**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.

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

[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.

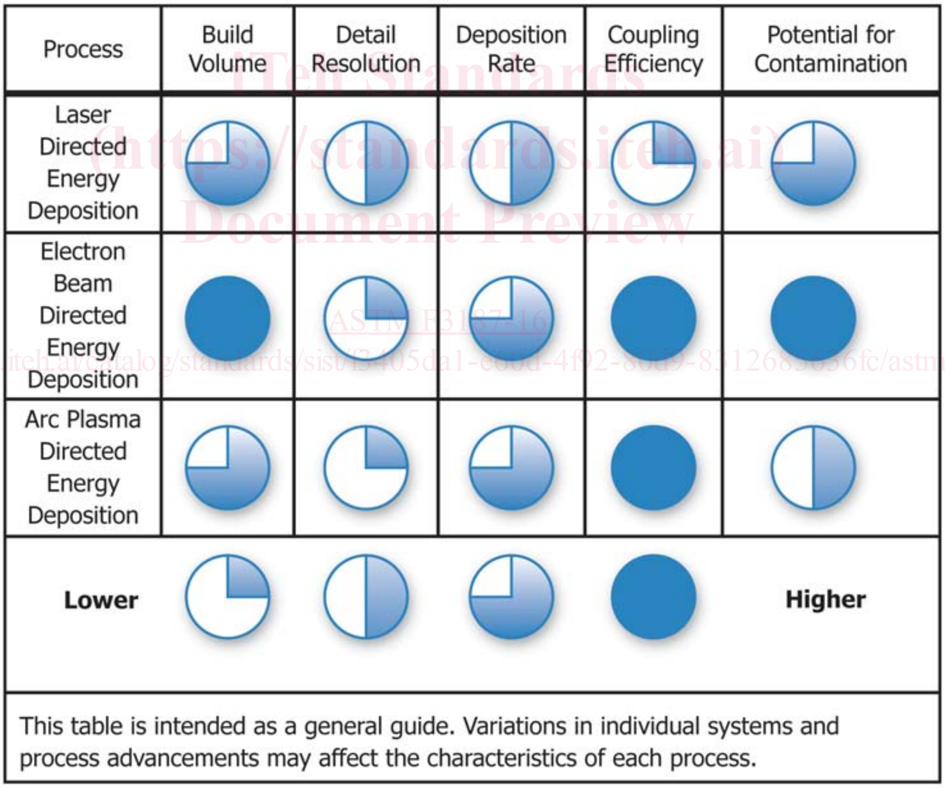
5.3 Although DED systems can be used to apply a surface cladding, such use does not fit the current definition of AM. Cladding consists of applying a uniform buildup of material on a surface. To be considered AM, a computer aided design (CAD) file of the build features is converted into section cuts 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