degrees if necessary for the specific configuration of the system.

(c) Sensors—Many deposition heads contain sensors, such as vision cameras, thermal imaging cameras, or closed-loop controls. The sensors may view the melt-pool directly, or may view the melt pool via a beam-splitter, which can be used to enable multiple sensors to view the melt pool together.

(d) Focusing Optic—The focusing optic focuses the collimated laser beam onto the work piece. Typically, transmissive optics are used for this purpose, though reflective optics are sometimes used with high power laser beams. The focal length for this optic is often in the range of 150–200 mm. The lens may be water-cooled, particularly if the deposition head is operating at high power. This water cooling is normally provided by cooling the lens holder.

(e) Cover Glass—After the focusing lens, the laser beam then typically passes through a cover glass slide, which is a replaceable optic designed to keep the more expensive focusing optics clean. The cover glass may become dirty during use, due to fumes and spatter from the melt pool. When overly dirty, the cover glass can affect the transmitted laser energy and must be replaced. Some means to easily remove and replace the cover glass is often employed.

(f) Purge Nozzle—Close to the workpiece, the laser normally passes through a final orifice, through which inert gas is usually flowing toward the workpiece. This inert gas purge can serve two purposes. The flow of gas impedes the ingress of spatter and fumes from the workpiece into the deposition head, thus keeping the interior components, particularly the optics, clean. The purge is also used to provide an inert shielding gas over the melt pool, thus reducing oxygen levels around the melt pool (which reduces oxidation) and thereby improving the quality of the deposited metal. This forced flow also serves to increase convective cooling of the substrate, when compared to natural convection alone.

(g) Powder Delivery Nozzles—The powder may be delivered in several ways, but all are designed to provide a steady stream of metal powder aimed generally at the melt pool. The powder may be delivered through one or more discrete nozzles surrounding the purge nozzle or can be delivered from a single direction. Alternatively, there may be a cone arrangement where there is effectively one powder nozzle that completely surrounds the purge nozzle. This arrangement may be referred to as a coaxial nozzle.

6.5.3.3 Important considerations for the laser powder deposition head include:

(1) Heat Load—The deposition head may be heated by the laser beam itself as it passes through the head, as well as by heat radiating from the melt pool. As the laser power increases beyond 1 kW, active cooling is typically required, and may become a significant design consideration as the power increases beyond 4 kW. Heat can cause the laser optics to break, or distort, and can increase the likelihood of powder becoming stuck in and clogging the powder nozzles rather than exiting freely.

(2) Atmosphere Control—When laser powder deposition occurs in a fully contained inert atmosphere, such as provided by a glovebox, the deposition head may not need to provide additional shielding gas. When laser powder deposition occurs in an open environment, the deposition head must be employed, in part to provide a local shield of inert gas onto and around the melt pool. Inert gas flowing through the deposition head to deliver feedstock or protect optics can also assist in shielding the molten pool and substrate during deposition.

(3) Alignment and Adjustability—Most deposition heads offer some degree of adjustability. These may include adjusting the focal position of the laser, adjusting the focal position of the powder, etc. It is usually important to ensure that the powder focal point is coincident with the laser beam at the substrate.

6.5.3.4 *Common Features*—Electron beam wire deposition head.

(1) A deposition head used for electron beam wire deposition may have the following common features:

(a) Focusing Coils—Electron beam guns used for DED typically use a focused electron beam, rather than a wide, defocused beam, in order to control the size of the melt pool. Electromagnetic coils are used to control beam focus over the, typically, large working envelope of the electron beam gun. Focal spot size can range from fractions of a millimeter to several millimeters in diameter.

(b) Deflection Coils—The electron beam may be magnetically deflected at very high rates to provide several process functions. The focused beam may be deflected in a pattern designed to control the width of the melt pool. The beam may also be "time shared" to provide pre- or post-heat of the deposit, as well as other functionality.

(c) Sensors—Modern electron beam guns typically have coaxial camera systems, which provide a view of the melt pool. Other sensors, such as IR cameras, spectrometers and closed loop control systems may be incorporated.

(d) Wire Delivery Nozzles—One or more wire delivery nozzles may be attached to the deposition head. Multiple wire feeders provide increased process flexibility.

6.5.3.5 Important considerations for the electron beam wire deposition head include:

(1) Heat Load—Electron beam guns used for DED are typically derived from welding systems. The workpiece in a DED system may experience continuous temperatures in excess of 600°C during deposition, while a welding system

typically does not experience continuous temperatures of that magnitude. Therefore, the cooling system for the electron beam gun needs to be able to handle this heat load. Higher power guns typically use a chilled water cooling system, however, smaller guns may be cooled by conduction through the manipulator or vacuum chamber. The positioning system, motors, gears, etc., also need to be able to handle this heat load.

(2) Atmosphere Control—Electron beam DED is typically operated in the high vacuum, 10^{-2} Pa, regime. At these pressures, no additional shielding is required, as the residual gas concentration is low enough to have little, or no, effect on material properties.

(3) Alignment and Adjustability—Most deposition heads offer some degree of adjustability. These may include adjusting the focal position of the electron beam, adjusting the entry angle, height and position of the wire, etc. It is important to ensure that the wire entry height is such that molten wire dripping does not occur.

6.5.3.6 *Common Features*—Arc plasma wire.

(1) A deposition head used for arc plasma wire deposition may have the following common features:

(a) A torch with either a consumable electrode (Gas Metal Arc (GMA)) or a nonconsumable electrode (Gas Tungsten Arc (GTA), Plasma Arc (PA), or Plasma Transferred Arc (PTA)). In the case of torches used with a nonconsumable electrode process, a wire feeder is also part of the deposition head. The PTA process, a derivative of PA, is typically used with powder feed heads. Torches may be gas or water cooled, with the latter more typical for higher duty cycle operation expected in DED processes.

(b) Atmosphere Control—Shielding gases delivered through the torch are used largely for protection of the molten weld pool from oxidation, and usually comprise inert gases for GTA, PA, and PTA processes, and inert or combinations of inert and active gases for GMA. The choice of gas is influenced by process and material selection.

(c) Power Supply—A power source to provide welding power to the arc. This can be constant current (CC), constant voltage (CV), or CC/CV, with or without current pulsing, depending on the DED process selected. A CC power source is typical for GTA, PA, and PTA operations, while a CV or CC/CV power source is used with GMA.

6.5.4 Process chamber or appropriate process environment or working envelope, build space.

6.5.4.1 All DED processes require careful control of the working environment. To ensure that the deposited metal is free of gaseous contamination, appropriate processing environments need to be considered for each type of heat source: laser beam, electron beam, and arc plasma.

6.5.4.2 DED systems that use localized shielding will typically be able to accommodate larger parts than systems that use an inert gas glovebox or vacuum chamber. The desired part size should be considered when specifying the working envelope.

6.5.4.3 For DED systems that use a laser or arc heat source and powder feedstock, an inert gas-fed glovebox in conjunction with a recirculating gas purifier system is recommended. An antechamber of appropriate size is commonly used to minimize processing chamber contamination during loading and unloading of substrates and parts, respectively. Auxiliary atmosphere control devices, such as refrigeration units or trace gas sensors, should be included based on the AM system manufacturer's recommendation. Any windows should be laser safe with the appropriate optical density (OD) and intended use wavelength requirements.

6.5.4.4 For DED systems that use a laser or arc heat source and wire feedstock, and for some laser-powder applications, a local inert-gas shield may be utilized. The work area should be adequately contained and climate controlled to minimize moisture. The flow rate of the inert gas should provide adequate shielding of the melt pool and adjacent heated metal, while maintaining a stable melt pool and minimizing gas waste. A local exhaust system may be positioned close to the laser heat source to minimize contamination of the laser optics surfaces from process emissions. The exhaust system can be used in conjunction with a localized cross-stream of inert gas to prevent laser optics contamination. Care should be taken in adjusting the flow rates of the inert gas cross-stream and exhaust system so that they do not cause turbulence that entrains oxygen, nitrogen, or moisture into the inert gas supply used to shield the melt pool and adjacent heated metal. HVAC units in the vicinity of the work area should be adjusted to minimize cross-currents of air near the process heat source.

6.5.4.5 For AM systems that use an electron beam heat source and wire as a feedstock, a vacuum chamber is normally used to minimize beam spreading and to mitigate part contamination.

6.5.5 *Toolpath Generation System and Software:*

6.5.5.1 While it is possible to manually write the code required to control a DED system, it is often preferable to have software to automate the process. The steps typically required are:

(1) Conversion of the 3D CAD file of the part to a DED machine readable format, such as STL or AMF.

(2) Slicing the machine readable file into individual layers corresponding to the layer thickness being deposited by the DED system. When the build direction is kept constant, the slicing results in parallel layer data. Adaptive slicing algorithms can be employed for 5-axis motion systems where the build direction can vary during manufacturing, resulting in non-parallel layer data.

(3) Conversion of the individual layers, or "slices", of the part to the motion and process control format for the DED system, typically comprising contours to define the perimeter or each slice, and hatching to fill in the contours.

(4) The software may also offer additional features, such as the ability to remove artifacts resulting from the conversion process or the ability to nest multiple parts in the build envelope.

(5) The software may be embedded in the machine in the as-purchased condition, or may be provided by a third party.

6.6 *Control System:*

6.6.1 The hardware and software of the control system should provide (at a minimum) the following functions:

6.6.2 The motion subsystem is a critical component of the DED process, requiring not just point-to-point accuracy, but also tight control of the path and velocity traveled between points. The system should be able to control the position, orientation, and velocity of the deposition point.

6.6.2.1 *Hardware:*

(1) Linear and rotary axes are typically actuated with servomotors. Position and velocity are typically determined through relative encoders, although some systems may add absolute encoders or an optical glass scale to lend confidence to the reported position. Stepper motors are generally not used for DED due to their lower accuracy.

(2) The motion processor may be a separate processor or the motion processor may run as an embedded function in the supervisory processor (see 6.6.4).

6.6.2.2 *Software:*

(1) Cartesian motion systems are typically controlled using a version of standard computer numerical control (CNC) programming language, also known as G-code (ISO 6983).

(2) Commercial articulated arm robots are typically driven with proprietary programming languages specific to the robot geometry.

6.6.3 Other major subsystems, such as power, feedstock delivery system, and environmental chamber, will have input channels for controllable functions and output channels for reported values.

6.6.3.1 The power source has controls for on/off, power ramp rate, power level, and other parameters such as beam shape or beam deflection, or both.

6.6.3.2 The material feed sub-system controls feed rate and mix ratios in the case of multiple material feed systems. Material feed sub-systems often have the capability to alert the user if the feedstock hopper is empty or feedstock flow is interrupted.

6.6.3.3 The environmental chamber control sub-system controls flow of shield gas or sequencing of vacuum pumps, and may monitor oxygen content in the process environment.

6.6.4 *Supervisory Functions:*

6.6.4.1 Supervisory control is typically instituted on a programmable logic controller (PLC) or personal computer (PC). Supervisory control coordinates the actions of the various subsystems, responds to the human machine interface, monitors interlocks, and controls safety systems. It may also provide a storage system for recipes that contain parameters for a given task. The software and programming language used will depend on the DED platform.

6.7 *Process Monitoring, Controls and Recording:*

6.7.1 A wide range of sensors can be utilized with DED processes in order to measure various process parameters and characteristics. Data from these sensors can be used for real time process monitoring, data logging for statistical process control and archival reporting, and as feedback for closed-loop control.

6.7.2 Process parameters, such as heat source power, travel speed, material feed rate, and environment sensors (to monitor vacuum level or oxygen content) are often directly available as output from the DED subsystems. These can be monitored to ensure that process setpoints remain consistent throughout a build.

6.7.3 Additional sensors can be introduced to monitor other process characteristics. Examples of such sensors include co-axial imaging sensors (visual or IR) to monitor the melt pool, displacement sensors to monitor standoff, non-contact pyrometers to monitor local temperature, and spectroscopes to monitor optical emissions. Other sensors may also be employed.

6.7.4 Data collected from these sensors can be used in raw form, or it can be processed with algorithms to reduce the data into a more useful form, for example, estimating the width of the molten pool from coaxial imaging data.

6.7.5 In addition to real time or archival data reporting, or both, the data can be utilized in a control system to adjust the process variables in real time for improved quality. Examples include adjustment of heat source power based on perceived melt pool size to maintain consistent fusion width or control of material feed rate to maintain consistent layer height.

6.8 *Calibration:*

6.8.1 *Mechanisms and Systems and Methods:*

6.8.1.1 Calibration of any mechanism is crucial. No matter what the capability of the technology, when used for production the user and recipient of the products must be comfortable that the product they receive is what was intended. Manufacturing today is performed with calibrated equipment and if AM is to take its place in the manufacturing world, the purchaser and user must know that the AM system is accurate and repeatable.

6.8.1.2 The items needing calibration are numerous, including the heat source, positioner, feedstock feed and control system. The heat source must deliver the power required accurately to each location and must do so reliably. Too little heat at a given location can result in an unmelted portion, however small, thus introducing a flaw. Conversely, too much heat can enlarge grain size, affect surface finish, and add to the overall heat contained in the substrate, which may impact distortion and residual stresses. The intersection of the heat source with the substrate must be in the correct location to accurately build the shape. Likewise, the feedstock must arrive at the correct location in the proper amounts with respect to substrate. Any control system is vulnerable to faults, either as a result of failed hardware or programming error. Thus, comprehensive self-test routines may be warranted for inclusion in the overall calibration and maintenance program. The calibration recommendations of the manufacturer must be followed, as a minimum. The user may even want calibration checks to occur more frequently than recommended, and implementation of more rigorous checks may be considered based on experience.

6.9 *User Manual:*

6.9.1 At a minimum, the equipment manufacturer's supplied user manual should contain any critical safety warnings, operating instructions for the equipment, including procedures for emergency stops, maintenance instructions, including required frequency, and calibration instructions, including required frequency and test equipment.

7. Atmosphere Control

7.1 *Introduction*—Most materials commonly used in DED processes will react with oxygen, nitrogen, moisture in air, or combination thereof, forming significant oxides or nitrides, or both, on the surface, and gas porosity within the deposited metal. As with fusion welding processes, air is normally excluded from the vicinity of the DED process in order to prevent oxide scale formation. Processing atmosphere is typically controlled by operating in a vacuum; with a local inert gas purge; or with a fully inert gas purged enclosure. The presence of oxygen is one of the most significant causes of poor quality in DED processes. If the material is deposited in the presence of even a relatively small quantity of oxygen, there will be a thin layer of oxide on the surface of the deposited layer. When the next layer is deposited, that oxide layer may cause lack of fusion or porosity, or both, to form in the next layer. This process repeats as more layers are added, with potential to produce porosity and lack of fusion throughout the part. The degree of porosity is dependent on several factors: the material being deposited; the oxygen concentration at the melt-pool; the oxygen concentration away from the melt pool; the temperature of the top of the part; and the time at which the part is at high temperature. Process specifications will typically provide a permissible concentration of oxygen or nitrogen, or both, in the process environment. Oxygen levels at the melt pool typically need to be less than 100 parts per million (ppm), and are often specified at less than 10 ppm for oxygen-sensitive materials such as titanium. Extremely oxygen-sensitive materials, such as some rare-earth materials, may require oxygen levels to remain below 1 ppm to be successfully deposited without excessive porosity. Other materials that may need special considerations include aluminum, wherein hydrogen can be a significant source of porosity.

7.2 *Vacuum:*

7.2.1 Processes using an electron beam energy source are normally operated in a vacuum environment; processes using a laser may be operated in a vacuum environment, but typically are not. Processes that operate in a vacuum environment typically use feedstock in the form of wire, which is mechanically fed from a spool. While it is possible to use feedstock in the form of powder in a vacuum, it is difficult, as the powder flow is typically assisted by an inert carrier gas, which adds to the vacuum pumping load. Electron beam systems typically require a vacuum level of 10^{-2} Pa or lower. Vacuum chambers are typically constructed from steel, stainless steel or aluminum. The vacuum chamber must provide adequate strength to withstand the pressure loads involved, as well as shielding from X-rays in the case of an electron beam. There are many types of high vacuum pumps available; selection of pump technology is based on chamber size, desired vacuum level, speed of pumping, and cost. Examples of high vacuum pump technology are turbomolecular pumps, diffusion pumps, and cryogenic pumps. A properly sized vacuum system should attain a usable vacuum level in 15–60 min. Processes operated in a vacuum typically have extremely low contamination with oxygen or nitrogen. Unless special airlocks are incorporated with the equipment, the chamber must be vented to atmosphere to remove parts. DED processes operating in a vacuum produce metal vapor, which condenses on surfaces within the chamber. If this vapor deposit is permitted to accumulate, it will increase the chamber pumping time, coat the optics and windows and may flake off and land on the part.

7.3 *Local Inert Gas Shielding:*

7.3.1 Local inert gas purge is commonly used with arc plasma processes and may be used with laser processes. Local inert gas shielding typically protects the area around the melt pool until it solidifies and cools to the point where it will not oxidize. For some more reactive materials such as titanium, a trailing shield, which provides additional shielding behind the molten pool, may also be used. Typically, the gases used are inert, such as argon or helium, but quantities of active gases, such as hydrogen, may be added with some processes and materials. Excessive gas flow rate is to be avoided from both a cost and quality standpoint; excessive flow rate can lead to turbulence, which will entrain air, leading to deposit contamination. Local inert gas shielding will typically produce the lowest quality components, however it is also the lowest cost and quickest option, with a usable atmosphere achieved in seconds. Local inert gas shielding is usable with all materials, although there is increasing difficulty in obtaining an acceptable deposit quality with oxygen-sensitive materials such as titanium.

7.4 *Full Inert Gas Enclosures (Chambers):*

7.4.1 Full inert gas enclosures are often used for laser processes, although they may be used with arc plasma processes as well. The full environmental chamber is normally constructed to similar specifications as a glovebox. Indeed, gloves are often provided so the user can reach inside the system to manipulate parts. Full environmental chambers usually include some gas purification system to continuously remove oxygen and moisture from the chamber gas. These gas purification systems run continuously, and if sized properly, with a suitably leak-free chamber, can provide oxygen levels as low as 1 ppm in the chamber. Key design considerations for the enclosure include: suitable leak-proof construction; oxygen gettering system suitably sized to allow continuous low-oxygen operation; some type of antechamber to allow parts and tools to be loaded and unloaded without opening up the chamber to ambient air; windows to allow the user to view the process, with laser safety glass to ensure safe operation; overpressure safety protection. Drawbacks of the full environmental enclosure center on the difficulty of moving parts easily into and out of the enclosure. Once inside the enclosure, the parts may be inaccessible to the operator's reach, and thus complex parts handling systems may be needed. The interior of the chamber may also become hot with continuous operation at high power, so cooling schemes may need to be employed.

8. Feedstock

8.1 *Introduction*—Feedstock is considered to be the raw material that is deposited in a DED system to build up features or geometries. Feedstock for DED is delivered to the melt pool in coordination with the energy source. Feedstock is commonly in either powder or wire form. Purchasers of feedstock for DED should be careful to exactly specify the material required, and should obtain a certificate of conformance from the feedstock supplier to verify that the specification has been met.

8.2 *Powder Feedstock:*

8.2.1 *General Comments*—It is important to carefully specify, handle, and control powder in order to produce high quality deposition. Chemical composition and impurities in feedstock dictate final deposition chemistry. Contaminants such as surface oxidation, scale, moisture, solvents, and lubricants can result in formation of inclusions or porosity. Particle size, morphology, and particle size distribution impact flowability and can contribute to clogging and process instability. In some cases, powders can be blended to produce unique alloy chemistry or to grade material composition. In some cases, powders can be reused or recycled. Powdered metals pose safety hazards that must be addressed.

8.2.2 *Specifying Powder:*

8.2.2.1 *Chemical Composition*—Chemical composition and impurities in feedstock dictate final deposition chemistry and properties. It is recommended that powder should be specified to ensure the composition after processing meets requirements.

8.2.2.2 *Pre-alloyed vs. Mixed*—Powder may be pre-alloyed or mixed, or both. For pre-alloyed powder, each powder particle reflects the composition of the alloy. Examples include 316L, IN625, and Ti-6Al-4V powders, wherein each powder particle will have the chemistry of the alloy. For mixed powders, elemental powders are combined to produce a specific mean composition. In this case, elemental powders may be pre-mixed using orbital mixers or shakers to create the required mean composition. Mixed powders may be used to minimize cost of the powder feedstock material. The use of mixed powders should be agreed upon between the AM manufacturer and the part purchaser. Prealloyed powders typically result in more uniform chemical composition in the final product. Mixed powders can result in local segregation of chemical composition, so extra care must be taken to assess and mitigate the risk of segregation by maintaining uniform distribution of the individual powders. Note that in some circumstances, a combination of mixed and pre-alloyed powders are used intentionally. For example, a common combination is to use a tungsten carbide powder with a nickel alloy matrix. The tungsten carbide is intentionally not melted during deposition, but remains as discrete particles within a nickel alloy matrix.

8.2.2.3 *Particle Size, Morphology, and Particle Size Distribution*—Particle size distribution and powder morphology impact flowability, which can contribute to clogging and process instability, and should be specified as recommended by the DED system supplier. Powder size is often specified in terms of mesh size, which corresponds to the number of openings per inch, for example, a 100 mesh screen has 100 openings per inch (25.4 mm), therefore the larger the mesh size, the smaller the particle size. Since mesh wire may be different diameters, in general mesh size is not a precise measurement of particle size. However, mesh size has been standardized (as in Specification E11, ISO 565:1990, DIN 4188, and others) and conversion charts that relate mesh size to particle size in microns are readily available. Particle size may be specified as –100/+325 mesh, which means 90 % of particles will pass through a 100 mesh (149 by 149 micron square gaps) and be retained by a 325 mesh (44 by 44 micron square gaps) sieve (theoretically corresponding to particle size diameters of 44–149 microns). Other methods are available for measuring powder particle size and morphology, including techniques that use laser diffraction/scattering. Sieve analysis for incoming powder can be made in accordance with Test Method B214, by particle size distribution analysis, or as agreed between component supplier and purchaser.

8.2.2.4 *Contaminants*—Contaminants such as surface oxidation, scale, moisture, solvents, and lubricants, can result in formation of inclusions or porosity, and should be avoided, or, if unavoidable, be carefully monitored and controlled.

8.2.3 *Handling and Controlling Powder:*

8.2.3.1 *Receipt*—Upon receipt from the material supplier, powder should be inspected to ensure it is free of contaminants and a valid and complete lot matching certificate of conformance is present.

8.2.3.2 *Storage*—Powder should be stored in a conditioned environment that limits exposure to environmental contaminants. Alloys especially susceptible to oxidation or moisture should be stored in a dry, inert gas environment.

8.2.3.3 *Handling*—Powder should be handled in a safe manner that limits opportunity for contamination, for example, cross contamination with powders used in earlier processing, foreign materials, lubricants, etc. Additional important safety considerations are discussed in 8.2.6.

8.2.4 *Grading Composition*—Powders may be mixed during deposition to create functionally graded parts. For example, low cost carbon steel may be deposited for the bulk of a component, but regions that will be exposed to seawater may be graded to a nickel-based alloy for improved corrosion resistance. Or, a low cost steel deposit may be graded to incorporate increasing amounts of hard ceramic particles on a surface subject to wear. Such functionally graded materials are typically produced by varying the feedstock composition during a build-up, either by continuous adjustment of the feedrates of multiple powder feeders, or through discrete changes in powder composition. Note that compatibility of materials is a key consideration, as materials may be insoluble or can result in formation of brittle intermetallic phases or other undesirable compounds. or both.

8.2.5 *Reusing Powder*—When reusing powder, all powder should be sieved to remove agglomerates and contaminants. Sieve analysis (via B214) or particle size distribution analysis can be used to assess changes in particle size distribution that can impact process quality. Reused powders may be blended with virgin feedstock so long as they are not heavily oxidized or bonded to other powder particles as agglomerates. Reused powder is only permissible if its use is agreed in advance between the supplier and the purchaser. The maximum number of times powder can be reused, as well as the number of times any portion of a powder lot can be processed in the build chamber, should be agreed upon between component supplier and purchaser. For each new blended powder, an appropriate characterization criteria and manufacturing plan documentation should be agreed upon by the component supplier and purchaser.

8.2.5.1 Note on terminology: Powder which is reused is often referred to as “recycled” powder. Here we use the term “reused” instead of “recycle” to differentiate between reusing powder directly within the DED process (typically after post-process sieve), and recycling powder by, for example, returning powder to the powder supplier to be remelted.

8.2.6 *Powder Safety:*

8.2.6.1 Powders present a variety of hazards, including fire and personal health. In addition to the information in this section, consult Section 12 of this standard, and the powder Safety Data Sheet (SDS).

8.2.6.2 *Personal Protective Equipment (PPE)*—Powders may cause skin and eye irritation. Proper gloves, clothing, and eyewear should be worn to avoid exposure. Dust masks and, in some cases ventilators, should be used to avoid inhalation of the powders during handling and distribution into powder feed mechanisms. It may be appropriate to consider wearing appropriate protective clothing to prevent injury in the case of a flash fire. Applicable safety standards must be met.

8.2.6.3 *Storage*—Powder feedstock should be stored in sealed containers and in accordance with supplier and purchaser recommendations. If excess moisture is suspected, a baking procedure can sometimes be used to dry out the powder before use. Any powder not used for processing should be stored remote from the processing area, preferably in another location of the facility that does not contain an ignition source. Processed powder that will not be reused should be contained within sealed containers until final disposal occurs. Metal powder should be kept dry and stored in moisture-resistant containers or bins. Powders may need to be stored under inert atmosphere or vacuum to prevent contamination. In addition, powders may need to be agitated prior to use to ensure a uniform distribution of different particle sizes.

8.2.6.4 *Handling Powder*—Powder that accumulates in processing areas should be removed via vacuum that contains static-charge control capability. For reactive powders, such as certain aluminum or titanium alloys, explosion-proof vacuums should be considered. Accumulated powder should be regularly removed from the DED system to avoid ignition during processing. Vacuums and ventilation equipment that collect fine powder particles should be regularly cleaned and emptied according to the manufacturer specifications to avoid accumulation. Powders should be kept from becoming airborne during handling and disposal. Proper handling and use of powder should be performed in accordance with the Safety Data Sheet (SDS) included with the powder product, and all other applicable safety standards.

8.2.6.5 *Fire Hazards*—Fires can be caused by the presence of powder, an ignition source (heat source), and oxygen. Class D fire extinguishers (for combustible metals) should be readily available in the vicinity of the powder storage area and working area. Powders should be used in the absence of oxygen whenever possible, such as in an inert gas-filled glove box, to avoid fire hazard. All applicable safety standards should be employed, including National Fire Prevention Association (NFPA) code 484.

8.2.6.6 *Explosion Hazards*—Explosions can occur when a powder dispersion is in a contained area with an oxygen source, a powder supply (fuel), and an ignition source. For reactive powders, the ignition source can be interparticle friction. Concentrations of powder in the work area atmosphere should be kept well below the minimum explosible concentration (MEC) for each specific metal powder used. Users should follow all instructions listed on the Safety Data Sheet (SDS) according to Fire and Explosion Hazard Data, Reactivity Data, Health Hazard Data, Precautions for Safe Handling and Use, and Control Measures.

8.3 *Wire:*

8.3.1 *General Considerations*—It is important to carefully specify, handle, and control wire in order to produce high quality deposition. Chemical composition and impurities in feedstock dictate final deposition chemistry. Contaminants such as surface oxidation, scale, moisture, solvents, and lubricants, can result in formation of inclusions or porosity. Wire feedstock poses certain unique safety concerns that must be addressed.

8.3.2 *Specifying Wire*—Due to the extensive and long-term use of wire feedstock in arc welding, there are numerous standards available. AWS A5.01/A5.01M and AWS A5.02/A5.2 can be used to specify wire for arc, laser, and electron beam operations. Specific standards for nickel, titanium and their alloys are contained in AWS A5.14/A5.14M and AWS A5.16/A5.16M. Similar specifications exist for other alloy systems. Precision layer winding is important for many applications involving robotic applications, and particular attention to wire surface cleanliness is recommended for meeting low interstitial content. In some cases, alloying elements with low vapor pressure, such as Al in Ti alloys, should be specified with higher concentration than desired in the final product, in order to account for evaporation during deposition. Wires used for DED are commonly pre-alloyed, solid wire. Occasionally, cored wires may be used with a metallic sheath that surrounds a powder core. In these cases, the wire should not normally contain any flux, as can be found in flux-cored wires. Flux is not used in the DED process, as the slag formed by the flux would need to be removed, thus preventing automatic layer-by-layer build-up.

8.3.2.1 *Wire Diameter*—Selection of wire diameter depends on the feature sizes and deposition rate desired. Typically, larger wire diameters are employed for larger features and higher deposition rates, and smaller diameters are employed for lower deposition rates and small features. Wire diameters typically range from 0.75 to 3.2 mm, although larger sizes can be used. For laser processes, the focused spot size will typically determine the wire size selected. For electron beam deposition, larger diameter wires are commonly used.

8.3.2.2 *Finishing*—AWS A5.02 can be used to specify characteristics such as finish and uniformity, packaging and winding. It is recommended that spools, if used, are constructed of plastic, metal or other nonporous material for vacuum compatibility and to avoid moisture absorption.

8.3.3 *Safety*—Wire feedstock can have sharp ends and can have a tendency to uncoil. For this reason, gloves and eye protection should always be worn when handling wire.

9. Process

9.1 A key aspect to any DED process is heat input and its control. Generally, the heat input per length of deposition depends on the power input and travel speed. For electrically based systems such as electron beam and arc the power is related to the voltage and current. Power is typically varied over a wide range. At the lower end, the melt pool is small and finer surface finish can be achieved, but rate of deposition is sacrificed. At the higher end, very high deposition rates can be achieved, but surface finish will probably be rougher.

9.2 Key process variables ("essential variables" or "critical variables") are those variables that, if changed, will affect the mechanical (or other) properties of the finished build. They should be recorded and should not be changed without requalification. Any of these key process variables may be controlled using an open or closed loop control system. For DED, they include (but are not limited to):

9.2.1 *Energy Source:*

9.2.1.1 *For Laser:*

(1) Laser wavelength—Typically either a ~1.07 µm laser in the fiber laser, disk laser or Nd:YAG laser class is used, or a 10.6 µm CO_2 laser. Other wavelengths can be used for specialized applications.

(2) Laser power (or pulse (duty cycle) conditions)—Typically a continuous wave (CW) laser is used.

(3) Spot size at the part—The laser beam is normally defocused at the part, although it can be used at focus. The size of the laser beam on the part significantly affects the intensity (power density), and so is normally specified.

(4) Beam profile—A beam profile provides full information on the intensity of the converging/diverging laser beam, and may be specified if there is a significant change in the position of the focal point in relation to the part surface during deposition. These are defined, in part, by the laser transverse electromagnetic mode (TEM) and the laser beam quality (M^2). Note that the beam polarization may also impact processing.

(5) Position of focal point—In addition to the working spot size, the actual position of the focal point can be important since variations in the standoff from the deposition head to the part may affect the actual spot size due to the converging/diverging laser beam.

9.2.1.2 *For Electron Beam:*

(1) Electron Beam Power (or Pulse Condition)—Electron beam systems are typically operated in a constant power mode.

(2) Spot Size at the Part—The electron beam spot size is a function of the focus parameters used and the gun-to-work distance. The effective spot size can be modified through use of beam rastering. More complex beam manipulation may also be employed.

(3) Position of Focal Point—The electron beam can be under focused, that is, the focal point is below the surface of the workpiece, sharp focus, or over focused, that is, the focal point is above the surface of the workpiece. These conditions are strongly dependent on a constant gun-to-work distance.

9.2.1.3 *For Arc Plasma:*

(1) Arc Power—Arc plasma systems may be operated in either constant current (CC), constant voltage (CV) or pulsed modes. In pulsed mode operation, the wire feeder is typically pulsed to match the power pulses. Pulsing helps to control heat input to the process.

(2) Arc Length—Feedback control units must be employed to regulate the arc length during the arc plasma process. For GTAW power supplies, constant current is utilized to maintain the arc length between the non-consumable tungsten electrode and the part being built, while the consumable feedstock wire is fed at an acute angle with respect to the horizontal axis of the part. For GMAW power supplies, constant voltage is utilized and is linked with the wire feeding mechanism to actively control arc length between the consumable feedstock wire and the part being built.

9.2.2 *Materials:*

9.2.2.1 *Base Material Alloy*—This is the material on which DED is being performed.

9.2.2.2 *Filler Material Alloy*—This is the chemistry and specification of the powder or wire feedstock being used.

9.2.2.3 *Feedrate*—This is the rate at which the feedstock is being delivered to the melt pool. In the case of powder fed DED, not all the powder that is fed will enter the melt pool. Care must be taken to clarify whether the feed rate corresponds to the rate of material provision or the rate of material deposition.

9.2.2.4 *Powder Capture Efficiency*—This is the percentage of powder provided that actually becomes part of the final deposition, as opposed to the unfused powder that is not consolidated in the part.

9.2.2.5 *Powder (or Wire) Characteristics*—Powder characteristics include the particle size range, method of manufacture, chemistry, shape of the powder particles, and flowability. Wire characteristics include wire diameter, chemistry, and the method of manufacture.

9.2.3 *Environment:*

9.2.3.1 *Chamber Gas*—Depending on the deposited material, process environment gases typically include argon, nitrogen or helium.

9.2.3.2 *Supplemental Gas/Flow Rate/Nozzle Orifice*—The gas flowing through the nozzle may be specified by the type of gas (typically argon or helium), flow rate, and the actual geometry of the deposition head supplying the gas. Supplemental gas flow devices may also be employed to better shield the area from oxidation.

9.2.3.3 *Vacuum Level*—The required vacuum level to perform deposition should be specified, but is typically 10^{-2} Pa or lower.

9.2.4 *Manipulation and Toolpath:*

9.2.4.1 *Travel Speed*—Differing speeds may be used for different portions of a toolpath. The operator may also have the ability to use a feedrate override, and it should be specified if this is permissible or not.

9.2.4.2 *Layer Height*—This is the programmed layer height, that is, the distance that the deposition head will rise before starting a new layer. The actual layer height may differ from this programmed layer height.

9.2.4.3 *Hatch Spacing*—The lateral distance between subsequent, adjacent passes of the deposition head whilst depositing a layer.

9.2.4.4 *Mechanical Arrangement*—Spatial orientation between feedstock delivery apparatus, energy source, and component.

9.2.5 *Other:*

9.2.5.1 *Temperature*—Preheat temperature and interpass temperature may be key process variables for certain processes and materials.

9.2.5.2 *Dwell Times,* including dwells between each individual pass and each layer can be used to control interpass temperature.

9.3 *Considerations for Process Specification:*

9.3.1 When specifying a particular process, it is important that processing should be conducted per applicable standards as agreed upon between supplier and purchaser according to an approved manufacturing plan as described in Section 13.

9.3.2 Test specimens for quality assurance may be required to be built and tested with each DED build cycle or before-and-after production run as agreed upon between supplier and purchaser.

9.3.3 Permissible process parameter changes and extent of external intervention during the DED build cycle accomplished through either manual control or feedback control should be identified in the manufacturing plan, traveler or run log. All process changes should be continuously monitored and key process variables recorded. When agreed to by the purchaser, changes to the manufacturing plan are permissible without process requalification.

9.3.4 Permissible pauses, whether planned or unplanned, should be identified in the manufacturing plan. Planned pauses might include pausing at the end of a shift, or pausing the process to refill a powder feeder. Unplanned pauses might be caused by power outages or identification of an out-of-tolerance condition by an operator. Corrective actions to be taken in these scenarios should be detailed in the manufacturing plan. Planned and unplanned pauses should be reported.

9.3.5 Condition and finish of the component should be agreed between the supplier and purchaser.

9.3.6 Measurement/calibration of thermal energy (power), feedstock introduction rate, and other key process variables should be agreed between the supplier and purchaser.

9.4 *Distortion:*

9.4.1 DED processes produce near-net-shape material depositions. The accuracy of the process is dependent on the inherent accuracy of the deposition process, but also on the degree of distortion during the process. Distortion is caused by uneven heating and cooling in the deposited material, as well as the shrinkage of the material as it cools from the melting point. Distortion can be severe in DED processes. There is currently no accurate way to predict the level of distortion that might be encountered, and distortion mitigation is done by experience or experiment. However, active research is underway to use thermal modeling as a predictive tool to determine the stress and distortion resulting from the DED process.

9.4.2 The level of distortion can be significant, and normally needs to be considered and mitigated. Parts can be significantly out of tolerance if mitigation steps are not implemented. For example, distortions of many centimeters can be encountered on parts >1 m in size.

9.4.3 Methods to control distortion include:

9.4.3.1 *Physical Clamping*—The base plate, or the actual part itself, may be clamped to prevent movement during deposition. The forces generated can be very significant, so care must be taken to design the clamping system to prevent clamp breakage, or cracking within the build. Post process stress relief while clamped may be required if clamped geometry is to be retained after fixturing is removed.

9.4.3.2 *Heating*—By applying a pre-heat to the base plate, the level of distortion can be reduced. The temperature and methods to do this are not standardized, but even relatively moderate temperatures can significantly reduce distortion.

9.4.3.3 *Intermittent Stress-Relief*—In some cases, parts are removed from the DED equipment mid-process and a stress-relief heat-treatment is performed. The part is then returned to the DED equipment for continued processing.

9.4.3.4 *Process Parameters*—In general, using lower heat input reduces distortion.

9.4.3.5 *Overbuild*—One of the simplest ways to mitigate distortion is to add extra material to the build. In this way, if the part distorts, there will still be sufficient material present that can be machined away in order to end up with the desired final part geometry. This method increases the amount of material that needs to be deposited, and thus increases the amount of material that may need to be subsequently removed. If stress relieving is not employed, the part can be expected to distort during machining operations.

10. Machine Preparation / Conditioning / Calibration / Monitoring

10.1 This section reviews the need for machine conditioning, calibration and monitoring which is paramount to ensure consistent and reliable equipment performance and process output. The principles of best practice relative to service intervals are suggested below with deference to the manufacturer to set the frequencies and specific procedures for such activities.

10.2 *Feedstock Delivery*—The delivery mechanisms for appropriately selected and qualified feedstock may require maintenance and calibration including the following:

10.2.1 *Powder Feeder*—At regular intervals, the feed mechanism should be calibrated using external measurements. Common intervals may include whenever the powder feeder is refilled, or at the beginning and end of a production run. Calibration may be achieved with varying levels of sophistication; however a discrete measurement can give an indication of calibration by weighing the output of five repetitions of feeding for a fixed amount of time (such as 1 min). During these service intervals it is also appropriate to clean out the hoppers and feeder to inspect for signs of wear on moving parts including the feeder disc(s), exhaust, spreader/suction units, etc. When utilized, gas flow, built in scales, and closed loop feedback devices should also be maintained, calibrated and documented as per manufacturer's recommendations.

10.2.2 *Wire Feeder*—As with powder feeders, wire feeders should also be routinely checked for calibration with either a continuous or discrete approach and be maintained. A service interval should include inspection for signs of wear on the moving mechanisms, particularly the drive rollers, cable liners, spool brake, etc. Linear feedrate should be calibrated against the machine settings.

10.3 *Energy Source*—Heat input is a critical factor in the DED process. As such, calibration of the energy source is vital to a repeatable process.

10.3.1 *Laser*—Power calibration, monitoring (continuous, discrete), laser maintenance considerations. At regular intervals, the laser power should be calibrated using external measurements. Common intervals may include weekly, or at the beginning and end of a production run. Since delivery optics can considerably affect the amount and distribution of energy it is recommended that measurements be made after delivery optics. Laser beam profiling should be conducted at routine intervals to determine beam diameter and power distribution to ensure acceptable beam quality. Laser beam characteristics known to affect the deposition quality include the laser transverse electromagnetic mode (TEM), the laser beam quality (M^2), and the beam polarization (random, S, or P). Routine cleaning of the protective cover slides/optics may be required to keep them free of debris. Furthermore, replacement optics should be kept away from any dust or fine particles before installation and should be kept in a clean and sealed enclosure during laser operation. Laser optics should be replaced according to procedures recommended by the manufacturer.

10.3.2 *Electron Beam*—Maintenance and calibration of electron beams should follow similar principles as outlined for lasers including power calibration, monitoring (continuous, discrete), and any necessary physical maintenance.

10.3.3 *Arc Plasma*—Calibration of the arc includes measurement of arc length, using a suitable vision system. Arc power source voltage and current are typically calibrated using a load bank traceable to NIST standards. Parts, such as contact tips, should be replaced when worn according to manufacturer's recommended practice.

10.4 *Atmosphere Control*—Whether localized shielding is used, or an inert gas or vacuum chamber, the mechanisms for the supply of gas or evacuation of air, or both, should be inspected routinely. Any sensors used to measure the atmosphere chemistry should be calibrated according to manufacturer's recommendations.

10.5 *Motion:*

10.5.1 Both Cartesian type motion platforms and robots should be assessed routinely to ensure geometric tolerances can be achieved. Although motion control has reached a high level of reliability through closed loop feedback, it may be necessary to inspect, calibrate, or maintain encoders, vibration mitigation mechanisms, tune servo drives, etc.

10.6 *Melt Pool Monitoring:*

10.6.1 Visible light or infrared cameras may be used to monitor the size, temperature and position of the melt pool. Melt pool monitoring allows feedback control systems to regulate melt pool growth so that components are built to the appropriate size and shape.

10.6.2 An imaging sensor can be used to monitor the melt pool during additive manufacturing. The imaging sensor is typically capable of intermittent or continuous viewing of the melt pool during deposition. The imaging sensor can utilize the visible or infrared bands depending on application. The visible band can be used to image the molten pool directly or various infrared bands can be used to image the temperature or emitted energy within the respective bands. In-band surface reflectance, emissivity, transmission, and melting temperature are important parameters to consider for selecting the correct imaging sensor wavelength band. The imaging sensor should be calibrated according to the manufacturer's stated intervals. For spatial calibrations, a target with known dimensions is typically used to determine the sensor's spatial resolution. If changes in the optical components, sensor distance/angle, or aperture size are made then the sensor must be spatially or radiometrically re-calibrated, or both.

10.6.3 The imaging sensor must be connected to a computer with an image acquisition system for sequential image acquisition, processing, and archiving. The acquisition frequency should be known and for radiometric measurements the integration time and gain must be recorded. The imaging hardware typically displays the acquired images in real time. Analysis software, using the calibration image data, can be used to process the images to obtain the melt pool metrics such as shape, size, and temperature as a function of time or position. The melt pool's shape can be determined by using standard image processing techniques by comparison to a known or desired shape function. The melt pool size can be estimated by threshold techniques based on visual or temperature boundaries. The melt pool temperature should be determined using the proper emissivity value for molten metals. Based on these metrics, changes from a desired state to an anomalous state can be measured. These measurements can be used in a closed loop system where the information is used to control metal deposition parameters such as beam power so that components are built to the appropriate size and shape.

10.7 *Monitoring:*

10.7.1 It is recommended that the process be monitored to ensure adequate quality of material deposition is achieved. Monitoring should be conducted by appropriately monitoring the key process variables, including laser power, powder feed rate, and other essential process variables as needed.

10.7.1.1 Inert gas supplies should be monitored for laser and arc plasma-based systems, while vacuum pressures should be monitored for electron beam-based systems.

10.7.1.2 Atmosphere conditions including inert gas flow rates or vacuum pressures, or both, should be maintained according to the manufacturer's specification. Oxygen and trace element sensors and analyzers should be calibrated and operated according to manufacturer specifications.

10.7.1.3 *Feed Supply*—Feed supply should be monitored within powder hoppers and wire feeders. Feed supply mechanisms should be calibrated and tuned based on manufacturer specifications, and feeding lines should be inspected to verify that no obstructions are present.

10.7.1.4 *Leak Checks*—Leak checks should be carried out for inert gas processing chambers and vacuum chambers, including the source and all feed lines. Leaks can be located by using a helium sniffer, soap and water bubbles, or by listening. Leaks should be remedied so that positive pressure is continually maintained within inert gas chambers and vacuum conditions are maintained in vacuum chambers.

10.7.1.5 Prior to any deposition, the alignment of the energy source and feedstock should be verified. To achieve a proper build, the center of the energy source and the center of the feedstock focus need to coincide. This alignment should also be verified if in operation it is noted that contours build differently on one side than another.

10.7.1.6 *Toolpath*—Critical parameters from each toolpath that merit recording, at a minimum, include: travel speed, layer thickness, hatch spacing and the orientation of the build geometry relative to the build surface.

10.7.1.7 Any optical equipment should also be aligned prior to any build. This may include: alignment cameras, machine vision, feedback cameras, or any analytical cameras.

10.7.1.8 All fixturing should be aligned with the motion of the machine. Depending on the type of fixture used, alignment methods may vary.

10.7.2 *Machine Setup:*

10.7.2.1 An established machine setup should be followed, or a new one documented, prior to any set of depositions. This should include gas type, energy source information, fixturing type, feedstock information, substrate information, etc. This may also include a sign off to show that all alignments and proper checks were done prior to any deposition.

10.7.3 *Run Logs:*

10.7.3.1 It is strongly recommended that run logs be kept for each build. They should capture the critical parameters, as agreed upon between manufacturer and purchaser, and conditions of each deposition and note if there were any interruptions (or events) to the build and atmosphere conditions before, during and after the build.

11. Post Processing

11.1 After a deposition is complete, there are numerous post process steps that can be performed to improve or assess, or both, deposition quality. The selection of specific post processing steps to perform is dictated by the application.

11.2 *Stress Relief Heat Treatment*—Deposition of molten metal introduces significant stresses in the component and substrate. For any case in which the deposition must be removed from a substrate or for which post process machining may be required, the use of stress-relief heat treatment should be considered to reduce residual stresses and mitigate distortion during machining or removal. Stress-relief is normally performed at the completion of the DED process, however intermittent stress relief can be performed during the DED process, particularly for large parts and crack-sensitive materials.

11.3 *Non-Destructive Testing (NDT)*—Non-Destructive Testing should be performed as appropriate to the function and service environment of the component. Such inspection should employ accepted industry standards as agreed to by the supplier and purchaser. Typical NDT procedures applicable to DED include radiographic (RT), ultrasonic (UT), dye penetrant (PT), magnetic particle (MP), and visual (VT) testing. More detailed inspections, for example, by linear or matrix phased array ultrasonic (PA-UT), eddy current (ECT), process compensated resonance (PCRT), or computed tomography (CT) testing may be used depending on (1) the complexity of the part (accessibility of inspection surfaces), (2) type, size and distribution of the flaw(s) of interest, or (3) the criticality of the intended service of the component. Testing is often performed on components after some finishing is performed, since the normally-rough surface finish can significantly impede some inspection techniques. Note that in certain cases, the unique microstructure developed during deposition has been shown to impact transmission of ultrasonic energy, and may have a detrimental effect on the ability to perform UT inspection.

11.4 *Surface Finishing*—For DED processes, finishing is often required in selected areas to meet the dimensional and surface roughness requirements. Surface finishing may be accomplished by any method acceptable to the supplier and purchaser. Typical processes include machining, grinding, honing, electropolishing, bead blasting and shot peening, or other methods as suitable to the desired surface finish requirements.

11.5 *Heat Treatment*—The use of thermal treatments to enhance mechanical properties will be dictated by the metallurgy of the part and the final condition as specified and agreed to by the purchaser and the supplier. Details will vary based on the alloy family and particular alloy in question, and its end use application.

11.6 *Hot Isostatic Pressing (HIP)*—Hot Isostatic Pressing is a method that can be used to reduce or eliminate internal porosity in some alloys (surface-connected porosity will not be affected). It is often used for components in critical applications. Hot isostatic pressing (HIP) of the deposit may be required by the purchaser.

12. Safety

12.1 *Introduction*—There are numerous potential hazards associated with operation and maintenance of DED equipment that can affect the safety of personnel and equipment. All personnel associated with the equipment, including management, supervisors, operators, and maintainers should maintain a high level of safety awareness and a general understanding of DED equipment safety. Operators and maintainers must possess a thorough understanding of specific hazards associated with the individual components of the DED equipment and with the process itself. Operators and maintainers must be knowledgeable of safety protection devices and controls, and possess a thorough understanding of how they operate. They should be familiar with all applicable equipment manuals and should be provided machine-specific training if applicable.

12.1.1 It is critical to establish specific safe operating practices and procedures. These procedures should include vehicles for reporting new hazards or violations. These requirements are outlined in Occupational Safety and Health Regulations: CFR Title 29, Chapter XVII, Part 1910—Occupational Safety and Health Standards.

12.1.2 To quickly check that general practices meet minimum requirements, consult the OSHA Standards Checklist: Volume 15.

12.2 Procedures should be established for each item below. All items below should be considered when developing a safe operating plan.

12.3 *Warning Information:*

12.3.1 *Highest Priority*—Denotes high probability of personal harm and potential for equipment damage.

12.3.2 *Caution*—Denotes high probability of equipment damage or potential for personal harm.

12.4 *Laser Emission*—Lasers utilized in deposition processes may emit ultraviolet and infrared radiation that may be hazardous to eyes and skin. Systems should be designed to have appropriate shielding and safety features. Laser systems are classified as Class 1, 2, 3 or 4. Class 1 laser systems fully contain all laser hazards. Class 4 laser systems do not contain the laser hazard. However, Class 1 systems can become unsafe during system set-up, alignment, calibration or maintenance. Only qualified personnel utilizing appropriate PPE should be utilized during system alignment or maintenance.

12.5 *High Energy Beam Reflections*—Under certain set-up and operating conditions, DED processes can produce severe reflection hazards. Combinations of reflective materials (for example, copper, aluminum, precious metals, etc.) and beam angles of incidence (perpendicular and acute) can cause severe damage to system optics (from back-reflection) and other system components, tubing and safety coatings. Appropriate process monitoring precautions should be taken during DED process set-ups, calibration and operation.

12.6 *X-ray Emission*—Electron beam systems produce X-rays that can be dangerous to humans. Systems from reputable suppliers will typically be designed to have appropriate shielding and safety features. Leakage surveys should be considered if there is any reason to believe shielding has been compromised. Only qualified personnel should be utilized during system maintenance.

12.7 *Electromagnetic Radiation*—The deposition process emits electromagnetic radiation in wavelengths that may be hazardous to eyes and skin, such as IR and UV. Systems from reputable suppliers will typically be designed to have appropriate shielding and safety features. Only qualified personnel utilizing appropriate PPE should be utilized as required during system alignment or maintenance.

12.8 *High Voltage*—Lasers, electron beams, arc plasma systems, and ancillary system equipment may utilize high voltage electricity. Only qualified personnel should perform maintenance on these systems. Appropriate lock out/tag out (LOTO) and high-voltage safety practices and procedures should be utilized.

12.9 *Hot Surfaces*—DED processes produce parts that can be hot enough to produce severe burns. They can also incorporate the use of process-assist equipment, such as heating plates, which can represent similar burn hazards. Appropriate precautions should be taken when handling or working adjacent to hot parts.

12.10 *Heavy Lifting*—Some DED systems can produce parts that are too heavy to safely manipulate without mechanical assistance.

12.11 *Crush and Pinch Hazards*—DED systems require automated manipulation involving linear stages, rotary stages, robotics, or combination thereof. Care is required to avoid crush and pinch points.

12.12 *Residual Stress*—DED can induce significant residual stress in a component and build plate, which can in turn place significant stress on any clamping devices used to restrain the build plate. Care should be taken when removing clamps, since the stress in the build plate can cause clamping devices to fracture or move unexpectedly.

12.13 *Sharp Edges*—DED systems can produce parts with edges sharp enough to cause bodily harm. Care is required when handling such components.

12.14 *Cleaning Agents*—Cleaning agents and solvents, such as acetone, may be required to remove contamination from substrates prior to processing. These chemicals may be flammable or may be inhalation, skin and eye hazards. Appropriate precautions must be taken when using and storing such agents.

12.15 *Noise Levels*—Gas handling and other processing equipment may create dangerous noise levels. When applicable, appropriate PPE must be used.

12.16 *Emergency Stops*—DED process equipment typically requires one or more emergency stop buttons or switches. Emergency stop buttons or switches should be clearly visible and accessible to the operator and appropriately described in all operation and safety manuals.

12.17 *System Safety Interlocks*—DED systems often include safety interlocks to protect the system or the operator, or both, from certain process hazards. Appropriate care must be taken to monitor the status of safety interlocks.

12.18 *Feedstock Safety*—DED process feedstock, whether powder or wire, can often present certain handling and process hazards. Appropriate care should be taken during process set-up, feedstock additions (coil replacement, hopper refill, etc.) or replacement to a different material. Feedstock SDS should always be available to operators, and the identified hazards addressed.

12.19 *Fire Safety*—Fires can be caused by the presence of powder, an ignition source (heat source), and oxygen. Class D fire extinguishers (for combustible metals) should be readily available in the vicinity of the powder storage area and working area. Powders should be used in the absence of oxygen whenever possible, such as in an inert gas-filled glove box, to avoid fire hazard. All applicable safety standards should be employed, including National Fire Prevention Association (NFPA) code 484.

12.20 *Gas Safety:*

12.20.1 *Inert Shielding Gases*—DED processes often require the use of inert shielding gases in confined spaces. In high concentrations these gases can represent a severe respiratory hazard. Appropriate precautions (ventilation and evacuation/dilution procedures) should be taken in work areas where these gases are in use.

12.20.2 *High Pressure Gas Tanks (Bottles)*—DED processes require assist gases that are often supplied in high pressure containers. These containers are often unstable (susceptible to falling over) and represent a severe explosion/projectile hazard when not properly secured or anchored. Appropriate precautions should be taken when handling and storing these containers.

12.20.3 *Cryogenic Containers*—DED processes require assist gases that are often supplied in cryogenic containers or dewars. Fittings on these containers can be extremely cold and cause severe skin damage. Appropriate precautions should be taken when handling these fittings and containers.

12.21 *Reactive Materials Safety*—DED processes can often utilize materials that can become reactive under certain conditions. Care should be taken to reference Safety Data Sheets (SDS) and follow the referenced procedures for handling and storage of all materials that are utilized in DED processes.

12.22 *Powder Safety*—Fine metal powder can be explosive due to large surface area to volume ratios, and may become airborne and result in inhalation, skin and eye hazards. Appropriate PPE and spark mitigation strategies must be employed when handling or storing metal powders.

12.23 *Handling of Powders, during and after vacuuming or collection with other mechanical or manual methods*—DED processes often utilize vacuum cleaners or other mechanical and manual methods to facilitate maintenance and process change-over activities from one job to another. With fine powders, conventional vacuum cleaners and other electro-mechanical devices can often trigger explosions from electric motor sparks and can be a respiratory, skin and eye hazard when collected manually. Care should be taken to utilize vacuum cleaners and other electro-mechanical equipment that are certified for use with fine powders. Appropriate PPE should be used for manual methods. Disposal of fine powders can also represent both personal and environmental contamination hazards. Care must be taken to ensure that powders collected are reused, recycled, or disposed of, or combination thereof, utilizing appropriate and approved methods.

12.24 *Handling of Filters, or other items exposed to soot and dust*—In many DED systems, filters are used to catch and contain dust, fines and soot, and collect them for later disposal. Even if the original powder or wire feedstock is not flammable, the soot often is flammable. These filters are often kept in an argon environment, and may not be exposed to air until removed by the system operator. On removal and abrupt exposure to air, the filter can spontaneously combust. Any part of the machine, including filters and interior surfaces, that is normally kept in an inert environment but may be exposed to air, should be treated as potentially flammable. To mitigate this issue, common practice is to slowly expose the filter or component to air, rather than abruptly exposing it. Thus, oxidation occurs in a slow, controlled manner rather than rapidly. Procedures should be developed for disposal and management of filters according to local, state and national standards.

13. Manufacturing Plan

13.1 The manufacturing plan is a document that the purchaser may require in order to control the quality and repeatability of a deposition. Where standard test specimens are to be produced and properties reported, the manufacturing plan should comprise the components set out in Practice F2971 including *(a)* a material specification for the feedstock and finished material state *(b)* a process specification recording critical process parameters (such as the DED parameters suggested in this section and §14) and any post processing, and *(c)* a test specification describing the test specimen geometry and quantity and test procedure. Finally, all data reported must be tied to the location and orientation of test specimens during the build according to Practice F2971 and ISO/ASTM 52921.

13.2 The format of a manufacturing plan for purchaser components may be more flexible as agreed between purchaser and supplier, however the remaining portion of this section and Section 14 review the essential components of the plan and related specifications concerning parts made by DED processes. The process specification should include details of any critical parameters that can affect the deposition quality. Items that would typically be included in a manufacturing plan include: details of the energy source (for example, laser, electron beam, arc plasma, pulse energy, focal spot size, etc.), process parameters (preheat, travel speed, feed rate, gas nozzle orifice diameter, gas flow rate, etc.), feedstock (for example, form, composition, supplier, etc.), equipment (power supply, positioner, build chamber, accuracy and repeatability of positioner, software used for positioning, motion and control of all parameters (including software version), calibration, etc.), and path and geometry information. The criticality of the component should dictate the level of detail required.

13.3 Components manufactured using DED processes should have a manufacturing plan that may also include, but is not limited to, those items listed below:

13.3.1 *System Calibration*—A machine and manufacturing control system qualification procedure may be specified and agreed upon between component supplier and purchaser.

13.3.2 *Deposition Qualification*—A plan for producing and testing process control test specimens in accordance with applicable standards may be specified.

13.3.2.1 Relevant DED standards are currently being developed by several Standards Development Organizations, including AWS, ASTM and ISO.

13.4 *Build Plan*—The location, orientation on the build platform, number of test specimens for each machine qualification DED build cycle, and relationship between specimen test results and component quality can be agreed upon between component supplier and purchaser. It is recommended that location, orientation, and quantity be documented according to ISO/ASTM 52921. Safeguards may be included to ensure traceability of the digital files, including design history of the components. All steps necessary in preparation for and during the deposition, including build platform selection, machine cleaning, atmosphere control, and feedstock handling, may be included as part of the plan or in the process specification. Data logging requirements and upper and lower limits of the parameters affecting component quality may also be specified.

13.5 *Operator Certifications*—The requirements for training and approving machine operators may be specified.

13.6 *Post-processing Procedures*—List and sequence of post-processing steps and the specifications for each step. This can include thermal processing (heat treatment), machining, finishing, and inspection.

14. How to Specify a Process

14.1 *Overview*—DED processes can be specified by mechanical properties and material chemistry via material specification. In addition, the DED processes can be specified by orientation, and post-processing methods via process specification.

14.2 *Mechanical Properties*—The applicable mechanical properties of the part will depend on the specifications of the purchaser. These may include yield strength, ultimate tensile strength, percent elongation, fatigue strength, hardness, and toughness, among others.

14.3 *Units*—The specification of units for process variables is shown. Laser power in watts (W), electron beam accelerating voltage in kilovolts (kV), electron beam current in milliamperes (mA), arc plasma power in watts (W), arc voltage in volts (V), arc current in amps (A), travel speed or scan rate in mm/s, powder feed rate in grams per minute, wire feed rate in mm/s, wire feed deposition rate in g/min, layer thickness in mm, hatch spacing in mm, beam diameter in mm, melt pool width in mm.

NOTE 1—STL files do not contain units of measurement so the purchaser directions should define units used for clarity.

14.4 *Chemistry*—Chemical composition of the built part must adhere to the material specification of the purchaser. Threshold values for oxygen, carbon, nitrogen, and hydrogen will vary among applications.

14.5 *Orientation*—The layer orientation of the built part can be varied using part preparation or part file manipulation software. The layer orientation can be parallel, orthogonal, or varied by a specified rotation angle. The orientation can also be varied as such: 0°, 45°, 90°, and so on until one complete revolution is attained. The layer orientation should be defined relative to the machine coordinate system as defined in ISO/ASTM 52921.

14.6 *Handling in Clean Environments*—In some cases, it may be necessary to specify if any controlled environment and other specialty processes or testing are required for post processing the parts. This may include use of an ISO Class 8 cleanroom, a Cleanliness Controlled Area (CCA), ultrasonic cleaning, thermal rinsing/disinfection, sterile packaging (including any special labeling, laser marking, handling with gloves, transit packaging, manufacturing residual and biocompatibility testing, assembly, etc),sterilization, etc. This can be critical when processing medical devices, aerospace, and electronic components.

14.7 *Post-processing (thermal, surface finishing) etc.*—Residual stresses may accumulate for each DED process and will depend on the deposition rate of the process and many other factors. Higher deposition rates tend to increase the magnitude of residual stress in the built part. A stress-relief heat treatment may be required to alleviate the stress in the built part. Heat treatment may be required if the desired mechanical properties are not met by the as-built part. Material specification based on the purchaser's requirements must be considered to meet mechanical property thresholds. Surface finish must be considered and is based on the purchaser's part specification. DED processes will generally require post-process CNC machining in order to meet dimensional tolerances of the final part. Multi-axis CNC machinery equipped with ball-nose end-mill tools may be required to remove the necessary material on contoured parts. If the part geometry is simpler, lacking complex contours for instance, then a conventional 3-axis CNC system will often suffice. Cylindrical components will generally be required to be machined using a CNC lathe or CNC turning center. The machining requirements will be specified by the manufacturing engineer of the purchaser. Any finishing methods (grinding, electrochemical polishing, belt grinding, shot peening, bead blasting etc.) should be carried out according to surface finish requirements, which are based on purchaser guidelines.

14.8 The request for quotation (RFQ) for a part built using one of the DED processes should include the following information:

14.8.1 *General Part Description*—Includes description of part and service type, and general performance requirements. This should include drawings of the part with all relevant perspectives. Inclusion of solid model, such as a STEP file, is generally highly desirable. AMF files (mesh with solid texturing and rich metadata), and to a lesser extent STL files (exclusively mesh without solid modeling) can also provide relevant information about the part and its attributes.

14.8.2 *Dimensions*—Includes two-dimensional engineering drawings with part dimensions. Tolerances should be reported here.

14.8.3 *Part Orientation*—This will specify the orientation in which the part is to be built. This will specify the top of the build as well as the left, right, front, and back perspectives. It should be specified as per ISO/ASTM 52921.

14.8.4 *Layer Orientation*—This will specify the orientation of the passes within the layer as well as the orientation of subsequent layers.

14.8.5 *Weight*—This should reflect the weight of the final part (after post-process machining to achieve final condition of part if any is needed).

14.8.6 Due to the wide variety of DED systems described herein, this document does not attempt to specify property values, however the measure of a good process is consistent realization of minimum mechanical properties or threshold values of the same. A mechanical property specification, such as AMS, ASTM, MIL, or ISO would be applicable in regard to the property values and guidance for reporting the test data for specimens prepared by AM, and can be found in Practice F2971 and ISO/ASTM 52921. Physical property threshold values may also be included, if applicable to the purchaser part description. Chemical composition ranges may also be specified here.

14.8.7 *Final Condition of Part*—This will indicate whether the as-deposited surface of the part is acceptable or whether post-processing such as machining is required.

14.8.8 *Surface Roughness*—This measurement is not available until after the build is complete, in which case, R_a value should be specified. This measurement is dependent on the individual component shape and complexity.

14.8.9 *Heat Treatment*—This will indicate whether post-process heat treatment(s) are required, whether said treatment(s) are used to stress-relieve the built part or to induce metallurgical phase transformation, or both, for property modification.

14.8.10 *Feedstock Material Grade*—This will include the type or grade of material (titanium alloy Ti-6Al-4V) for example. Chemical composition specifications for the feedstock should be listed here or may be included in a referenced material specification.

14.8.11 *Feedstock Material Form*—This will include whether the feedstock material is a powder, wire, or other form. Further details, such as powder production process, morphology, and particle size distribution can be specified here or may be included in a referenced material specification.

14.8.12 *Other*—This will include company name and contact information. The part manufacturer will review the manufacturing instructions and generate a process schedule, which will in turn help to determine process parameters such as hatch spacing, deposition rate, and DED build cycle time.

15. Keywords

15.1 additive manufacturing; arc; arc plasma; directed energy deposition; electron beam; functionally graded material; laser; near net shape; powder bed fusion; residual stress

APPENDIX

(Nonmandatory Information)

X1. ADDITIONAL STANDARDS

INTRODUCTION

Directed Energy Deposition technology is closely related to other similar technologies, such as various forms of welding. As such, many standards from other fields are relevant to DED. Below is an incomplete list of standards that were not mentioned in the main body of this standard, but which the reader may find of interest.

X1.1 SAE-AMS Standards

X1.1.1 4999 Titanium Alloy Direct Deposited Products 6Al-4V Annealed

X1.2 AWS Standards

X1.2.1 A5.10/A5.10M Welding Consumables—Wire Electrodes, Wires and Rods for Welding of Aluminum and Aluminum-Alloys—Classification

X1.2.2 A5.32/A5.32M Welding Consumables—Gases and Gas Mixtures for Fusion Welding and Allied Processes

X1.2.3 A5.7/A5.7M Specification for Copper and Copper-Alloy Bare Welding Rods and Electrodes

X1.2.4 C5.1 Recommended Practices for Plasma Arc Welding

X1.2.5 C5.10/C5.10M Recommended Practices for Shielding Gases for Welding and Cutting

X1.2.6 C5.5/C5.5M Recommended Practices for Gas Tungsten Arc Welding

X1.2.7 C5.6 Recommended Practices for Gas Metal Arc Welding

X1.2.8 C7.1M/C7.1 Recommended Practices for Electron Beam Welding and Allied Processes

X1.2.9 C7.2M Recommended Practices for Laser Beam Welding, Cutting, and Allied Processes

X1.2.10 C7.3 Process Specification for Electron Beam Welding

X1.2.11 C7.4/C7.4M Process Specification and Operator Qualification for Laser Beam Welding

X1.3 ANSI Standards

X1.3.1 Z136.1 Safe Use of Lasers

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