Designation: F3413 – 19$^{\varepsilon 1}$

Guide for Additive Manufacturing — Design — Directed Energy Deposition[1]

This standard is issued under the fixed designation F3413; 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.

ε^1 NOTE—Copyright permission information was added to Fig. 8 in January 2022.

INTRODUCTION

Directed energy deposition (DED) describes a class of additive manufacturing (AM) processes in which focused thermal energy is used to fuse materials by melting as they are being deposited, described in detail in Guide F3187, and offers an additional manufacturing option alongside established processes. DED has the potential to reduce manufacturing time and costs, and increase part functionality. Typically, DED is used to process metal feedstock to perform one of the following tasks: fabricate net and near-net shape parts, fabricate features on conventionally processed parts, surface modification (cladding) for wear and corrosion protection, or repair metal parts by adding metal to a broken or worn part.

DED processes differ according to several dimensions, including feedstock type (wire or powder), energy source (laser, electron beam, arc, plasma), number of energy sources, and machine architecture. Some implementations include a subtractive process to machine parts and features to final dimensions. Some implementations utilize one or more real-time sensors to monitor various indications of performance, such as melt pool temperature or size.

Practitioners are aware of the strengths and weaknesses of conventional, long-established manufacturing processes, such as cutting, joining and shaping processes (for example, by machining, welding or casting), and of giving them appropriate consideration at the design stage and when selecting the manufacturing process. In the case of DED and AM in general, design and manufacturing engineers only have a limited pool of experience. Without the limitations associated with conventional processes, the use of DED offers designers and manufacturers a high degree of freedom, and this requires an understanding about the possibilities and limitations of the process.

This design guide provides guidance for different DED technologies by providing information about typical characteristics of DED parts and features, insights into the process-based causes of these characteristics, and an understanding of process capabilities and limitations. The information and understanding should provide guidance to designers that they can exploit to take advantage of DED capabilities, design around limitations, and avoid process disadvantages. This document extends ISO/ASTM 52910, the general design guide, and complements powder bed fusion design guides for metal and polymer materials (ISO/ASTM 52911-1 and -2), as well as other process-specific design guides that are under development. In addition, it specializes and builds upon the general DED descriptions in Guide F3187.

1. Scope

1.1 This document specifies the features of Directed Energy Deposition (DED) and provides detailed design recommendations. This document also provides a state-of-the-art review of design guidelines associated with the use of DED by bringing together relevant knowledge about this process and by extending the scope of ISO/ASTM 52910.

Some of the fundamental principles are also applicable to other additive manufacturing (AM) processes, provided that due consideration is given to process-specific features.

[1] This guide is under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.04 on Design.

Current edition approved Dec. 1, 2019. Published April 2020. DOI: 10.1520/F3413-19E01.

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

2. Normative references

2.1 The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

2.2 *ASTM Standards:*[2]

F3187 Guide for Directed Energy Deposition of Metals

2.3 *ISO/ASTM Standards:*[2]

52900 Additive Manufacturing — General Principles — Terminology

52904 Additive Manufacturing — Process Characteristics and Performance: Practice for Metal Powder Bed Fusion Process to Meet Critical Applications

52910 Additive Manufacturing — Design — Requirements, Guidelines and Recommendations

52911-1 Additive Manufacturing — Design — Part 1: Laser-based powder bed fusion of metals

52911-2 Additive manufacturing — Design — Part 2: Laser-based powder bed fusion of polymers

52915:2014(E) Specification for Additive Manufacturing File Format (AMF) Version 1.2

52921 Terminology for Additive Manufacturing Coordinate Systems and Test Methodologies

2.4 *VDI Standard:*[3]

VDI 3405 Part 3:2015 Additive manufacturing processes, rapid manufacturing - Design rules for part production using laser sintering and laser beam melting

3. Terms and definitions

3.1 **General Sources of Terms**

For the purposes of this document, the terms and definitions given in ISO/ASTM 52900, Guide F3187, and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *5+ axis system*—a DED system with five or more degrees of freedom.

3.2.2 *blown powder*—a variant of DED systems with a deposition head that uses powder as feedstock material and pressurized gas to eject the powder feedstock.

3.2.3 *buy-to-fly ratio*—the ratio of the mass of material purchased to the mass of the finished component.

3.2.3.1 *Discussion*—The term originated in the aerospace industry and refers to the finished component mass that is flown on the aircraft.

3.2.4 *deposition axis*—the direction in which the deposition head deposits material.

3.2.5 *hybrid system*—an additive manufacturing machine that has both additive and subtractive processes; in the context of DED, the term typically indicates that a machining capability has been added to the DED additive process.

3.2.6 *overhang*—a feature with a downfacing surface that is a candidate to be supported with support structure.

3.2.7 *symmetric build, symmetric build configuration*—a build where two parts are fabricated on opposite sides of the substrate, typically alternating between parts after each layer.

3.2.8 *tool path*—the set of scan vectors that the deposition head traverses when fabricating a part.

3.2.9 *wire-fed*—a variant of DED systems with a deposition head that uses metal wire as feedstock material.

4. Symbols and abbreviated terms

4.1 *Symbols*

The symbols given in Table 1 are used in this document.

TABLE 1 Symbols

Symbol	Designation	Unit
Ra	roughness average (**1**, **2**)[A]	µm
Rz	average maximum height of the profile (**1**, **2**)	µm
Wa	waviness average (**1**, **2**)[A]	
θ	angle	degrees

[A] The boldface numbers in parentheses refer to a list of references at the end of this standard.

4.2 **Abbreviated terms**

The following abbreviated terms are used in this document:

AM	additive manufacturing
AMF	additive manufacturing file format
BTF	buy-to-fly
DED	directed energy deposition
DED-LB	laser-based DED
DED-EB	electron-beam-based DED
DED-Arc	wire-arc DED
DOF	degree of freedom
HIP	hot isostatic pressing
PBF	powder bed fusion
PBF-LB	laser-based powder bed fusion
PBF/M	laser-based powder bed fusion of metals (also known as, for example, laser beam melting, selective laser melting)
STL	stereolithography format or surface tessellation language

5. Characteristics of directed energy deposition processes

5.1 **General**

Consideration should be given to the specific characteristics of the manufacturing process used in order to optimize the design of a part. Examples of the features of AM processes

[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] VDI - The Association of German Engineers; available online.

which need to be taken into consideration during the design and process planning stages are listed in 5.2 to 5.12. With regards to metal processing, a distinction can be made between powder and wire feedstocks, energy source options of laser, electron beam, and arc, and usage of several different types of post-processing operations such as machining or rolling.

DED describes a class of AM processes and offers an additional manufacturing option alongside established processes. DED has the potential to reduce manufacturing time and costs, and increase part functionality. Typically, DED is used to process metal feedstock to perform one of the following tasks:

- fabricate net and near-net-shape parts,
- fabricate features on conventionally processes parts,
- surface modification (cladding) for wear and corrosion protection, or
- repair metal parts by adding metal to a broken or worn part.

DED processes differ according to several characteristics, including feedstock type (wire or powder), energy source (laser, electron beam, arc), number of energy sources, and machine architecture or platform. These different DED processes are presented in Table 2. Some implementations include a subtractive process to machine parts and features to final dimensions; these system implementations are commonly referred to as hybrid systems. Some implementations utilize one or more real-time sensors to monitor various indications of performance, such as melt pool temperature or melt pool size. For all DED processes, deposits are fabricated on a build surface or substrate, which is the material, work piece, part, component or substance that provides the area on which the material is deposited. Refer to Guide F3187 for a thorough discussion of DED machine architectures, subsystems, controls, etc.

It is important to note that DED processes, as with many AM processes, represent one step in the process chain for part manufacture. After part design and process planning, build preparation and part fabrication can be performed. Heat treatment and finish machining often follow the DED process to achieve desired final part properties, dimensions, and surface finish. Inspections may be performed at several points in the process chain, as well.

5.2 **Build options and variations**

It is important for designers to understand the range of options available with DED processes in terms of build set up and fixturing, part orientation, whether or not the substrate is incorporated into the part, and the degrees of freedom of the DED system. The range of options is highly dependent on which of the four tasks from 5.1 is being addressed. See Ref (**3**) for more information on these topics.

5.2.1 **Build set up and fixturing**

For tasks related to building features on existing parts, surface modifications, or repair, build options are more limited than for building net-shape or near-net-shape parts. In the former cases, the existing part should be oriented and fixtured in a manner that facilitates metal deposition efficiently and to achieve objectives. Guidelines are provided in Section 6.

For part fabrication, many options are available. Consider the part shown in Fig. 1. Part orientation is obvious in this case: it should be oriented such that the flange is parallel to the substrate. However, several build configurations should be investigated, as described in the next subsections.

5.2.2 **Incorporate substrate into part**

For part fabrication, a build plate must be used as the substrate on which the part is fabricated. It is a common practice to incorporate the substrate into the part, for example, such that the substrate forms a flat wall. Fig. 2 shows an option where the substrate is incorporated into the part; specifically, the flange is formed by cutting it out of the substrate after the cylindrical feature and gussets are deposited.

5.2.3 **Symmetric build configurations**

In many cases, symmetric build configurations are utilized, where two parts are built at the same time on opposite sides of the substrate. In this case, the substrate is flipped 180° periodically to build up layers alternately on the two parts. Symmetric build configurations are used to help avoid thermal distortions caused by residual stresses. The frequency of flipping is highly dependent on part shape and size. For some large parts, the substrate can be flipped several times per layer, while for other parts, flipping after each layer is sufficient to avoid thermal issues. In some cases, several layers can be fabricated before flipping the substrate. Heat treatment may be required even if the symmetric build configuration is utilized.

Fig. 3 shows a symmetric build configuration where a thick substrate forms the flanges for both parts, which must be cut in half to separate the parts. See 6.4.6 for more detailed work holding and fixturing methods.

Fig. 4 shows a rectangular part with a central rib. Additional build options are available since any of the walls or ribs could be incorporated into the substrate and different symmetric build options can be explored.

5.2.4 **Degrees of freedom of the DED system**

As described in Guide F3187, the DED system includes a motion system that controls the relative movements between the deposition head and the part or feature being fabricated.

TABLE 2 DED process options

Platform	Energy Source	Feedstock
Robot	Laser	Powder
3 or 5-axis Machine Tool	Electron Beam	Wire
Gantry	Arc	

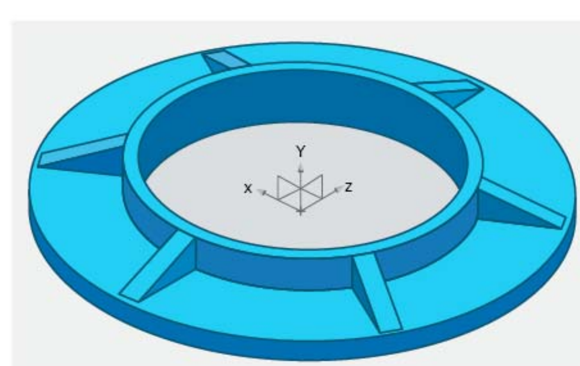


FIG. 1 Cylindrical flange part

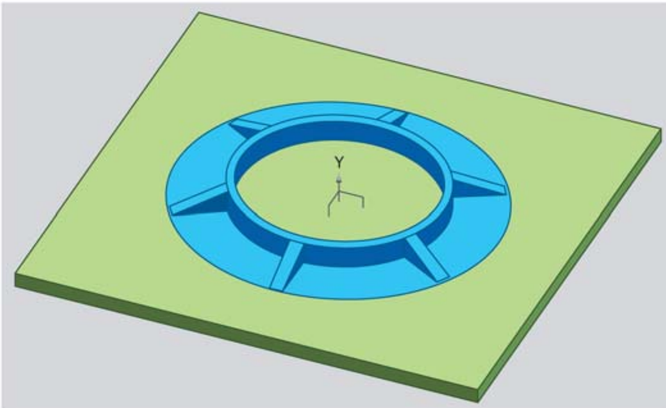


FIG. 2 Incorporating the substrate into the part

The motion system is characterized by the number of degrees of freedom between the deposition head and the part and by how those degrees of freedom (DOF) are allocated to the head and the part. Typical DED machine configurations have either 3 or 5 axes of motion, unless a robot arm is used to carry the deposition head or manipulate the substrate and part. 3-axis systems usually provide three translational DOF in the global *x*, *y*, and *z* directions (see ISO/ASTM 52921 for explanations). 5-axis systems typically contain additional rotations to change the relative orientation of the deposition head and the part. These rotations may be incorporated into the manipulator for the deposition head, or may be provided by separate stages for the substrate and part. When building parts symmetrically, as shown in Fig. 3 and Fig. 4, the substrate is rotated after each layer to balance the residual stresses during building. If a robot arm carries the deposition head, the robot typically has 5 or 6 DOF. Even with a robot arm, a separate rotary table may be used to rotate the substrate and part, giving up to 8 DOF. The notation 5+axis system will denote DED systems with at least 5 axes of DOF.

5.2.5 **Avoidance of overhangs**

If overhangs are present in a part, several approaches can be pursued to fabricate them. Sacrificial support structures could be utilized to support the overhang as it is fabricated. Alternatively, the part could be reoriented relative to the deposition head if 5 or more DOF are available in the DED system. This reorientation is illustrated in Fig. 5. Note that guidance on overhang fabrication and the use of support structures is provided in Section 6, and deposition head accessibility is addressed in 5.8.4.

5.3 **Size of the parts**

Part size is limited by the working area/working volume of the DED machine and depends significantly on the machine architecture. DED machines based on gantry systems or with translating substrates can have working volumes measured in several meters. However, thermal management plays a role in part size. The occurrence of cracks and deformation due to residual stresses can limit part size. Another important practical factor that can limit the maximal part size is the cost of production having a direct relation to the size and volume of the part. For blown powder systems, powder reuse rules impact part fabrication cost significantly. If no reuse is allowed, then all excess powder is scrapped. Excess powder is defined as all powder that was deposited but was not melted into the part, which can be in the range of 30-50 % of total powder deposited. Wire-fed processes are less prone to this issue, because the entirety of the raw material is melted at the point of deposition.

5.4 **Typical advantages of the DED process**

DED processes can be advantageous for manufacturing and repairing parts where the following points are relevant:

– Many materials are available. As a general rule, any weldable metal alloys that are prepared as powder or wire feedstocks can be processed. Since feedstock material is fused as it is deposited, DED systems may have higher power lasers or electron-beam sources, compared to PBF systems, which can enable a broader range of feedstock materials.

– Multiple materials can be used for one part. This is achievable readily by feeding multiple powders into the deposition head for blown-powder systems, by using multiple wires for wire-fed systems, or by utilizing both blown-powder and wire deposition heads. With this capability, functionally graded materials (FGMs) and composites can be fabricated.

– Denser and mechanically stronger printed materials compared to PBF-M in many cases.

– Tailored mechanical and material properties can be achieved by changing process parameter settings, even with the same material.

– Part characteristics can be selectively configured by adjusting process parameters locally, including tailored mechanical and material properties, surface characteristics, and feature dimensions.

– Printing either full parts or local features, coatings, or repair in a single machine.

– High deposition rates are achievable.

– Suitable for large parts.

– Applicable to 3D substrates. Deposition of parts and features can be accomplished on arbitrarily shaped substrates. This is particularly useful for repair applications. It is also useful for fabrication of features on parts produced using other manufacturing processes.

– Integration of multiple functions in the same part.

– Parts can be manufactured to net shape or near-net shape (that is, close to the finished shape and size).

– Design freedom is typically high relative to conventional manufacturing processes. For DED machines with 3 axes of motion (3 degrees of freedom), 3D complexity is limited, but complexity in each layer is achievable. For DED machines with additional DOF, greater design freedom is available. Note that geometric capabilities are related to both the DED process and to any additional machining steps.

– A wide range of complex geometries can be produced, such as

(a) – free-form geometries, for example, organic structures,

(b) – topologically optimised structures, in order to reduce mass and optimize mechanical properties, and

(c) – internal features, although post-fabrication machining considerations may be important.

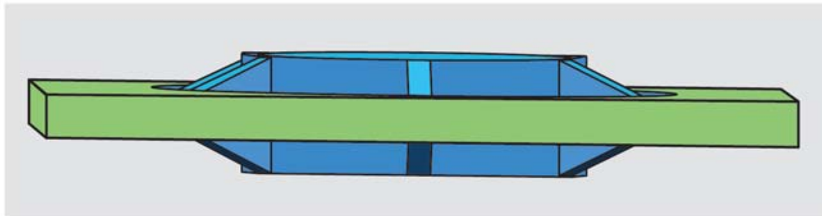


FIG. 3 Symmetric build configuration

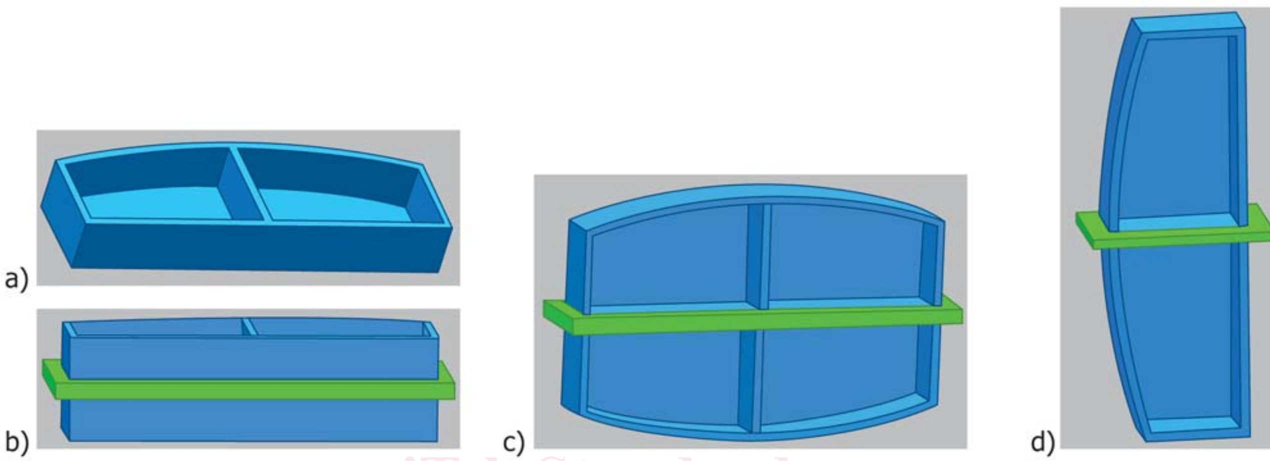


FIG. 4 Build configuration options for rectangular part (a), showing three alternative symmetric build configurations (b-d)

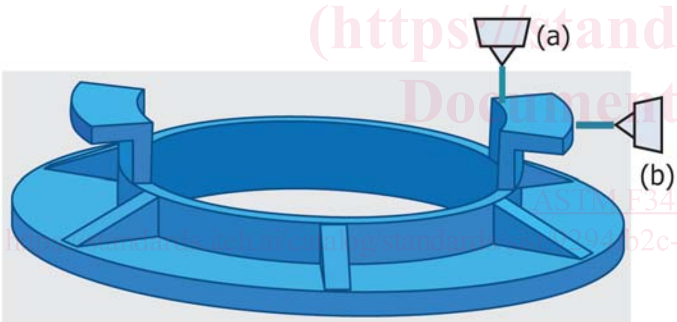


FIG. 5 Taking advantage of 5+ axis motion capability for non-vertical feature fabrication. Vertical orientation (a) is used to deposit most of the features, including the cylindrical extensions, while orientation (b) fabricates the tabs on the extensions.

– Assembly and joining processes can be reduced through part consolidation, potentially achieving *en-bloc* construction.

– High technology readiness level (TRL)/manufacturing readiness level (MRL) compared to some other AM processes.

– Reduction in lead-time for production runs, for example, compared to traditional machining from forging or billet routes.

– Reduced waste material compared to conventional machining from billet.

– Some DED machines include machining capability to achieve hybrid additive-subtractive manufacturing (i.e., a hybrid system).

– DED feedstock materials are typically less expensive than PBF-M powders. Powders for DED can be larger; wire feedstock is significantly less expensive than powder.

– For wire-fed systems, DED processes are significantly safer to operate than PBF-M systems since fine powders are not being used.

– Printing in zero-gravity environment is possible when combining wire feed, electron beam and vacuum environment.

5.5 **Typical disadvantages of the DED process**

Certain disadvantages typically associated with DED processes should be taken into consideration during product design:

– Shrinkage, residual stress and deformation can occur due to local temperature differences.

– DED has lower dimensional resolution (and sometimes accuracy) that PBF-LB/M with larger surface waviness.

– In blown powder systems, higher surface roughness compared to PBF-LB is typical since DED systems utilize powders that have larger particle sizes than powders used in PBF-LB processes.

– Complexity of parts can be limited depending on the DED system, particularly for 3-DOF machines.

– In many cases, DED processes are used for near-net-shape fabrication, which means that post-fabrication machining is required.

– If a near-net-shape fabrication strategy is adopted for part manufacture, additional material must be deposited in the form of a machining allowance. Then, specified geometric tolerances can be achieved by precision post-processing.

– Process planning can become complicated particularly for complex part geometry that takes advantage of 5+axis deposition or hybrid systems.

– Anisotropic material characteristics can arise due to the layer-wise build-up and shall be taken into account during process planning and to identify needs for post-processing.

– Material properties can differ from expected values known from other technologies like welding, forging and casting. Material properties can be influenced significantly due to process settings and control.

– Substrates and fixturing may need to be incorporated into build preparation process, which can lead to an increase in manufacturing lead time compared to PBF-M.

– Often, lower recyclability of powders compared to PBF.

5.6 **Material, economic and time efficiency**

The efficiency of a DED build in terms of waste material, cost and time is highly dependent on the build orientation, substrate location and build sequence. Various different criteria for optimization are available depending on the number of units planned.

The material efficiency is referred to in the Aerospace industry as the buy-to-fly (BTF) ratio, which is defined as the ratio of the mass of material purchased for a component to the mass of the finished component that is flown on the aircraft. The BTF can be used to compare the efficiency of different build options and to compare the efficiency of DED with conventional manufacturing processes.

Some considerations related to material efficiency include:

– The substrate is often incorporated into the final part in order to reduce the amount of material that must be deposited. Parts should be designed with this in mind to aid material efficiency. A corollary to this is that DED processes are often used to deposit features onto conventionally manufactured parts, where the conventional manufacturing process would exhibit difficulties or excess costs if it was used for those features.

– It is common to build on both sides of the substrate due to the significant heat input in the process, which causes residual stresses. Since shrinkage during cooling has the largest affect in the deposition direction, a symmetrical deposition strategy can be used where layers are deposited alternatively on each side of the substrate by rotating it between layers. This balances the build up of residual stresses and minimizes the risk of distortions during the manufacturing process. For parts without a suitable plane of symmetry, it may be possible to build two parts in a back-to-back manner to achieve a near-symmetrical build.

– The strategies of incorporating the substrate in the part and utilizing symmetric builds have significant impacts on the selection of suitable build orientation. Furthermore, the designer may want to redesign parts to incorporate the substrate, provide symmetric builds, and other aspects of build orientation when designing the part in order to achieve material, economic, and time efficiencies.

– Material utilization depends on the size of the powder focus diameter, wire diameter, and the size of heat source of the DED process. In order to maximize the material efficiency, the heat source size needs to be bigger than the powder focus diameter or wire diameter.

– Tool path planning and optimization need to be considered during the design stage. An optimized tool path should help in evenly distributing the heat, so that the material microstructure can be homogenized and the residual stresses can be reduced.

Some other considerations of economic and time efficiency are given here.

– If the intention is to manufacture a larger number of units, then the build space should be used as efficiently as possible. Parts should be oriented so as to minimize the number of build runs required. If the same parts are oriented differently for best packing, i.e. results in building at different angles, then the mechanical properties can vary from part to part. Heat management and cooling considerations are important when packing parts on the substrate.

– Many poorly designed parts (particularly those designed for conventional processes with little or no adaptation) necessitate a specific orientation either to minimize the use of supports or to increase the likelihood of build success. Indeed, parts designed for AM should be devised such that build orientation is obvious or specified, or both.

– With an optimized tool path, machine idle times and other inefficiencies of the process can be minimized.

– Designers should consider the effects of heat build-up and cooling when designing parts and laying out builds, particularly as they impact wait times and other delays.

5.7 **Design feature types**

5.7.1 **General**

Design features are intended to indicate typical shapes with which designers design parts. They are also known as form features or geometric features.

When incorporating the substrate into the final part, the interface between the deposited part material and the substrate should include a fillet in order to minimize the stress accumulation and avoid delamination of the built material from the substrate. The designer should select a proper radius for this fillet to avoid delamination, while not adding needlessly to part weight.

5.7.2 **Design feature hierarchy**

In DED, most design features can be considered as some type of wall. A wall feature can be considered as a high-aspect ratio geometric region, where the feature thickness is small compared to its lateral dimensions. One or several deposited beads typically comprise the wall thickness. In addition to walls, other types of positive and negative features are found in many DED parts, such as bosses, thick sections, pockets, and holes. The high levels of a design feature hierarchy are shown in Fig. 6. Walls are varied enough that they will be considered in 5.7.3. Bosses are typically positive, cylindrical features that may be solid or hollow (can be considered a short closed wall). Thick sections can be considered short, very wide walls. They represent bulk material regions that may take on many different kinds of shapes. Pockets are relatively shallow negative features that occur in walls or thick sections. They are often added into a part to reduce weight or to provide clearance for other parts when assembled. Holes are common negative features. The distinction between large and small holes is intended to indicate whether or not the hole will be fabricated during the DED process (large hole) or will be produced by a secondary

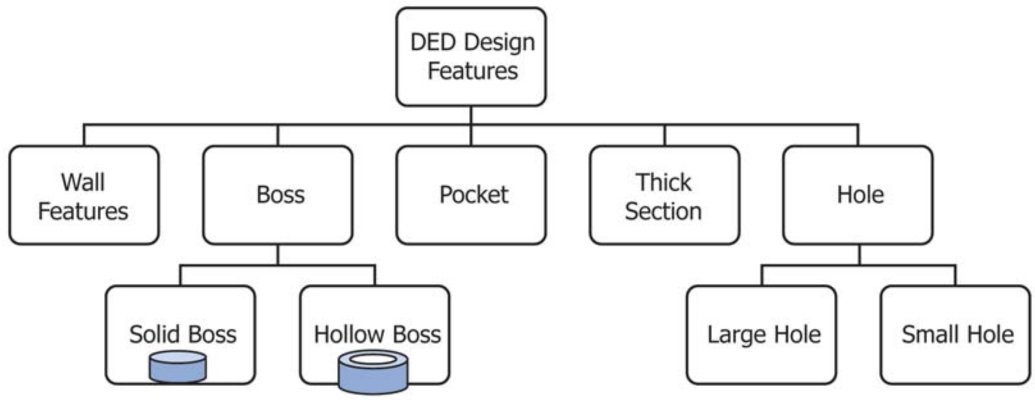


FIG. 6 Top levels of a design feature hierarchy (wall features are expanded in Fig. 7)

operation, such as drilling, punching, or machining, after DED fabrication of the part (small hole).

5.7.3 **Wall features**

A useful hierarchy of wall features is shown in Fig. 7. Broadly, features involving walls can be divided into walls, wall intersections, and wall connections. A wall intersection occurs when two walls cross one another. This situation is noteworthy since they are sites of high deposits if deposition occurs twice at the intersection site. In contrast, wall connections occur when walls are joined edgewise. Broadly, walls can be classified as closed, meaning that cross-sections are cylindrical such as a tube (which can be produced using continuous deposition), or open, meaning that they would be fabricated by rastering back-and-forth along the wall. Walls can be further classified according to their orientation (for example, vertical versus inclined) and according to their shape.

Parts to be fabricated by DED processes would typically be designed using the features in Fig. 6 and Fig. 7. Wall intersections are highlighted so that designers are aware of the complications that arise in their fabrication.

5.8 **Manufacturing features and effects**

Manufacturing features represent shapes that manufacturing personnel associate with potential manufacturability limitations. These include overhangs, islands, and wall intersections.

Manufacturing effects represent part geometric characteristics that emerge as a result of the process, such as the stair-step effect that leads to surface roughness, and limitations on accessibility.

5.8.1 **Overhang**

Not all overhangs can be fabricated. Their success depends on many factors, including the design of the overhang feature,

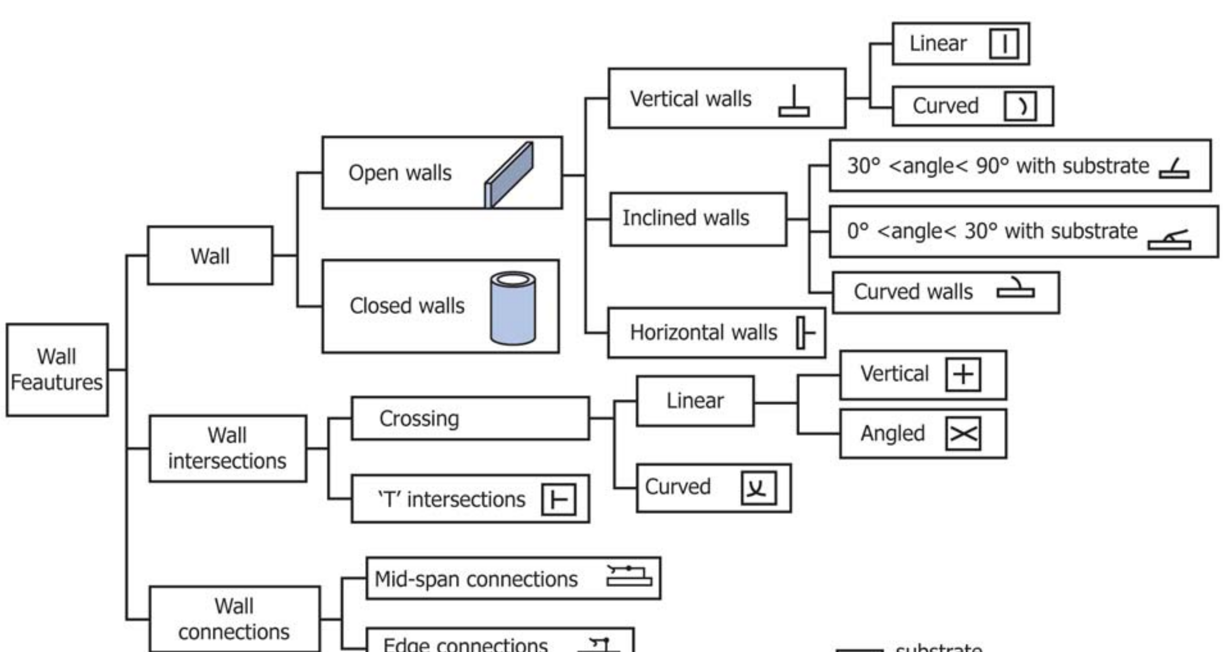


FIG. 7 Hierarchy of features related to walls (an earlier version of the feature hierarchy appeared in (4))

the DED machine architecture and numbers of degrees of freedom, and the design of the deposition head (nozzle for blown powder systems; welding torch for wire-arc systems).

For blown powder systems, it is often better to tilt the substrate to keep the powder nozzle at a vertical position. If it is not possible to tilt the substrate, the maximum tilting angle of the nozzle needs to be considered during the part design stage.

For wire-fed systems, it is often better to tilt the substrate or part to achieve a horizontal build plane. The deposition head could be tilted at various angles from vertical to avoid fabrication problems.

It is important to control heat inputs when fabricating overhangs, since their heat transfer characteristics will be different than bulk regions that conduct heat directly to the substrate. This is important for feature shape quality as well as material microstructure.

5.8.2 **Islands**

Islands (*I*) are features that connect to form a part (*P*) only at a later stage of the build process. How this connection will occur should be taken into consideration at the design stage. Shapes such as the inverted *V* part are not common for DED since the apex region will likely have some shape errors. Parts that are stable in terms of their overall design can be unstable during the build process (see Fig. 8, left and center).

5.8.3 **Wall intersections**

As highlighted in Fig. 7, wall intersections are an important class of features. If nominal process settings are used for two intersecting walls, twice the amount of metal will be deposited around the wall intersection point, resulting in a raised region. Process settings can be adjusted, or alternative toolpaths can be utilized in order to compensate. The designer should be aware that intersections can cause manufacturability issues.

5.8.4 **Stair-step effect**

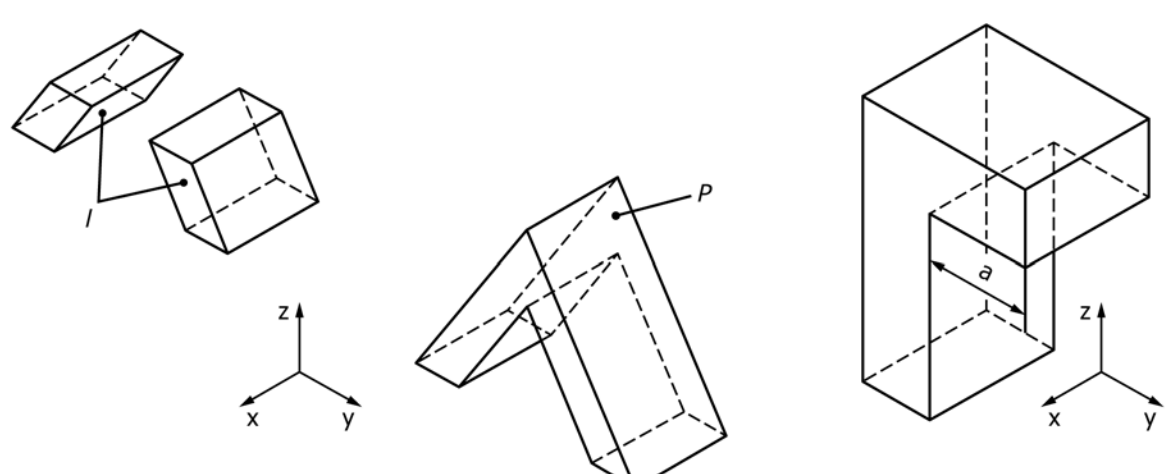
Due to the layer-wise build-up, the 3D geometry of the part is converted into a series of extruded layers before production, with discrete steps in the build direction. The resulting error caused by deviations of these extruded layers compared to the original geometry is described as the stair-step effect. The extent of this is largely dependent on the layer thickness (see Fig. 9).

Thinner layers have an additional benefit related to DED processes in that better surface finishes enable less finish machining to achieve desired finishes. Hence, an important tradeoff exists between build rate, surface finish, and extent of machining. Note that in some cases, machining will not be needed to achieve desired finishes. Additionally, adaptive slicing can be used to adjust layer thicknesses in order to use the largest layers when local shape and finish requirements allow.

5.8.5 **Accessibility**

Accessibility concerns in DED are analogous to those of CNC milling. That is, the deposition axis requires a clear line of sight to the work surface as well as sufficient radial clearance from the deposition axis for the geometry of the deposition head (powder nozzle or welding torch and associated components). In most cases, the deposition axis direction is kept close to normal to the current working surface. Fig. 10 illustrates the issue of deposition head collision with the workpiece and avoidance strategies for 3-axis and 5+axis deposition.

In the classical 3-axis AM part production case, accessibility is not normally an issue as all previous layers will be below the plane of the current layer's tool path (barring some severe distortion issues). However, when the substrate is not a simple planar surface, such as in the case of DED-based repair applications, the safety of the deposition head is not guaranteed by the nature of the process. For 3- axis systems, clearance can be provided by pre-machining to an appropriate relief angle (see Fig. 10b). 5+axis systems can often achieve better accessibility in repair applications by altering the angle of incidence of the deposition head. In general, collision detection checks can be worthwhile to evaluate proposed tool paths. For the 5+axis case in 3D, collision detection can be computationally expensive and is still an active area of research. However, some commercial tool path generation software can perform



Source: VDI 3405 Part 3:2015.
Reproduced with permission of the Verein Deutscher Ingenieure e. V.

FIG. 8 Islands *I* (left) and overhang *a* (right) during the construction of part *P* in *z*-axis *Z*

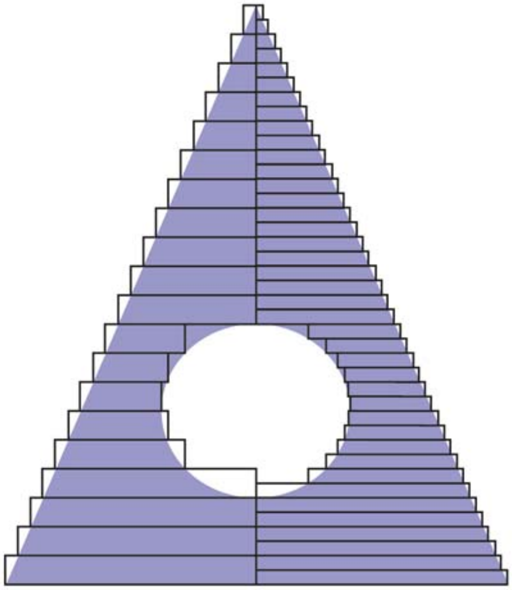


FIG. 9 Impact of different layer thicknesses on the stair-step effect

collision detection in 2D based on slices, which is far less computationally demanding. See Refs (**5**, **6**) for tool path generation issues and approaches.

5.9 **Dimensional, form and positional accuracy**

It is very critical to maintain constant deposition layer thickness to match the pre-set layer thickness. Even small deviations can accumulate and amplify small errors when large numbers of layers are deposited. This will cause poor dimensional accuracy or even print failures.

Typically, it is not possible to produce the tolerances and surface finish that can be achieved with conventional subtractive manufacturing processes. For this reason, machining and other post-processing steps may be necessary to meet geometrical requirements. These additional steps may include post-process machining, or in-process machining if a hybrid system is being used, surface finishing, thermal processing, or other operations according to ISO/ASTM 52910.

In this respect, it is particularly important to be aware of and consider process parameters that will influence the characteristics of the final part. Machining and surface finishing operations necessitate the addition of a machining allowance to part surfaces. Additionally, build orientation to some extent determines the level of accuracy that can be achieved. Directionally dependent (anisotropic) shrinkage of the part can occur due to the layer-wise build-up. As another example, layer-wise consistency can be affected by the location of the deposit on the substrate. Residual stresses and heat treatments are considered further in 6.4 and 6.6.

5.10 **Software workflow for DED**

The use of DED requires 3D geometric data to represent the component to be produced. The digital workflow typically involves creating a 3D model in a solid modeling based computer-aided design (CAD) system, converting it into one or more neutral data exchange representations, and loading the representation into build preparation software to perform process planning and generate an executable build file.

Several variations to this workflow may arise, depending on the situation and software available. Increasingly, AM modules are being added to CAD/CAE/CAM software that enables process simulation, residual stress prediction, distortion prediction, build time estimation, and recognition of manufacturability issues. Additionally, process planning capabilities are being added to some of these software systems that provide slicing, tool path generation, and code generation capabilities, which could eliminate the need to generate neutral data exchange files. Note that this is a rapidly changing area, so designers will benefit by keeping up-to-date on AM software offerings.

Different workflows can arise in repair scenarios, where a 3D representation of the material to be added on the part is needed to facilitate tool path planning.

5.11 **Data quality, resolution, representation**

Two broad types of neutral data exchange representations are used in AM: curved geometry representations (such as STEP and IGES) and tessellations, which consist of sets of triangles to approximate part surfaces. Curved geometry representations typically need to be converted to tessellations for process planning. As such, a tessellated model is commonly used in process planning for AM, but other representations that can also be used include voxels or sliced layer representations. For hybrid DED / CNC machining systems, a boundary representation model (often abbreviated B-rep or BREP) can be used to avoid faceting effects in the final machined component caused by the tessellation process

There are two important characteristics to consider for model representation:

- The model should be a manifold surface (sometimes referred to as "water tight"). A non-manifold model can have undesired effects on the computer-aided manufacturing (CAM) system.
- If a tessellated model is used, the resolution of the tessellation is generally influenced by a tolerance measure, often called "chord height", which describes the maximum deviation of a point on the surface of the part from the triangle face. Therefore, smaller tolerance values lead to lower deviations from the actual part surface. If the resolution is too low, the sides of the triangles defined in the STL file will be visible on the finished surface (that is, it will appear faceted). However, a tessellation with a resolution that is too high requires a lot of digital storage space and is slow to transfer and handle using processing software. The tolerance should be set to be appropriate to the CAM requirements of the DED process.

Common tessellation formats include STL, AMF (ISO/ASTM 52915), and 3MF from the 3MF Consortium. STL files contain only facet geometry (vertex coordinates and facet normal vectors), while AMF supports the representation of information beyond just geometry. For example, part units (millimetres, meters, inches), colors, materials and lattice structures are supported. 3MF files have some of the metadata

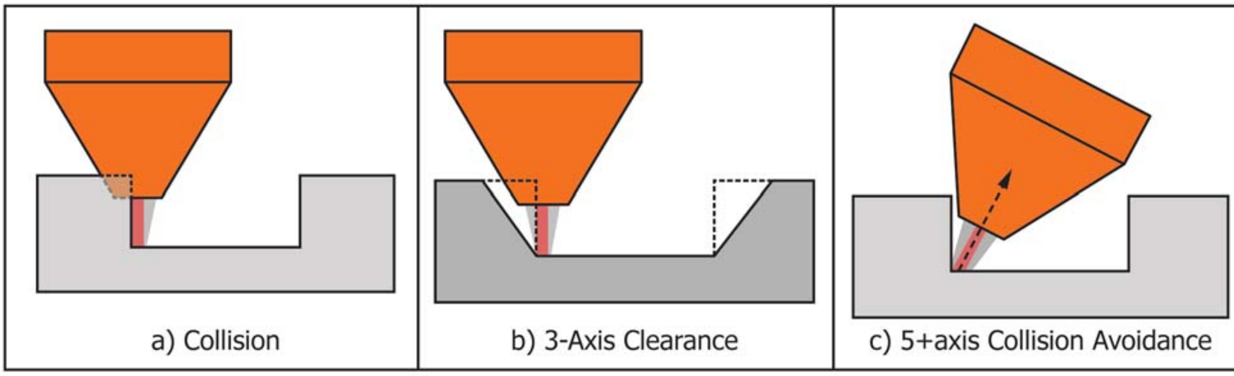


FIG. 10 Accessibility problem (a) and example strategies for collision avoidance in 3-axis (b) and 5+axis (c) deposition

representation capabilities of AMF. Having units incorporated into the data exchange file is very important in communicating part size.

5.12 **DED processes**

The key to DED processes is to balance heat and material inputs so that the deposited bead has correct size, shape, and position. A typical DED machine has dozens of process variables that can be adjusted to achieve this balance, related to heat input from the deposition head, material feed, movement speeds, atmosphere, and others. Of these many process variables, the deposition head power setting, material feed-rate, scan speed, hatch spacing, and layer thickness tend to be the most important.

To fabricate a given part geometry, many different process plans may be available to achieve the desired shapes and material characteristics. As part of each process plan, a specific scan pattern should be generated and selected. It is important that the designer is aware of the potentially broad range of process plans and settings that are available for their part designs.

The reader may refer to Guide F3187 for additional information about DED processes, process variables, and process specification, as well as ISO/ASTM 52904 on process characteristics for metal PBF to meet critical applications.

6. Design guidelines for DED of metals

6.1 **General**

6.1.1 **Selecting DED**

DED is a process with typical advantages and disadvantages, as described in Section 5. DED processes are often advantageous for large parts with thin features, such as walls, ribs, and bosses, that would otherwise be very time consuming to machine from stock. The technology offers some opportunities in complex design with integrated functions in one part, materials with internal structures or channels, or features with undercuts or structures, or both, that cannot be realized by casting, forging, or metal cutting processes. Hence, the flexibility of DED offers opportunities for production of unique products with properties that cannot be realized with other technologies.

DED has applications in part repair and remanufacturing, since it can be used to selectively deposit metal on existing substrates. This also enables the fabrication of features on parts that were fabricated using conventional manufacturing processes. An example is the fabrication of rib and boss features on a large cylindrical forged part. Although the simple shape of the forging may preclude its fabrication via DED, the fabrication of the features by DED eliminates the need to forge a thick housing that requires substantial machining in order to achieve those features. DED also reduces the lead-times for such components, and potentially eliminates the non-recurring costs associated with expensive forging dies.

Important constraints can be the availability of the required materials, limited size of the part, the approval of the technology in critical applications, the production costs, and the possible need for extensive post processing treatments. In comparison with PBF processes, PBF may be selected for smaller parts with high geometric complexity, or applications where extensive machining is not preferred.

6.1.2 **Design and test cycles**

Part optimization may be constrained by the current limits of the DED process. This might differ from material to material, from machine to machine, and from service provider to service provider. Often this means that practical testing of part features can be an aspect of the design cycle.

The general design guide, ISO/ASTM 52910, contains many design considerations that the designer should take into account, including the topics of product usage, sustainability, business, geometry, material property, communication, and process-specific topics.

6.2 **Materials and structural characteristics**

6.2.1 **Feedstock materials**

Metals and alloys are the materials most commonly used for DED. Similar to metal PBF, the successful processing of individual materials depends on a variety of factors, such as weldability, melting temperature, thermal conductivity, melt viscosity and surface tension of the melt. These factors will all affect the characteristics of the part being manufactured. Common metals include titanium and its alloys, aluminium-silicon-magnesium alloys, nickel-based superalloys (for example, Inconel 718), cobalt-based superalloys (for example, Stellite 21), tool steels, precipitation hardening (PH) and other stainless steels. A wide range of other materials has been explored in research, including refractories, copper alloys, high-entropy alloys (for example, AlCoCrFeNi), shape memory alloys (SMAs, for example, NiTi), magnetic alloys