



Designation: F3529 – 21

## Guide for Additive Manufacturing — Design — Material Extrusion of Polymers<sup>1</sup>

This standard is issued under the fixed designation F3529; 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 ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

### INTRODUCTION

Polymer material extrusion (MEX/P) describes an additive manufacturing (AM) process and offers an additional manufacturing option alongside established processes. Applications for MEX range from functional prototypes to simple fixtures and jigs to complex manufacturing aids and short manufacturing runs of parts with complex geometry. MEX has the potential to reduce manufacturing time and costs, increase part functionality, and has the capability of producing very large parts. 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, plastic welding or injection molding) and of giving them appropriate consideration at the design stage and when selecting the manufacturing process. In the case of MEX/P 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 MEX offers designers and manufacturers a high degree of freedom and this requires an understanding about the possibilities and limitations of the process.

Note that the term Fused Filament Fabrication (FFF) is sometimes used to specify the type of MEX process described in this document that refers to the extrusion of a thermoplastic filament in a layer. The term MEX will be used in this document, or MEX/P when it is desired to emphasize the deposition of polymer material, including thermoplastics, and other materials.

This document provides support to technology users, such as design and production engineers, when designing parts that need to be manufactured by means of MEX/P. It will help practitioners to explore the benefits of MEX/P processes and to recognize the process-related limitations when designing parts. It also builds on ISO/ASTM 52910 to extend the requirements, guidelines and recommendations for AM design to include the MEX/P process.

### 1. Scope

1.1 This document specifies the features of MEX/P and provides detailed design recommendations.

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

1.3 This document also provides a state of the art review of design guidelines associated with the MEX/P by bringing together relevant knowledge about this process and by supplementing the scope of ISO/ASTM 52910.

1.4 *This international standard was developed in accordance with internationally recognized principles on standard-*

*ization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

### 2. Referenced Documents

2.1 *ASTM Standards:*<sup>2</sup>

F3413 Guide for Additive Manufacturing — Design — Directed Energy Deposition

2.2 *ISO/ASTM Standards:*<sup>2</sup>

52900 Additive manufacturing — General principles — Terminology

52901 Additive manufacturing — General principles — Requirements for purchased AM parts

<sup>1</sup> 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.

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<sup>2</sup> For referenced ISO/ASTM standards, visit the ASTM website, [www.astm.org](http://www.astm.org), or contact ASTM Customer Service at [service@astm.org](mailto:service@astm.org). For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

52903-1 Additive manufacturing — Material extrusion-based additive manufacturing of plastic materials — Part 1: Feedstock materials

52903-2 Additive manufacturing — Material extrusion-based additive manufacturing of plastic materials — Part 2: Process equipment

52910 Additive manufacturing — Design — Requirements, guidelines and recommendations

52921 Specification for Additive Manufacturing File Format (AMF) Version 1.2

52921 Terminology for additive manufacturing — Coordinate systems and test methodologies

52950 Additive manufacturing — General principles — Overview of data processing.

2.3 VDI Standard:<sup>3</sup>

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

### 3. Terminology

For the purposes of this document, the terms and definitions given in ISO/ASTM 52900 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>

3.1 *air gap*—a process variable that specifies the scalar distance between successive beads in a layer.

3.1.1 *Discussion*—If the bead spacing is exactly the bead width, then the air gap is 0. An air gap greater than 0 means that neighboring beads do not touch, while an air gap of less than 0 indicates that beads overlap.

3.2 *bead*, *n*—the deposited filament of material.

3.3 *downskin angle*,  $\delta$ , *n*—angle between the plane of the build platform and the *downskin area* (3.4) where the value lies between 0° (parallel to the build platform) and 90° (perpendicular to the build platform).

3.3.1 *Discussion*—See Fig. 1.

3.4 *downskin area*, *D*, *n*—(sub-)area where the normal vector in relation to *z*-axis is negative.

3.4.1 *Discussion*—See Fig. 1.

3.5 *infill density*, *n*—a process variable that specifies the percentage of the interior regions of part cross sections that is filled with beads (3.2)

3.6 *nozzle*, *n*—tip of the material extrusion head through which the material is deposited on the build platform or previous beads.

3.7 *overhang*, *n*—part surface or feature with a downskin angle between 0° and 90°.

3.7.1 *Discussion*—See Fig. 2a.

3.7.2 *Discussion*—Synonym for *downskin area*.

3.8 *overhang length*, *a*, *n*—distance measurement for an overhang.

3.8.1 *Discussion*—See Fig. 2a.

3.9 *part consolidation*, *n*—a design strategy that involves combining multiple parts into one part, or fewer number of parts.

3.10 *support structure*, *n*—sacrificial material that is deposited to support part material in subsequent layers.

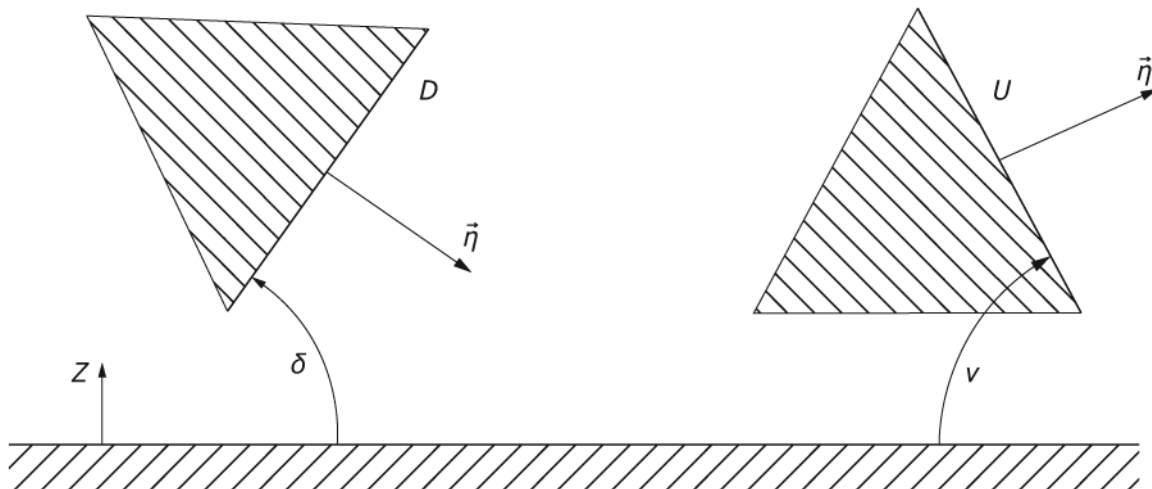
3.11 *unsupported bridge*, *n*—part surface or feature with a downskin angle of 0° that is supported on both sides.

3.11.1 *Discussion*—See Fig. 2b.

3.12 *unsupported bridge width*, *w*, *n*—distance measurement for an unsupported bridge.

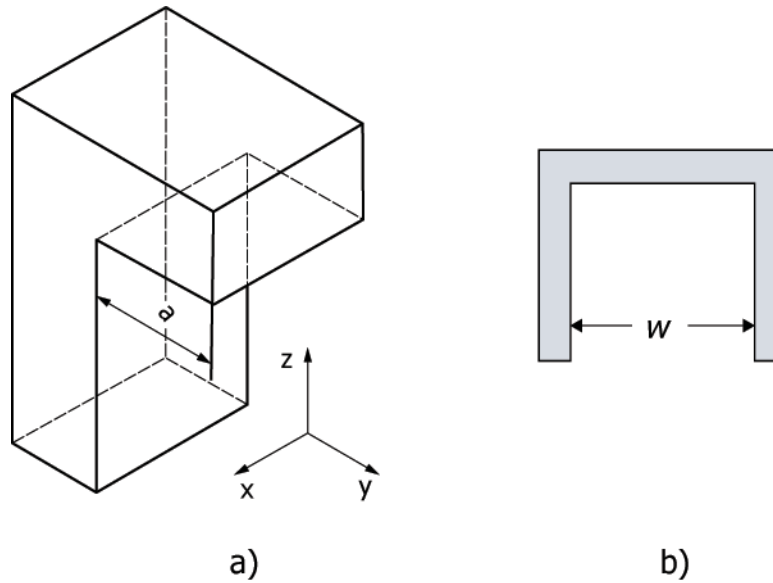
3.12.1 *Discussion*—See Fig. 2b.

3.13 *upskin angle*,  $\nu$ , *n*—angle between the plane of the build platform and an *upskin area* (3.14) where the value lies



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FIG. 1 Upskin and Downskin Areas *U* and *D*, Upskin and Downskin Angles  $\nu$  and  $\delta$ , Normal Vector  $\vec{n}$



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**FIG. 2 Overhang and Unsupported Bridge Features with Corresponding Dimensions** a) overhang with overhang length b) unsupported bridge with width  $w$

between  $0^\circ$  (parallel to the build platform) and  $90^\circ$  (perpendicular to the build platform).

3.13.1 *Discussion*—See Fig. 1.

3.14 *upskin area,  $U$ ,  $n$* —(sub-)area where the normal vector in relation to  $z$ -axis is positive.

3.14.1 *Discussion*—See Fig. 1.

3.15 *void,  $n$* —empty space in a part that is formed either intentionally, by setting the air gap (3.1) to a value larger than zero, or unintentionally as a consequence of the toolpath.

## 4. Symbols and Abbreviated Terms

4.1 *Symbols*—The following symbols are used in this document:

| Symbol    | Designation              | Unit            |
|-----------|--------------------------|-----------------|
| $a$       | overhand length          | mm              |
| $D$       | downskin area            | mm <sup>2</sup> |
| $\vec{n}$ | normal vector            | —               |
| $Ra$      | mean roughness           | μm              |
| $w$       | unsupported bridge width | mm              |
| $U$       | upskin area              | mm <sup>2</sup> |
| $\delta$  | downskin angle           | °               |
| $\nu$     | upskin angle             | °               |

4.2 *Abbreviated Terms*—The following abbreviated terms are used in this document:

|       |                                    |
|-------|------------------------------------|
| 3D    | three dimensional                  |
| ABS   | acrylonitrile butadiene styrene    |
| AM    | additive manufacturing             |
| AMF   | additive manufacturing file format |
| CAD   | computer aided design              |
| CTE   | coefficient of thermal expansion   |
| MEX/P | material extrusion of polymers     |
| MRI   | magnetic resonance imaging         |
| PA    | polyamide                          |
| PBF   | powder bed fusion                  |
| PEEK  | polyether ether ketone             |
| PEKK  | polyetherketoneketone              |
| PLA   | polylactic acid                    |
| PP    | polypropylene                      |

PPSU  
STL

$T_g$

polyphenylene sulfone  
stereolithography format or surface  
tessellation language  
glass transition temperature

## 5. Characteristics of Material Extrusion (MEX) 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 characteristic features of MEX processes which need to be taken into consideration during the design and process planning stages are listed in 5.2 to 5.10. Design guidelines and rules-of-thumb are given in Section 6.

### 5.2 MEX Process and Machine Configurations:

5.2.1 The MEX AM process has the characteristic that creates three dimensional (3D) objects by the continuous deposition of polymer material with relative movement between a single or various extrusion heads and the build platform. Although this process is being used to create objects with a wide range of materials, including biological cells, cement, and food, the most common are thermoplastic materials. These are liquefied by increasing their temperature inside the extrusion head and re-solidified after being deposited. Refer to ISO/ASTM 52903-1 for more information.

5.2.2 Although MEX/P is usually a single-step process, some available materials require further operations to consolidate the part to the fundamental properties of the intended material (metallic or ceramic); for example, removing of the polymer as carrier of the metallic particles and sintering. In these cases, the specific design considerations of these operations should be taken into account in addition to those described in this document.

5.2.3 Some machines allow the extrusion of multiple materials in the same build cycle. This usually enables the use of a different material for the object and the support structures (see 5.8.4).

5.2.4 Most MEX systems are based on a 3-axis configuration, and therefore base the building of objects by the sequential deposition of planar layers parallel to the build platform. However, some machine configurations include more axes, allowing the deposition of material in layers non-parallel to the build platform, or even non-planar layers.

5.2.5 For most MEX systems, feedstock material is in the form of a filament and the extrusion head softens or partially melts the filament and extrudes it at a much smaller diameter. In some systems, the feedstock consists of pellets (that is, feedstock for injection molding). In this case, the extrusion head is larger and more sophisticated since it liquifies the pellets and produces a filament that is much smaller than the pellet size.

5.2.6 Different MEX systems have different methods of controlling the thermal environment of the build volume. Some systems are open to the environment and have a platform heater. Others have an enclosed build volume, while others incorporate a heater into the enclosure.

### 5.3 MEX Processing Fundamentals:

5.3.1 *General*—An understanding of MEX process fundamentals is important to understand part characteristics and the advantages and disadvantages of MEX processes. The basics of filament deposition, bonding, and toolpath and infill patterns will be described in this section.

5.3.2 *Bead Deposition*—Regardless of the feedstock type (filament or pellets), MEX processes deposit a filament of material, called the *bead* (3.2).

5.3.2.1 Bead characteristics are determined by process variables including extruder temperature, material feed rate, extruder movement speed (relative to the build platform), layer thickness, and nozzle size. Fig. 3 illustrates the terms that were introduced in Section 3. Common practice is to use the nozzle to compact the bead during deposition, such that the deposited bead has a flattened shape and the bead width is greater than the nozzle size as illustrated in Fig. 3. By flattening the bead,

the contact area increases between the deposited bead and the previous layer which results in better bonding and a denser, stronger part.

### 5.3.3 Bead Bonding:

5.3.3.1 Bonding between filaments greatly influences part strength and stiffness. It should be recognized that bonding occurs between neighboring beads in a layer, as well as layer-to-layer.

5.3.3.2 Bond strength is highly dependent on processing conditions; all of the process variables mentioned in the filament deposition discussion apply. The local temperature history controls the degree of bonding between beads. When the temperature remains above the material's softening temperature (typically the material's glass transition temperature,  $T_g$ ) for a period of time, the polymer molecules in the beads can start to intermingle forming a bond. If the local temperature decreases too rapidly, weak bonds form between beads. A balance between material deposition rate, extruder temperature, local part shape, and build chamber temperature (if applicable) can achieve local temperatures that result in strong bonds, while preserving local part shape. If temperatures are too high for too long, the material will flow, resulting in part or feature deformation.

### 5.3.4 Toolpath and Infill Patterns:

5.3.4.1 Typical toolpath patterns use a combination of contour and infill patterns. Often, one contour will be deposited to provide the outline of the part cross section, then the cross section will be filled with a set of parallel deposits at a prescribed angle, called infill. These infill beads are often defined at specific angles to the platform's X axis. An example of a toolpath with one contour and an infill angle of 45 degrees is shown in Fig. 4. The distance between neighboring beads in the infill is called the bead spacing and is equal to the bead width plus the air gap (see 5.3.2 and Fig. 3). The bead spacing is related to the infill density, which is a common process variable, to control the density of the part interior. Often, infill densities that are lower than 100 % are used to reduce part weight, although part strength and stiffness will also decrease.

5.3.4.2 Although standard infills have been described so far, other infill geometries are commonly used, such as

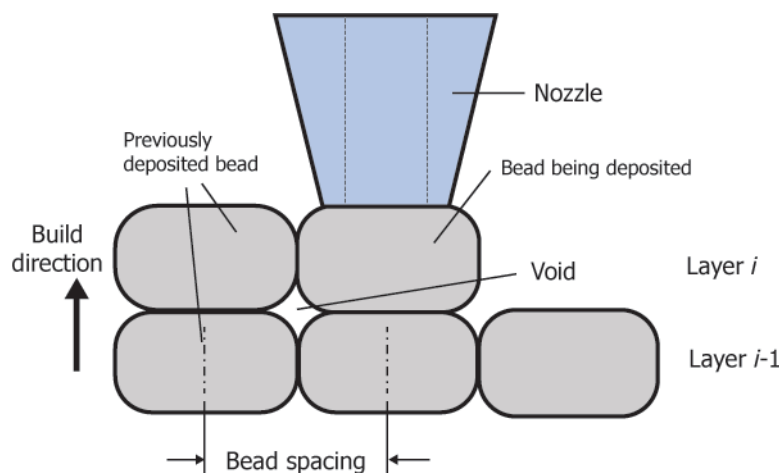


FIG. 3 Cross Section of Bead Being Deposited and Flattened by the Nozzle

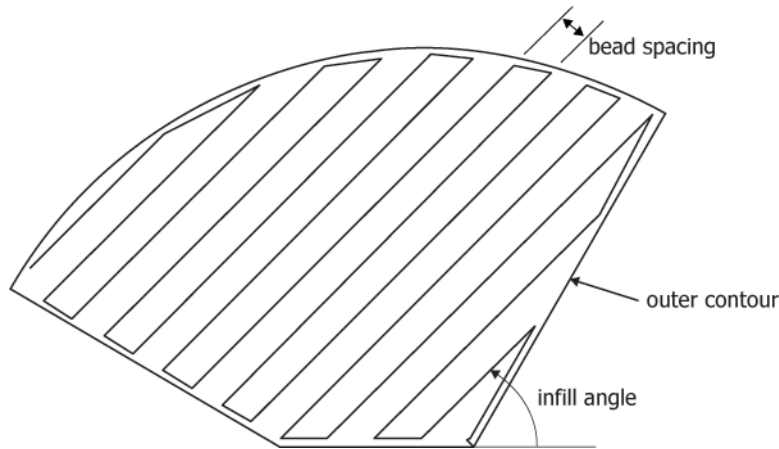


FIG. 4 Top View of a Toolpath Illustrating One Contour and Infill at an Angle of 45° with a Bead Spacing that Yields an Infill Density Less than 100 %

honeycomb, rectangular mesh, or diagonal mesh. In particular, infill angles are frequently alternated by 90 degrees in subsequent layers. For example, a 45°/-45° infill pattern is often used to provide a diagonal mesh. A 0°/90° alternate pattern produces a rectangular mesh. Similarly, other angle combinations can be used, such as 30°/-60°, 15°/-75°, etc. The specific type of infill geometry can significantly affect part properties and introduce directional dependence in these part properties beyond that normally seen related to build orientation. Additionally, some curved infill vector styles, such as gyroid infills, are offered in some pre-processing software.

5.3.4.3 Three other characteristics of MEX toolpaths will be illustrated. First, the typical contour+infill toolpath tends to leave voids between successive beads. Shown in Fig. 5a is a single contour and four infill beads, viewed in the XY plane, where each pair of infill beads results from the extruder head performing a 180 degree turn. Slight overlaps (over-extrusion) between the contour and infill beads are used to aid bonding and reduce void size, but a limit exists on how much overlap can be achieved before bulges or other defects occur at these turnaround sites.

5.3.4.4 The second characteristic is the result of very narrow part regions, where the region thickness is not a multiple of bead width. The schematic in Fig. 5b shows a narrow tapered region that transitions from more than three bead widths to two

bead widths. In the transition region, a void is formed since the region is too thin for an additional bead.

5.3.4.5 The final characteristic is the voids that form between beads from layer to layer. These voids were shown in Fig. 3 as the white areas between previously deposited beads and the bead being deposited. Flattened beads have shapes that are between ellipses and rectangles with rounded corners; their shapes depend on the material feed rate, deposition rate, nozzle diameter, and layer thickness.

5.4 Size of Parts—The size of parts is limited by the working area/working volume of the MEX machine. An enclosed build chamber will have a defined maximum part size. Larger format MEX machines can have an open build area that allows for very large parts. There should be consideration, however, that in larger parts the shrinkage effect from CTE and the deposition time are larger, increasing the risk of a weak inter-layer bonding. Another important practical factor that limits the maximal part size is the time and cost of production, having a direct relation to volume of the part and the bead size. Larger nozzle or layer thickness, and therefore larger bead size, reduce the time and cost of production, but there is a subsequent reduction of resolution. This is commonly counteracted in large-scale MEX by a machining post-process step to obtain the detailed features. Cost of production can be minimized by

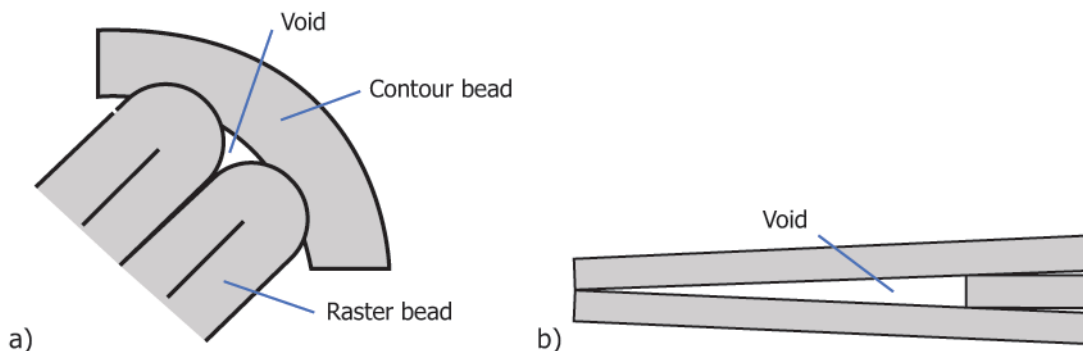


FIG. 5 Voids that Form in a Layer Between a) Infill and Contour Beads or in b) Narrow Regions of Parts

choosing build orientation in a way that allows reducing the volume of supports required. An orientation that increases the layer cross-section would minimize the time required as well, as with small cross-sections the deposition needs to slow down to allow the beads to cool down before the next layer is deposited.

#### 5.5 *Typical Advantages of the MEX Process:*

5.5.1 MEX processes can be advantageous for manufacturing parts where the following points are relevant:

5.5.1.1 MEX processes can be scaled up in size for large part fabrication, particularly if nozzle size is scaled up. The size scale-up can be easier than for other AM processes.

5.5.1.2 Parts with multiple polymers in a single part can be produced.

5.5.1.3 Degrees of design freedom for parts are typically high. Limitations of conventional manufacturing processes do not usually exist; designers do not need to consider:

- (1) draft angles, rounds and fillets for injection molding,
- (2) tool accessibility, and
- (3) undercuts.

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

- (1) free-form geometries, for example, organic structures,
- (2) topologically optimised structures,
- (3) infill structures, for example, honeycomb, sandwich and mesh structures,
- (4) hollow structures, for example, unbroken spheres and honeycomb structures with skins.

5.5.1.5 The degree of part complexity is largely unrelated to production costs.

5.5.1.6 The number of assembly and joining processes can be reduced through part consolidation or single-body construction.

5.5.1.7 Relative simpler working principle compared to other AM processes. This helps reduce the cost of this type of machine and knowledge required for operating them and the availability of a wide range of machine and material manufacturers.

5.5.1.8 Relative low cost of the feedstock material and machine cost compared to other AM processes.

5.5.1.9 Overall part characteristics can be selectively configured by adjusting process parameters locally.

5.5.1.10 Reduction in lead times until part production.

5.5.1.11 Tools for thermoforming, composites lay-up, and other forming processes can be fabricated with MEX/P with a relative improvement in cost and lead time compared to traditional machining processes.

5.5.1.12 Sacrificial support materials can be used to create geometries and assemblies that would be challenging for single material technologies. However, the use of support structures also has disadvantages (see 5.6).

5.5.1.13 Robust neat and reinforced thermoplastic material options.

#### 5.6 *Typical Disadvantages of the MEX Process:*

5.6.1 Certain disadvantages associated with MEX and typically associated with AM processes should be taken into consideration during product design.

5.6.1.1 Part support by way of a secondary, sacrificial material, may be needed due to part geometry, build space utilization, or both.

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

5.6.1.3 The surface quality of AM parts is typically influenced by the layer-wise build-up technique (stair-step effect). Post-processing may be required to improve surface quality, depending on the application.

5.6.1.4 Consideration should be given to deviations from form, dimensional and positional tolerances of parts. A machining allowance should be provided for post-production finishing. Specified geometric tolerances can be achieved by precision post-processing.

5.6.1.5 Anisotropic characteristics typically arise due to the layer-wise build-up and should be taken into account during part design and process planning.

5.6.1.6 Limited polymeric material selection, especially when compared to traditional polymeric manufacturing processes.

5.6.1.7 Parts typically have some porosity due to the inability to completely fill cross-sections.

5.6.1.8 Material properties can differ from expected values known from other technologies like injection molding. Material properties can be influenced significantly by process settings and control.

5.6.1.9 As in many manufacturing processes, MEX exhibits a trade-off between resolution and speed. Small layer thicknesses and deposition nozzles can be used to improve resolution, but will cause slower build speeds.

5.6.1.10 The physical interaction between the nozzle and the deposited part make MEX more prone to failure when producing complex geometries such as cellular structures.

5.6.1.11 Limited efficiency gains are realizable when building multiple parts, or packing the build platform, compared to other AM processes like PBF and binder jetting.

#### 5.7 *Economic and Time Efficiency:*

5.7.1 Provided that the geometry permits a part to be placed in the build space in such a way that it can be manufactured as cost-effectively as possible, various different criteria for optimization are available depending on the number of units planned.

5.7.1.1 For most parts, feedstock cost generally is the factor that has the greatest impact on build costs.

5.7.1.2 If the intention is to build concept parts not intended for testing or end use, then using the least expensive feedstock that can make the concept parts is generally the best first step to cost optimization.

5.7.1.3 If a large number of units is to be produced, limited benefits are achieved by building more than one part at one time. Some machine operations (such as tip wipes, extruder changes, and material purges) can be optimized with packing parts together, but overall time savings is limited. Part packing is most effectively used to create builds to optimize machine utilization, such as planning builds so that jobs will change at the beginning of a shift and at the end of a shift. If multiple parts are fabricated simultaneously, then the build space should be used as efficiently as possible.

geometry permits such orientation, strategies for reorientation and nesting should be utilized to maximize the available build space.

5.7.1.4 Sacrificial material used to support parts adds cost relating to the support material itself and the post processing needed to remove the support material. These considerations need to be taken into account when build space efficiency is being determined.

#### 5.8 Feature Constraints:

5.8.1 *General*—Since AM parts are built up in successive layers, separation of features may occur at some stage of the build. This depends on the part geometry and build orientation.

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. Parts that are stable in terms of their overall design can be unstable at some stage of the build process (see Fig. 6).

#### 5.8.3 Overhang:

5.8.3.1 Areas with a downskin angle of  $0^\circ$  produce an overhang with length *a* (see Fig. 2a). Small overhangs do not need any additional geometry in the form of support structures. In such cases, the projected area is self-supporting during manufacturing. The permissible values for *a* will depend on the specific MEX process, the material and the process parameters used.

5.8.3.2 A closer look at the beads along the surface provides insight into downskin (overhang) angles and when support structures are needed. Fig. 7 shows three walls with various downskin angles of  $90^\circ$ ,  $70^\circ$ , and  $45^\circ$ . At a  $45^\circ$  angle, beads deposited in subsequent layers overlap the bead in the previous layer by only half of its width. If downskin surfaces of less than  $45^\circ$  are attempted, the overlap between beads is even less which can cause poor bonding between layers and sagging of the surface.

#### 5.8.4 Support Structure:

5.8.4.1 Support structures in MEX processes serve primarily as a provisional support for a piece under construction. That

is, support structure provides a surface on which to deposit material if previously deposited part material is not in that location. As a secondary purpose, support structure can help prevent residual stress-induced warping.

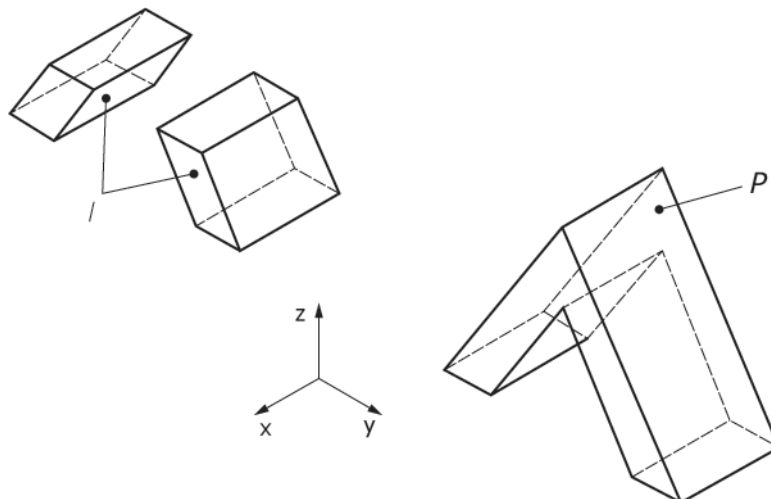
5.8.4.2 Support structures are common in MEX processes and can be generated for the downskin areas of a part. These part areas depend on the overall build orientation of the part and the dimensions of the downskin surface. Fig. 8 shows specific cases of overhangs that require support structures. In Fig. 8a, the downskin angle is less than  $45^\circ$ , measured from the horizontal, which often require supports. Note that  $45^\circ$  is a typical threshold value, but may depend on specific printers and materials. In Fig. 8b, the overhang length is greater than a threshold (usually no more than several millimeters).

5.8.5 *Support Removal*—Support structures of parts fabricated by MEX have to be removed after production. Support structures can be removed mechanically and chemically. When using soluble materials for support structure generation, the support structure can be removed in a solution, typically heated water and cleaning agent. When using non-soluble material for support structure generation, the support structures can be removed manually with tools.

5.8.6 *Stair-step Effect*—Due to the layer-wise build-up, the 3D geometry of the part becomes a stack of layers, where the shape of each layer is a 2.5D projection of its sliced geometry. This yields discrete steps in the build direction. The resulting error caused by deviation of this 2.5D image from the original geometry is described as the stair-step effect which is evident in Fig. 9. The extent of this is largely dependent on the layer thickness as shown in Fig. 7.

#### 5.8.7 Wall Thickness:

5.8.7.1 A part needs to be of a certain thickness to be manufactured without any distortion or breakage. Part walls should be at least as thick as required to provide suitable performance, while being manufacturable and maintaining suitable shapes after manufacture. Part warping and curling of corners are issues that come with designing very thin walls.



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FIG. 6 Islands / (left) Formed During the Construction of Parts