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ORIGINAL ARTICLE

Geometric considerations for the 3D printing of components using fused filament fabrication

Julián Israel Aguilar-Duque[1] · Jorge Luis García-Alcaraz[2] · Juan Luis Hernández-Arellano[2]

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Abstract

Demand in 3D printing products using fused filament fabrication (FFF) in industry has been growth a lot with 55% in development of prototypes, 43% in production, and 41% in conceptual models for testing. However, information regarding the manufacturing considerations of geometry-restricted components is still an opportunity area, generating printed components with quality defects. This article is aimed to present some characteristics in geometric components that should be considered during the developing process for components to be produced in FFF to avoid in quality defects. The methodology used considers three stages: first, the reproduction of basic geometric elements and a template that integrates elements with software design; second, the component analysis and the template with software for pre-processing of components, and third, the printing of a template for assumption validation identified in stage two. Findings obtained indicate that the spherical components are geometries with the greatest possibility of defect generation during the FFF printing process. The complexity of the template allowed to identify that the template orientation is a factor that generates defects; for example, with 0° orientation regarding the X axis generates 40,008 risk points for defect and for 30° orientation there are 6658 risk point defects. Therefore, it is advisable to consider avoid geometries associated with sphericity and cylindrical characteristics as possible in the design processes, since these geometries require specific processes to achieve the finishing quality.

Keywords Fused filament fabrication · Geometric components · Printing defects

1 Introduction

Due to the emergence of additive manufacturing (AM) in the early 1980s, the manufacturing industry expanded its field of production and specialization, breaking the paradigm of subtractive manufacturing processes (MS) [1, 2]. Figure 1 illustrates the number of articles published in the ScienceDirect database that have the phrase “additive manufacturing” in the title or keywords, where the evolution and exponential tendency of the use of that tool in manufacturing processes can be observed.

One of the reasons for the increase in the use of AM is that it allows the creation and development of new components in one or two stages, which with SM technology multiple stages are required [3–5] and, therefore, greater time or possibilities of quality breach.

In addition, it is necessary to mention that the growth of printing equipment in the sector of industrial and professional 3D printers will grow by 16% for this year [6] and that the market for personal or desktop printers will grow by 40% [7, 8]. Consequently, with these development percentages, North America has been focused on products for advanced aerospace technologies and defense, automotive, and three-dimensional printing of metal parts [9, 10]. In the case of Asia, China has been focused on the development of 3D mass printing for the manufacture of aerospace components, mostly for mass manufacturing at a cost at which the use of technology reduces future cost [11, 12]. In contrast, Europe has focused its efforts on additive manufacturing based on the use of laser adhesion for naval applications and industrial parts [13–15]. Although the aforementioned sectors are greatest boom for AM, there are other fields in developing as

✉ Jorge Luis García-Alcaraz
jorge.garcia@uacj.mx

1 Facultad de Ingeniería Arquitectura y Diseño, Universidad Autónoma de Baja California, Carretera Transpeninsular Ensenada-Tijuana #3917, 22860 Ensenada, Baja California, Mexico

2 Instituto de Ingeniería y Tecnología, Universidad Autónoma de Ciudad Juárez, Av. Del Charro #450 Col. Partido Romero.Ciudad Juárez, 32310 Chihuahua, Mexico

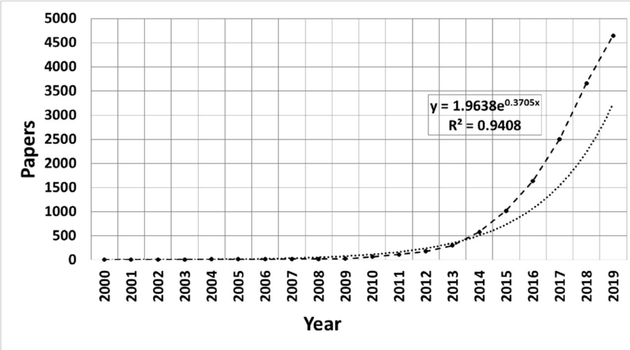


Fig. 1 Growth trend in research and publicity focused on additive manufacturing

construction [16–18], dental and medical industries [13, 19–21], fashion [22–24], food [25, 26], and many others.

Figure 2 presents the projections for the future of additive manufacturing by region [7, 13], where it is observed that they have caused a stir in the world markets through a continuous growth during the last decade, where it is projected to have a growth of 15% between 2019 and 2025. Specifically, the participation of the AM in the automotive industry will be 34% by 2019–2023, in the aerospace and medical industry 51% market share is expected by 2025, and in the medical industry, printing is projected for medical devices, which has an expected growth of 23% by 2025 [27].

The AM can be considered as the result of the evolution of digital transition mechanisms, where industrial manufacturing organizations have developed strategies focused on strengthening their computer-aided design (CAD), computer-aided manufacturing (CAM) systems, and computer-aided engineering (CAE) [28, 29], which has been focused on the modification of the methodologies used for the development and design of products, use of production systems supported by new robotic technologies, automated inspection systems and artificial vision, use of digital media for the control of production, feedback from the customers' needs in real time, use of modeling strategies, recreation of processes, and production microsystems [30–33]. However, the AM faces challenges associated with the development of printing equipment [34–36], development of new materials [37–40], the need for personnel training [41–43], and the need for strategies focused on improving the conditions of pre-processes, processes, and post-process printing [44–46].

1.1 The additive manufacturing industry

The AM is recognized as a recent manufacturing technique that uses cutting-edge technologies that make it easier for the designer and the manufacturer to create and produce components that are considered complex [4, 47]. The technologies of the AM are focused on the manipulation of material in solid or liquid state, allowing to work the material in micrometric scales, when is deposited in construction sequences layer by layer, achieve the manufacture of a solid elements [48].

The process flow presented in Fig. 3 presents in three stages in a generic way the activities that take place within an AM production system. The first stage begins with the design and development of the part or component using specialized design software, such as SolidWorks® [49] and AutoCAD® [50], among others. At this stage, computer-aided design and computer-aided engineering allow the designer to perform the feasibility, strength, shape, and materials analysis digitally to the designed element. The second stage of the process consists in the preparation of the elements that you want to print using pre-process software, as a Repetier® [51], Cura® [52], and Makerbot® [53], among others. Is in this stage that the extension file must be imported in STL (Standard Triangle Language), as well as specify the desired manufacturing properties, such as type of material, orientation, quality, and strength, among others.

The third stage is associated with manufacturing, which depends on the type of MA technology selected (Stereolithography, Laminate, Filament Manufacturing, Laser), the strength attributes

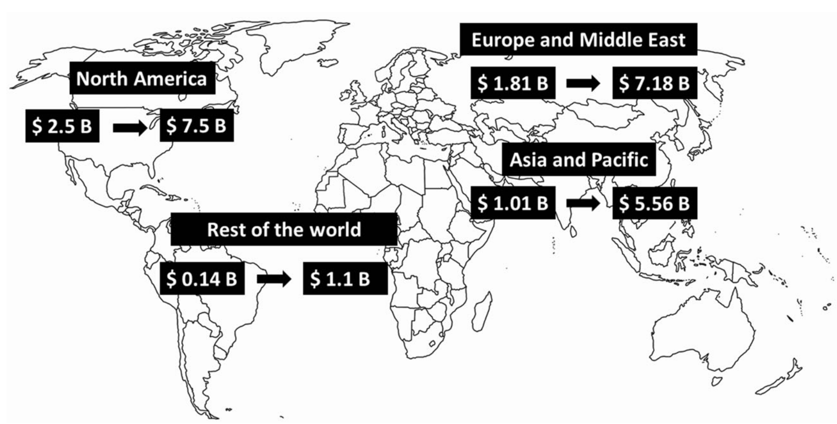


Fig. 2 Forecast of the economic development of additive manufacturing by 2025. Source Belman et al. [7]

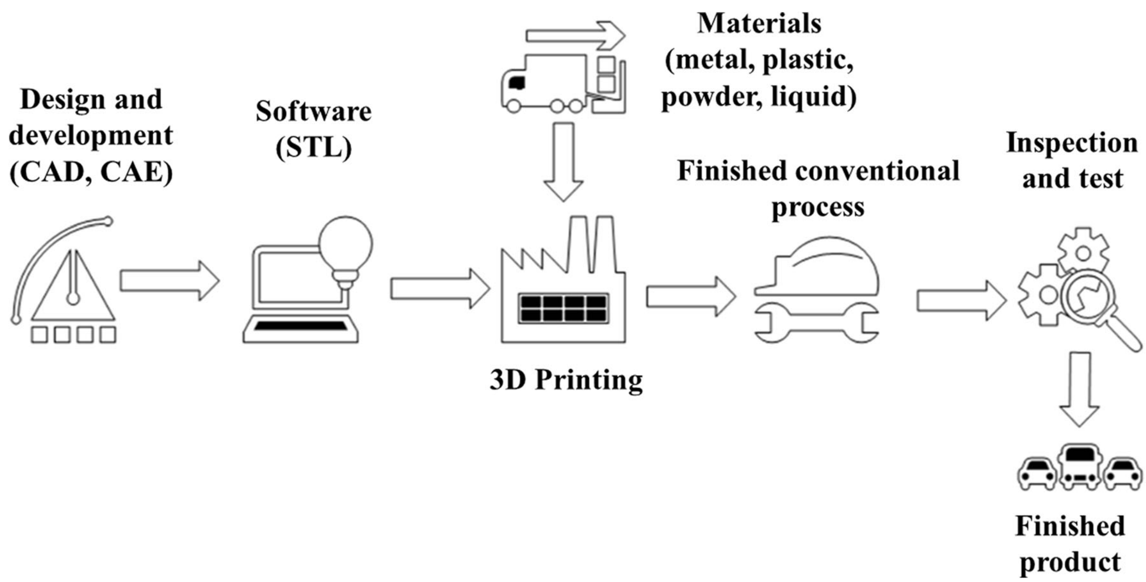


Fig. 3 Development process of fused filament fabrication (FFF)

associated with the type of material used, and quality of finish [28, 29, 54]. Once the component is manufactured, the user decided to give the last finish to the component using processes for extracting excess material, applying lacquers or paints, among others [55, 56]. Finally, in the case of small productions with a different approach to prototyping, the manufacturer can perform quality inspection tests for delivery to the end user [57, 58], and if they are prototyping elements, the components are sent to laboratories or research and development centers for its use.

1.2 Background and research problem

At an international level, the manufacturing processes of products, component parts, and assemblies have been classified according to (a) conformative technologies, (b) subtractive technologies, and (c) additive technologies [7, 28, 29]. These technologies have caused a stir in the world markets through a continuous growth during the last decade, and it is projected to have an exponential growth and evolution in the coming years, that is why several fields of investigation, application, and solution of associated problems have been generated to the different types of technologies that integrate it [2, 14, 59, 60]. From the commercial point of view and considering that the FFF process is the technology with more equipment around the world, users and developers of these technologies have directed their efforts to demand greater quality [3, 7, 61], greater precision in the dimensions of the components [62–64], better response time in manufacturing processes, and less time required for component manufacturing [4, 30, 65, 66].

In addition to the previous needs, users have begun to look for information on the equipment available in the market, generating a classification of these according to the software capacity, the capacity to generate components attached to the freedom of design and manufacturing efficiency [7, 47, 67, 68]. However, the problems identified in FFF technology are focused on the quality of the printed elements, the repeatability and preparation of the pre-process equipment and activities, the post-process activities prior to the finishing activities, the finishing activities, and maintenance service [1, 67, 69].

From an industrial point of view, low productivity, poor component quality, and uncertain mechanical properties of printed components represent a development niche for researchers and developers of FFF technology [68]. In this sense, the problems of repeatability in the dimensions of the printed components and proper finishing of the components represent 90% of the defects identified in printed elements by low-cost commercial equipment [70]; therefore, Alsoufi, Elsayed [71]; Bähr, Westkämper [62]; and Jiang et al. [63] have presented strategies for reducing the percentage of defects that are focused on the modification of tools, such as printing nozzles and feed gears, while Bähr, Westkämper [62]; Jiang et al. [63]; and Harikrishnan, Soundarapandian [72] have focused their strategies on the analysis of temperatures for the handling of several materials.

It is necessary to emphasize that the finish surface is one of the problems of the FFF and that the generation of bearings printed in a single process represents a problem for spherical elements [65, 71, 73]. Therefore, solutions have been sought based on the design of the component, orientation of the object during the design process, and selection of the pre-process parameters (speed, flow, and temperature) to the point of manufacture, which is affected by the quality of the material, the reliability of the equipment, the environment, and among others [67, 74–76].

Fortunately, the problems identified in FFF technology have decreased [1, 7]. However, there are still areas of opportunity that users should respect when developing their designs and manufacturing their components. In fact, it is necessary to declare that the information existing in social networks and Internet sites specialized in 3D printing, as well as information that has been published in research journals and books in the manufacturing area, is almost null [1, 29, 48, 70, 77, 78]. In addition, it does not present the design conditions and specifications that must be verified in the components to achieve a quality product.

Therefore, the aim of this article is to appraise the geometric shapes used for the printing of components using FFF technology and the considerations that users should keep in mind during the pre-process. The following research objectives were considered to achievement this aim: (1) identify the most common geometries used to print FFF a cross the cases reported in literature, (2) develop a set of geometries that considered the characteristics founded in the literature report, (3) identify during the pre-process the characteristics that should be considered at the moment to print an specific geometry, (4) validate the considerations suggested in this document through the analysis of the components printed in FFF, and (5) suggest a group of considerations that should be considering during the pre-process FFF components with specific geometries.

2 Materials and methods

The materials used during the development of the present research are as follows:

- Software SolidWorks® [49] for the design of geometric elements and components,
- Software Ultimaker® [52] for the pre-process component analysis,
- FFF Prusa® I3 equipment [79], and
- Filament polylactic acid (PLA) diameter 1.75 mm.

The methodology used is based on three stages; Figure 4 presents a diagram of the methodology. The stages are the following: design stage, pre-process stage, and process stage, which are described below.

2.1 Phase 1. Design

In order to integrate the most relevant geometric characteristics presented by Esposito Corcione et al. [47]; Gautam et al. [75]; Soriano-Heras et al. [20]; Song, Park [80]; and Salmi et al. [21] for the design and development of components printed by FFF, a set of elements that integrate flat bases, cubes, perforated cylinders, spheres, solid cylinders, and coned and angled surfaces must be developed using the software SolidWorks®, which according to Locker [81] is a design software used to create components for 3D printing.

The set of elements to be designed must comply with the characteristics of the International Standard Organization [82], such as the following:

(a) Basic dimensions ranges: 1 to 3 mm, 3 to 6 mm, 6 to 10 mm, 10 to 18 mm, 18 to 30 mm, 30 to 50 mm, 50 to 80 mm, and 80 to 120 mm.
(b) Blocks: To define flatness and linearity in the geometric element, six 4 × 15 mm base blocks with heights of 1, 3, 6, 10, 21, and 28 mm.
(c) Truncated cones: To define elements of geometric roundness and angles, two truncated cones are designed. The first one has the following dimensions: diameter greater than 20 mm, diameter smaller than 13.6 mm, and height 12 mm. Coaxial internal truncated cone; height of 10 mm, a main diameter of 10 mm, and a diameter of less than 6.5 mm. The second cone has a diameter greater than 5 mm, a diameter less than 4 mm, and a height of 6 mm. The external truncated cone with height of 9 mm, main diameter of 10 mm, and a diameter smaller than 6.8 mm.
(d) Coaxial cylinders: They are used to define the flatness and roundness of a geometry. Two sets are considered for this project: two 4 mm and 16 mm diameter cylinders, with two blind holes with 8 mm and 24 mm diameter,

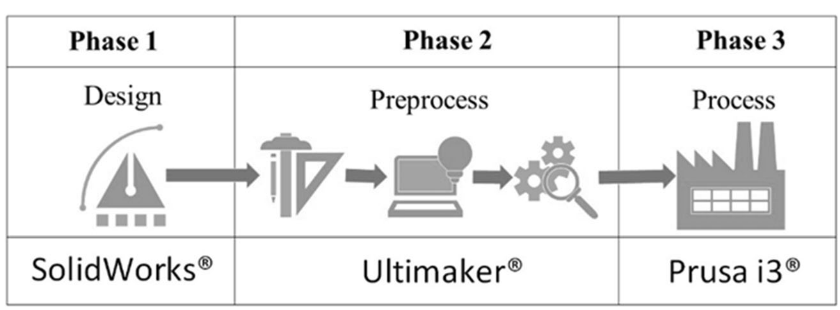


Fig. 4 Phases for the analysis of the geometries in printing FFF

8 mm height, which is inscribed in a 16 mm high hexagonal prism with a hexagonal base and an edge length of 16 mm. The second set has cylinders of the same dimensions with the restriction that the development is inversely.

(e) Hemic cylinders with horizontal axis: These geometries are used to define roundness. The first set consists of four convex hemic cylinders with a length of 10 mm, diameters that decrease in sequence of 24, 16, 8, and 4 mm. The second set is formed by four concave hemic cylinders of 10 mm in length; the diameter of these sets increases in ascent starting at 4, 8 mm, 16 mm, and 24 mm.

(f) Inclined planes: They are used to define angularity, flatness, straightness, quadrature, precision, and repeatability. This set consists of ten elements of 5 × 15 mm, with inclinations of the planes within the complementary set and with fan opening at an inclination to the base plane of the piece that increases from 0 to 45° by 5° steps.

(g) Combination for geometric set 1: It is used to define the combination of flatness and roundness from a cube; it is developed from the perforated cube, with dimensions for the cube of 100 × 100 × 100 mm, and cylindrical perforations passed from face to face of the cube with a diameter of 80 mm; the perforation should be carried out in the center of the face of the cube.

(h) Combination for geometric set 2: It is used to define flatness and roundness from a cylinder; a cylinder with a diameter of 100 mm and a height of 100 mm is developed. The cylinder is pierced with a square cut of 90 × 90 mm through the center of the cylinder height.

(i) Combination for geometric set 3: This set is used to define roundness, flatness, repeatability, and angles. The set consists of a cylinder that has a diameter of 100 mm and a height of 200 mm. The base 1 has a cylindrical cut of 80 mm × 15 mm deep, a second cylindrical cut of diameter of 60 mm × 30 mm deep, and a third cylindrical cut of diameter of 20 mm with depth of 40 mm. Base two has a quadrangular cut of 65 × 65 mm with depth of 40 mm, as well as a set of hemic cylinders: one with a diameter of 50 mm × 20 mm high and the second with a diameter of 40 mm and a height of 20 mm.

(j) Template: It is used to measure flatness and straightness, quadrature, parallelism, precision and repeatability, roundness, cylindricality, precision and repeatability of radius, spherical roundness, repeatability, and inclination on surfaces with inclination, coaxially, taper and angularity, use is made of the geometric dimensions set out in sections a–j in addition to the characteristics proposed by Minetola et al. [64].

Furthermore, because the FFF printing equipment uses the files from the Standard Triangle Language (.STL) [32, 40], the pre-process stage is concluded when generating the geometric elements designed in the .STL file.

The development of geometries must integrate the characteristics defined by Rylands et al. [2]; Srivatsan, Sudarchan [29]; Dong et al. [67]; Mohamed et al. [83]; Dabbour [73]; Moylan et al. [84]; Choi, Kim [19]; Sood et al. [78]; Bourell et al. [85]; and Mellor et al. [77]. Table 1 presents the characteristics associated with each geometry.

2.2 Phase 2. Pre-process

The software Cura of Ultimaker was used in this phase, Locker [81] declares that Cura of Ultimaker is the free most implemented software used during the last years by users of the FFF equipment during preprinting activities. During the preparation process, the software guides the user to determine values that the equipment operates, as well as the attributes that will be assigned to the component during the printing process. This project considers the parameters listed below as determined by Srivatsan, Sudarchan [29]; Mohamed et al. [83]; and Weeren et al. [61].

- Quality: layer height 0.1 mm, shield thickness 0.8 mm, material retraction enabled, initial layer thickness 0.3 mm, percentage of initial line width 100%.
- Infilling: Thickness of the top layer and bottom layer 0.6 mm, density of the filling 100%, the perimeters must be printed first, then the filling.
- Print speed: Transfer speed at 150 mm/s, top layer speed 20 mm/s, fill print speed 80 mm/s, top/bottom speed 15 mm/s, print speed outside of the element 30 mm/s, print speed inner layer of the element 60 mm/s.
- Support: Type of support on the whole object, adhesion to the platform in the form of brim.
- Nozzle dimension: 0.4 mm.
- Minimum cooling of 5 s per layer.
- Polylactic acid material in the form of a filament with a diameter of 1.75 mm.
- Equipment operating temperatures: 210 °C for the extruder and 60 °C for the printing plate.

2.3 Phase 3. Process

Finally, the process stage was designed using the FFF printing equipment for printing the proposed template. The equipment used is a single extruder printer, Prusa I3 brand, with a printing area of 200 × 200 × 200 mm, for material consumption of 1.75 mm.

Table 1 Geometric characteristics considered for the development of printed components in FFF

Characteristic	Purpose
Cube	Quadrature, parallelism, linear precision, and repeatability
Perforated cylinder	Roundness, cylindricality, accuracy, and repeatability of radio
Sphere	Sphere, relative adequacy, and repeatability on inclined surfaces with continuous curves
Solid cylinder	Roundness, cylindricality, accuracy, and repeatability of radio
Hollow cylinder	Roundness, cylindricality and coaxially of cylinder
Cone	Conicity, inclination of profile, and narrowing of the geometry
Angled surface	Angularity, precision, and repeatability of angles on angular surfaces

3 Results and discussions

The results and discussions are described in the section below according to the steps described in the methodology that was used.

3.1 Phase 1. Design

The set of blocks and their design is found in Fig. 5; these were developed according to the stages specified in the methodology section. Figure 6 shows the plan of the set of truncated coaxial cones.

Figure 7 shows the set of coaxial cylinders and the dimensions described in the methodology. Likewise, Fig. 8 presents the set of hemic cylinders used to review the roundness effect. Figure 9 portrays the set of inclined planes showing inclinations of the planes within the set which are complementary and open in a fan with an inclination to the base plane of the piece, which increases from 0° to 45°by 5° steps. Once the basic geometries were designed, more complex elements were designed. For this, the use of the perforated cube was made, which is a cube with dimensions of 100 × 100 × 100 mm, with cylindrical perforations passed from face to face of the cube with a diameter of 80 mm; Figure 10 presents the element.

Moreover, Fig. 11 shows in reverse the way described in Fig. 9, a cylinder 100 mm in diameter × 100 mm in height. The cylinder is pierced with a square cut of 90 × 90 mm passed through the center of the height of the cylinder. Figure 12 shows a cylinder with machining in the bases in view of hidden lines; the specifications were presented in the methodology section.

In order to integrate representative elements of a flat base, cubic elements, perforated cylinders, spheres, solid cylinders, cones, and angled surfaces, a template was developed with the mentioned elements. Figure 13 presents the template developed.

3.2 Phase 2. Pre-process

To perform the fault analysis through the pre-process, the use of the software was made CURA®. The first analysis considered is that of the block set, for them the overhand view generated by the software is used. This analysis is focused on determining characteristics of flatness, straightness, parallelism, linear precision, and repeatability. Figure 14a shows the set of blocks in orientation of the object against the printing plate at 0°, Fig. 14b shows the set of blocks in orientation of the object against the printing plate at 30°, and Fig. 14c presents the set of blocks in orientation against the printing plate at 60°. Finally, Fig. 14d shows the block assembly in orientation against the printing plate at 90°. From the analysis of

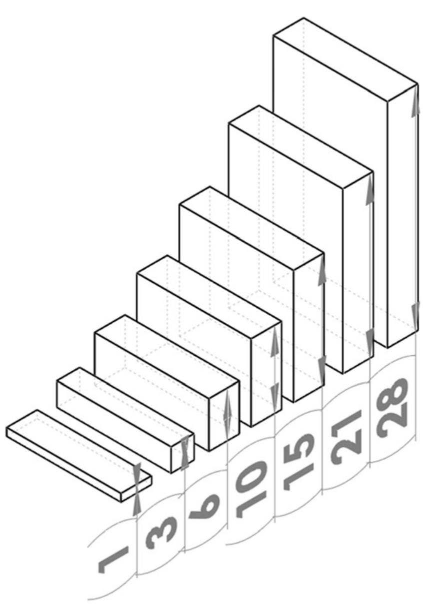


Fig. 5 Blocks for flatness and linearity

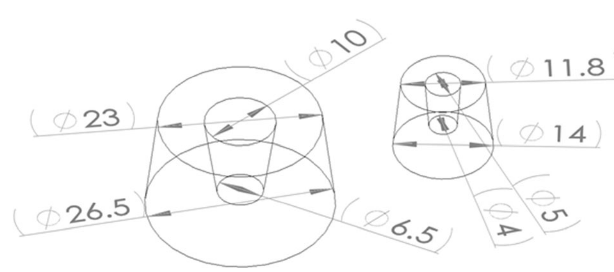


Fig. 6 Truncated coaxial cones for angles and roundness

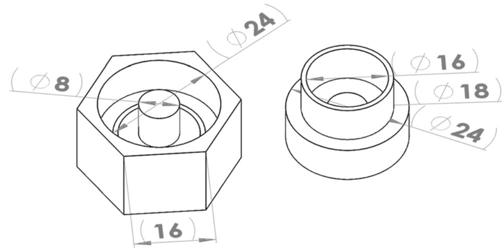


Fig. 7 Coaxial cylinders for flatness and roundness

images, it is possible to determine by the absence of indicators from areas or red segments; this visual indicator is very important due that the software indicates the absence of overhang material. The absence also indicates that the last mesh is normal, and the modal will not present quality defects, at least in surface. Conducting an analysis of vertices and faces highlights that the orientation of the object at 0° or 90° respect of the plate generates 56 vertices; these minimum number ensures that the component is well defined with a few vertices and faces. In general, the FFF printing equipment does not have problems to print homogeneous quadrangular elements, in which there are no geometric variations in the shape of the component. It is important to note, in addition, that the orientation of the object against the printing plate does not represent alterations in the time required for printing or in the consumption of material.

In addition, for the development of the second analysis of geometric components, the elements associated with truncated cones were used, in order to identify possible effects of failure in the roundness of the component, taper, inclination of the profile, and narrowing of the component during the change in diameter, since the analyzed element has an angled surface, the angularity, precision, and repeatability of the angles are also tested.

Figure 15a shows the set of truncated cones with 0° orientation regarding the printing plate. In Fig. 15b, it is possible to identify the set of truncated cones with 30° orientation regarding the printing plate. Figure 15c shows the set under analysis with an orientation of 60° regarding the printing plate. Finally, Fig. 15d presents the set of truncated cones with an orientation

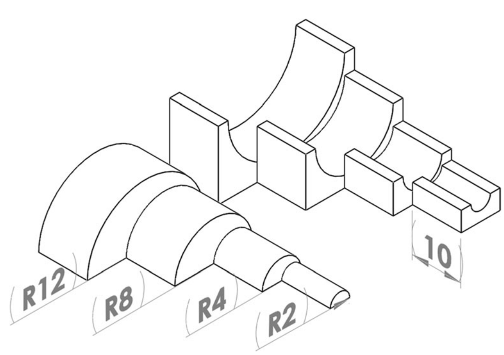


Fig. 8 Hemi cylinders for roundness

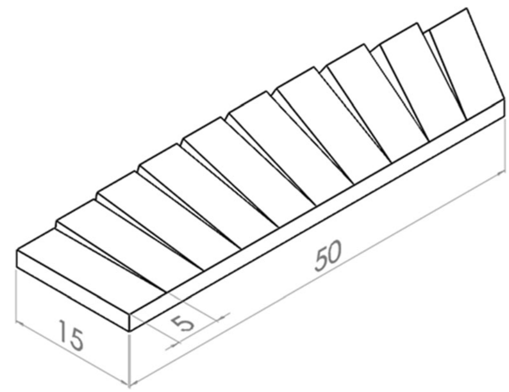


Fig. 9 Set of inclined planes for angularity

of 90° regarding the printing plate. As in the block components, it is possible to identify that no possible alterations of the component are identified by varying the orientation of the component related to the printing plate. The absence of red points indicates that the components do not have overhang; this finding is interesting due that the cones are geometries with an angle variation, and the absence of overhang assures that the component will not have surface quality; also, this characteristic discriminates if the angle is ascending or descending. Considering the analysis of faces and vertex is important to highlight that the best orientation to this kind of geometries is 90°; this orientation generates the minimum quantity or vertex and in consequence fewer quality defects. No matter the orientation of the component, the consumption of material is the same.

For the analysis of the characteristics of roundness, cylindricality, precision, and repeatability of radius in combination with the characteristics of quadrature, parallelism, linear precision, and angularity, the use of the components called cylinders and hemic cylinders was made. Through the view of the overhang pre-process component, it is possible to identify that the combination of the geometric elements is not altered, and the risk of defects is null, since no fault indicators (red dots) are identified. Considering a depth analysis, the combination of circular elements and angles supposes the risk of increase the quality defects over surfaces generated by excess of material or splicing layers. An assembly of coaxial

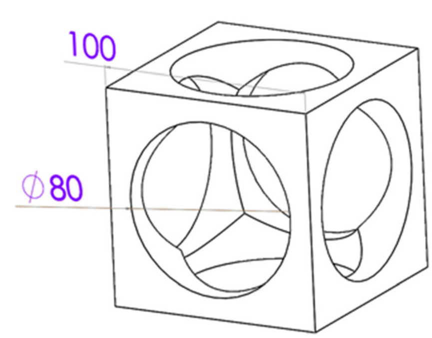


Fig. 10 Perforated cube, for flatness and roundness

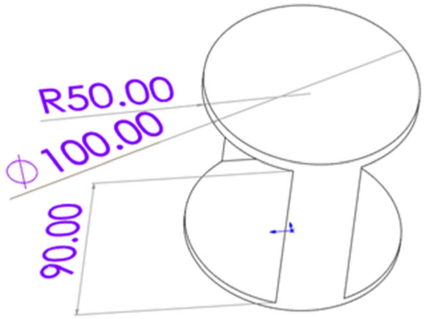


Fig. 11 Perforated cylinder, for flatness and roundness

cylinders increases the vertex number. However, it is possible according to the vertex and face analysis declare that the best orientation for this kind of components is 0° with plate respect. The 0° orientation of the object respect to the build plate is the most accurate, according to Cura Ultimaker software, for components that integrate angles and circumferences. Figure 16a shows the image of the cylinder component with 0° orientation related to the flatbed printer. Figure 16b presents the image corresponding to the orientation of the object related to the flatbed at 30°; Fig. 16c refers to the component oriented at 60° related to the flatbed printer. Figure 16d shows the image of the component with 90° orientation regarding the printing plate.

Once the components were analyzed individually, it is proceeded to make the analysis of the template that, being a more complex component due to the integration of all the geometries in different scales, the overhang view analysis has been considered. Figure 17a shows a front view of the template parallel to the printing plate. In this figure it is likely to identify possible printing failures generated by overhang in elements that require a type of support. As we mentioned the components that have red areas are potentially identified as effects for quadrangular, circular, and angled components that have been built without support, even Montero et al. [86] and Pennington et al. [87] remark that to eliminate overhang the structures require support, but in the case of the template, the stairs pyramid and the arcs were designed to be printed in a

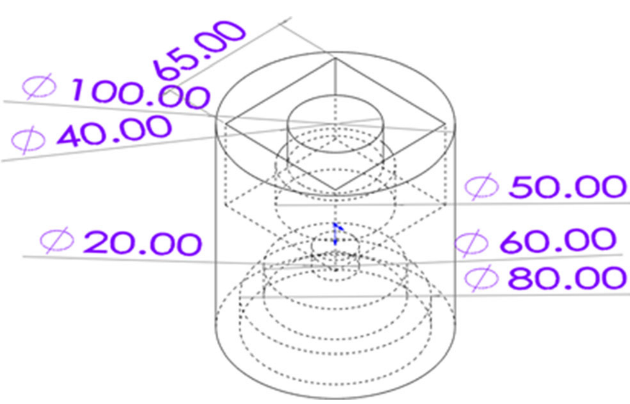


Fig. 12 Machined cylinder

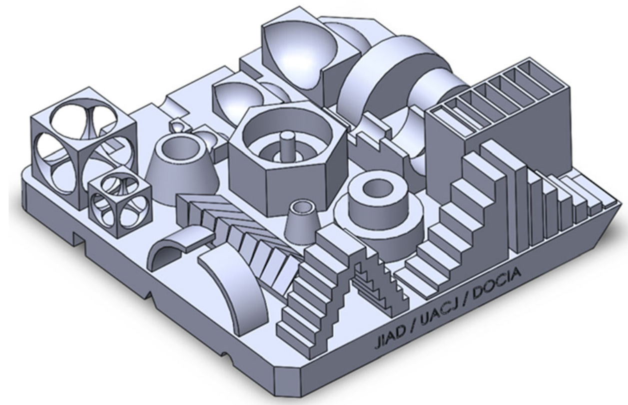


Fig. 13 Template with basic and complex geometry elements

staggered way; this alternative prevents the total layer floting. In contrast with the elements that were placed on the base of the template, in this cases the top of the geometry flies away, increasing the overhang as mentioned by Cheng, Chou [88]. Figure 17a presents the mentioned perspective.

In the case of Fig. 17b, it is possible to appreciate that the effect is not presented in angular elements with stepped growth, such as the pentagon, even this view allows to confirm that arcs still marked as a potential fail, as mentioned by Montero et al. [86]. For this image, a rotation of the template at 30° was considered. Figure 17c portrays the risk point associated with curved elements with support, which, despite having a stepped growth, the quality of the figure is restricted by the shape of the component, being roundness a disadvantage in the case of elements flown. Due that template is a complex element, the orientation is crucial; considering the number of vertex as a product of the geometric combinations, the orientation to 30° represents from the pre-process point of view the best alternative due that reduces the possibility or generates quality defects or surface defects.

Since the elements were identified with possible points associated with the generation of defects during the printing process, an analysis of the critical elements and the concentration of vertices for the template element were performed. It is necessary to clarify that the template represents the elements that projected possible defects together with the combination of the geometries considered, as well as the orientation of the template related to the flatbed printer. In Fig. 18, it is possible to confirm that elements with uniform quadratic geometries do not represent defect points, since the concentration of yellow points is low or almost zero, which only occurs to the vertices of the blocks.

Similarly, in the analysis developed in Fig. 18, through the analysis of vertices of the geometries, it can be identified that the elements with roundness represent a possible fault generator depending on the curvature or roundness as had been

Fig. 14 Block set with different orientation with respect to the printing plate. **a** 0°. **b** 30°. **c** 60°. **d** 90°

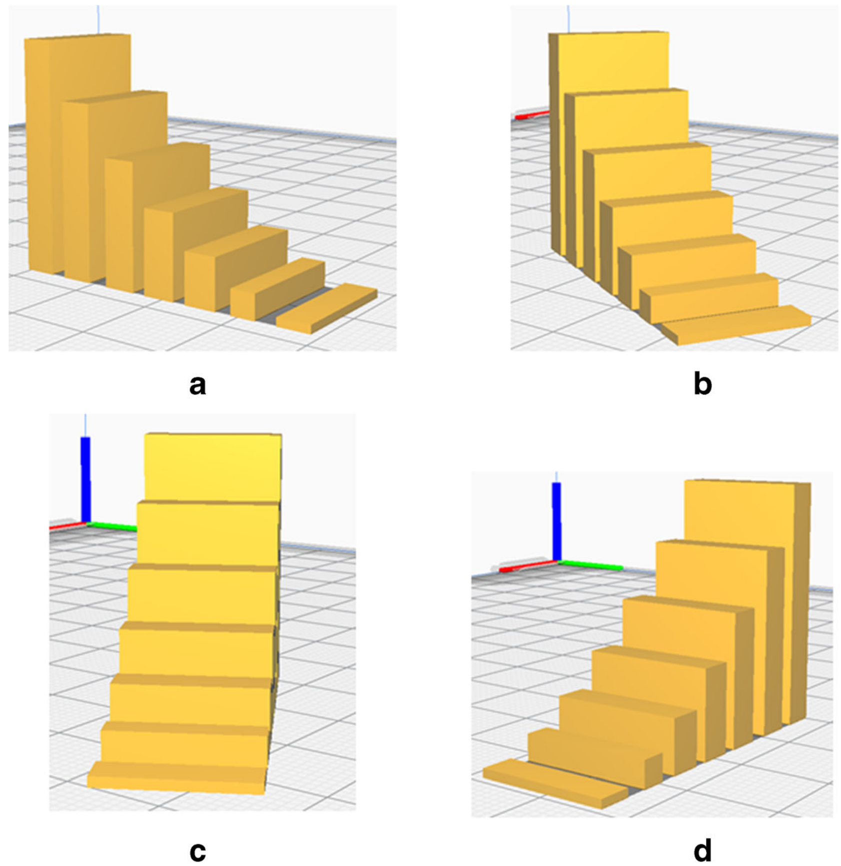
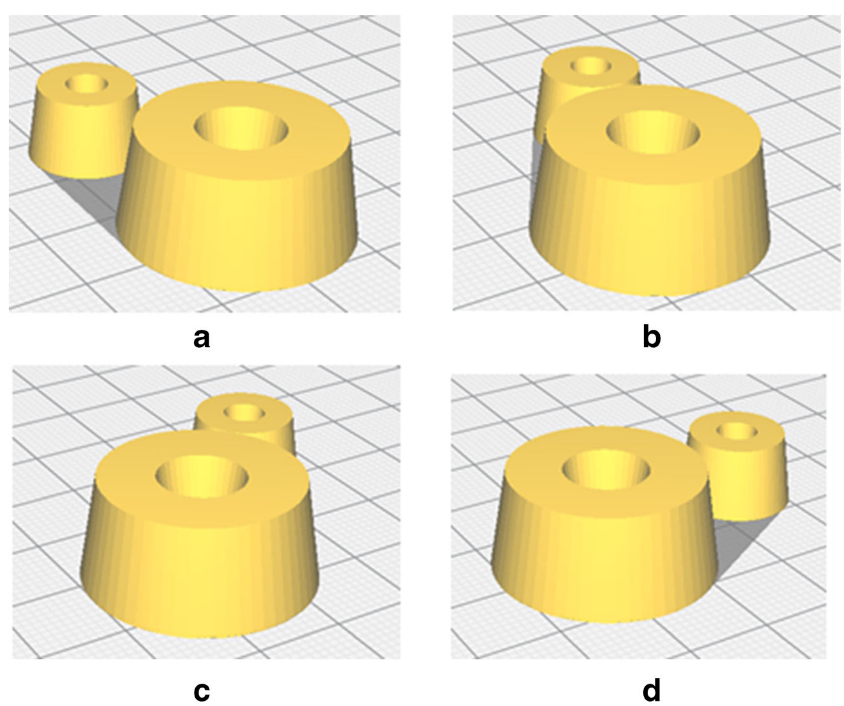


Fig. 15 Set of truncated cones with different orientation with respect to the print bed. **a** 0°. **b** 30°. **c** 60°. **d** 90°



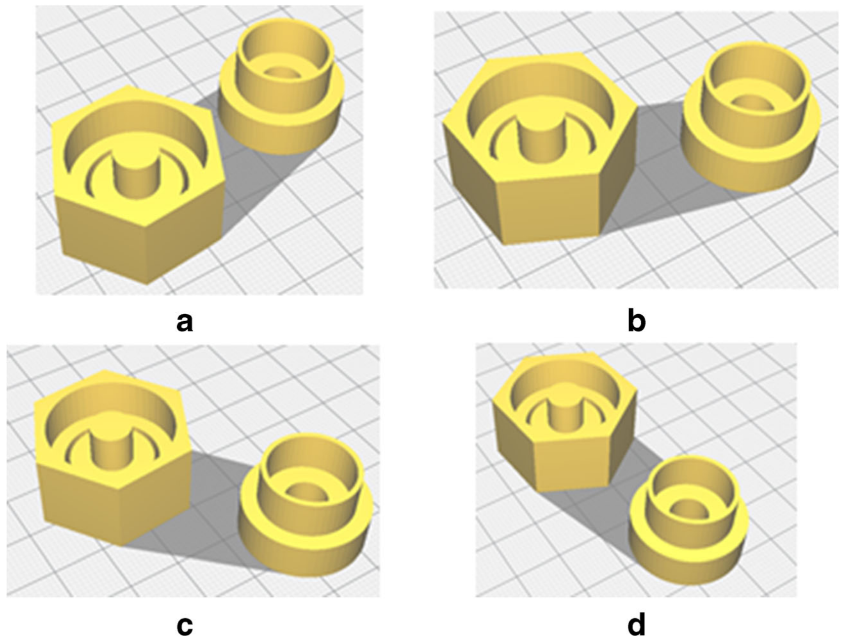


Fig. 16 Cylinder set with different orientation with respect to the print bed. **a** 0°. **b** 30°. **c** 60°. **d** 90°

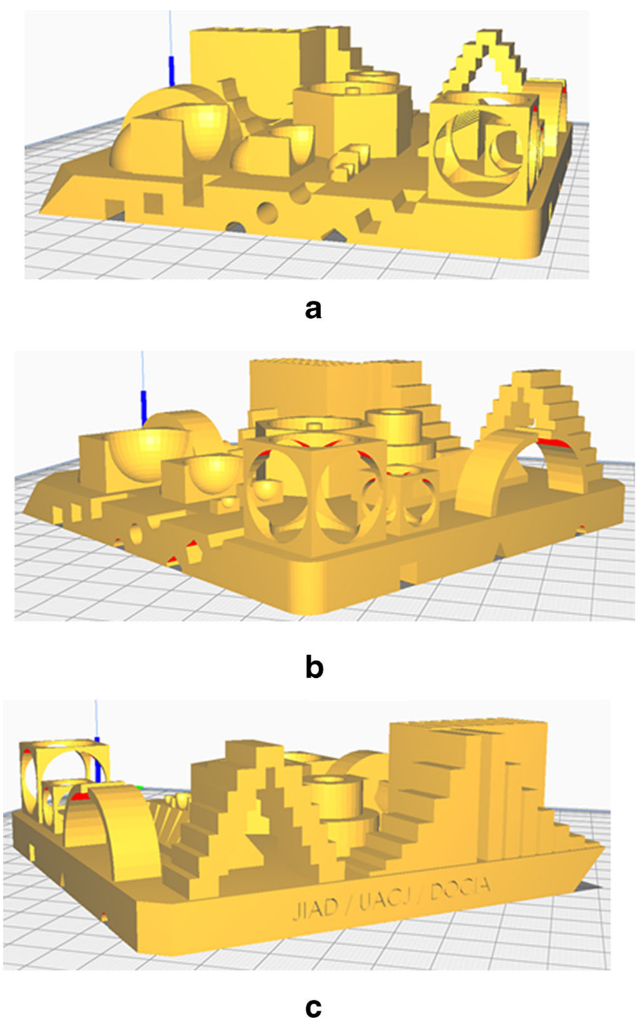


Fig. 17 **a** Template elements with possible fail generators. **b** Template elements with possible fault generators, 30° orientation with respect to the print bed. **c** Template elements with possible fail generators

mentioned by Zhang et al. [58] and Shanmugam et al. [35]. Figure 19 shows the elements called hemic cylinders, which with the combination of flatness and curvature it is possible to identify that the number of yellow dots is indicating defects, which is reduced. On the other hand, there is the sphere, and since it is a completely round element without flatness, allows to identify that the set of yellow dot indicators increases according to the increment in vertices required to create the component.

Once the file was generated for the analysis of vertices and faces, Table 2 was created, which presents a record of the number of faces and vertices of the components according to the orientation of the element.

It is important to notice that each vertex represents a possibility of defect in the component printed by FFF. Table 2 shows the orientation object regarding the flatbed printer. Columns labeled with the number 1 indicate the number of vertices generated in the component by orientation, while Column 2 indicates the number of faces identified in the component. A color code has been used in which green shows the minimum of vertices, which represents a smaller number of defects due to convergence of lines, whereas red color indicates a greater

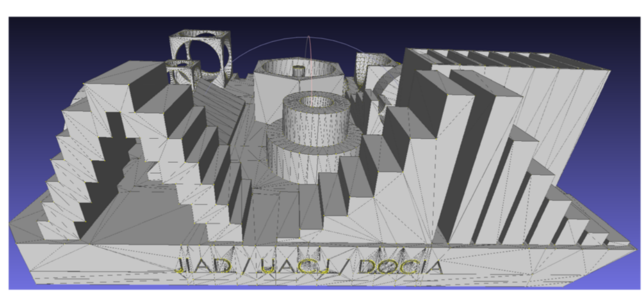


Fig. 18 Analysis of the template elements considering the set of vertices

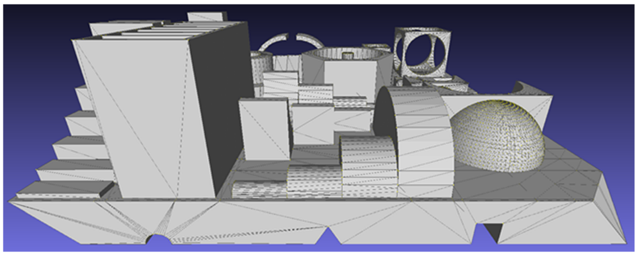


Fig. 19 Analysis of the template elements considering the set of vertices

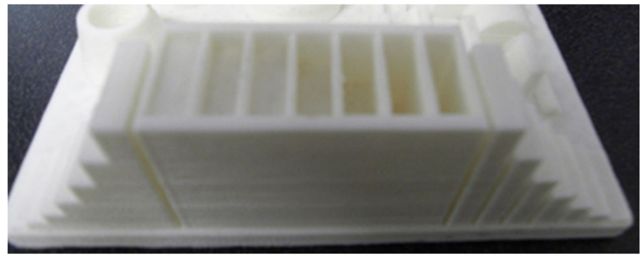


Fig. 20 Set of blocks printed in FFF

number of vertices that indicate a greater convergence of lines. The column with heading 2 has been left for each orientation in order to show that the number of faces of the component does not change despite the decrease in the number of vertices.

3.3 Phase 3. Process

Once the pre-process model was developed, the use of the printing equipment was made to validate the assumptions associated with the defect generating elements; the orientation of the template was carried out considering the orientation based on the least number of vertices. In the case of the template, it was verified that the geometries belonging to the set of blocks did not show printing defects; therefore, the teams do not have problems with cubic elements; that is, regardless of the orientation of the component, it is possible that the characteristics of quadrature, parallelism, linear precision, and repeatability are preserved as mentioned by Dabbour [73] and Moylan et al. [84]. However, depending on the desired quality in the printed component, it is possible to identify the staggering effect, which should not appear in elements with geometries corresponding to the block family. Elements such as blocks are considered in Fig. 20.

In the one hand, the case of hollow cylinders and components with spherical geometries, it was verified that the printing process generates defects associated with the shape of the geometry, in which excess material layers are generated, which do not correspond to the component. In Fig. 21, the surplus of matter in the hollow cylinder geometry is identified. On the other hand, spherical components are conducive to generating the staggering effect, which has a marked offset between each of the printing layers. In this case, it can be mentioned that this type of elements did not meet the characteristics of cylindricality, precision, and repeatability in the case of the cylinders. Regarding the sphere, it did not meet the characteristic of relative adequacy, repeatability, and inclined surface with continuous curves. These characteristics match the results mentioned by Moylan et al. [84]; Choi, Kim [19]; and Rylands et al. [2].

Likewise, in the case of the hemic cylinders, it was possible to verify that it is possible to print the component without generating excess material in the geometry. However, due to the cylindrical shape of the component and the variation of the scales, the staggering defect was presented, which can be reduced by decreasing the diameter of the printing nozzle under the premise of increasing the printing time. In the case of the set of inverted hemic cylinders, the staggering effect is presented when the arc height is increased. Consequently, with this effect, problems associated with roundness, cylindricality, precision, and radio repeatability are generated. Figure 22

Table 2 Orientation effect against the number of vertices

Component	Orientation							
	0°		30°		60°		90°	
	1	2	1	2	1	2	1	2
Set of blocks	*56*	84	224	84	**280**	84	56	84
Truncated cones set	676	764	1544	764	**2292**	764	*386*	764
Coaxial cylinder assembly	*782*	1560	**4680**	1560	3910	1560	2150	1560
Hemicylinders	*375*	1742	**2250**	1742	2226	1742	*375*	1742
Inclined planes	*53*	102	**306**	102	106	102	*53*	102
Geometric set 1	3240	1080	*532*	1080	1596	1080	**3724**	1080
Geometric set 2	**1212**	404	606	404	*202*	404	**1202**	404
Geometric set 3	**3162**	1054	*529*	1054	1587	1054	2116	1054
Template	**40,008**	13,336	*6658*	13,336	16,645	13,336	26,672	13,336

High values represent poor quality because of the greater number of vertices. The best orientation for each component is the one with the minimum vertex value

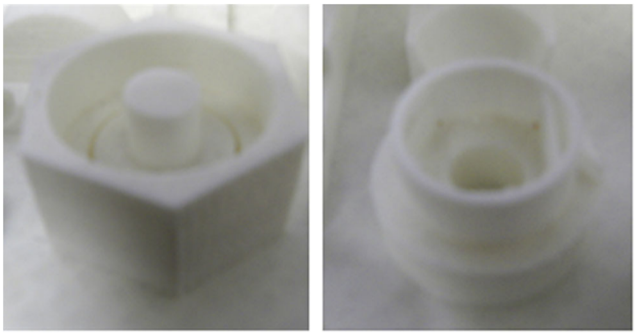


Fig. 21 Set of cylinders and spheres printed in FFF

presents the image corresponding to the set of hemic cylinders printed in FFF.

Finally, Fig. 23 is presented with the template image printed in FFF; this template was developed considering the basic geometric characteristics for the development of printed components in FFF.

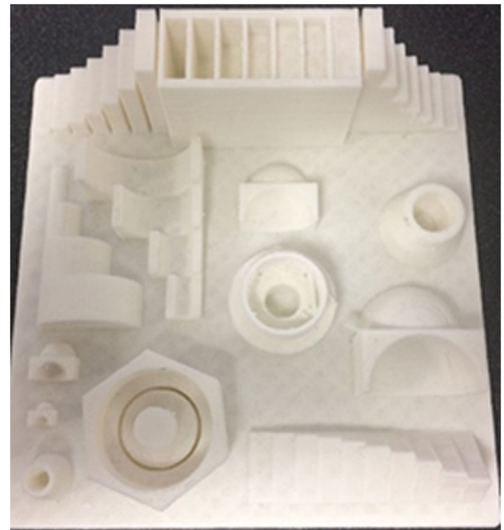


Fig. 23 Template printed in FFF

4 Conclusions

As a matter of fact, the FFF technology is an AM technology that is booming due to its high level of socialization. In this sense, the relevant information for the development of components regarding the specifications that users must consider should be available when they develop pre-process activities as well. Coupled with this information, it is important to mention that there are factors that definitely affect the quality of printed components, such as flexural strength, hardness, tensile strength, compressive strength, dimensional adequacy, surface roughness, and production time.

Specifically, in this research, pre-process for cubic elements, cylindrical elements, spheres, cones, and surfaces with variations of angles were considered; therefore, the analysis of other variables associated with the equipment, material, and environmental temperature were not considered but can be considered for future researches. For the design and development of component with cubic elements, such as blocks, the user must take into account that the orientation of the solid base of the block must be anchored to the printing plate; regardless the orientation of the block on the “X” axis of the platform, the quality of the component will not vary as it had been described; the absence of overhang allows liberty of design and process as long as the element has at least one of its sides parallel to the printing plane. However, it is essential that these types of elements are always printed out on their design basis.

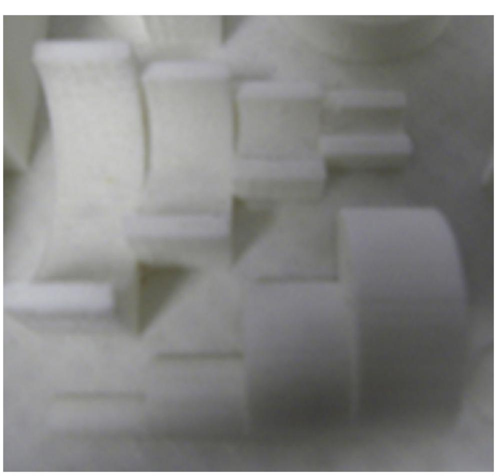


Fig. 22 Set of hemicylinders printed in FFF

In the same way, placing the construction of a block type element on one of the vertices of the component represents a risk of deformation in the component by generating quadrature defects, low linear precision, and little precision in the repeatability of the dimensions of the component, along with the appearance of the effect stepping on the side faces of the component. In order to define the degree of deformation present in block type components, it is recommended to perform a deformation analysis considering inclinations of printing angles with the help of supports and analyzing the red areas generated by the software; as it had been mentioned, these areas will create the effect of overhang in the layer or a defect in mesh.

The cylindrical elements used in this research represent a variation in the diameter of the component. The two elements analyzed were prepared for their printing process with the base of the component oriented parallel to the printing plate. This attribute ensures that the roundness of the element is not affected by the deposition of the material. However, the tool path generates a defect caused by the dragging of material. It can be feasible to research about the effect of reducing the height of the layer and the thickness of the shields, with the aim of increase flexibility in the deposition process.

Likewise, the thickness of the layers of the cylinders represents a critical consideration, since the number of shields assigned to the cylinder formation may directly affect the strength of the component. Depending on the desired quality of the component, the cylinder can be printed with the use of a small diameter nozzle (0.2–0.4 mm) with a minimum of 2 shields. Obviously, minimum size in nozzle diameter will increase the production time. This can be adjusted increasing temperatures and speed tool, under the risk of affect linked to this variables. The case of the cylinders is enhanced by the number of shields (at least 2) that are used to form the curvatures, and it is possible to ensure that being a circular geometry, the orientation towards the "Y" axis of the printer against the object does not affect the object definition; that is, the orientation of the object does not affect the attributes of roundness, cylindricality, accuracy, and repeatability of the element's radius. Like the block elements, the possibility of analyzing this type of components is left open when making a preparation by pointing the cylindrical part towards the printing plate considering more orientation angles.

Moreover, spherical elements are the most complex set in the FFF printing process. These elements are widely used for the development of articulated components where relative adequacy and repeatability are sought on inclined surfaces with continuous curves. Specifically, by being components with an infinite number of vertices, it is possible to rule out as a factor generating defects to the orientation of the element with respect to the printing plate. However, it is necessary to consider that this type of components tend to reproduce the staggering effect between layers by their nature, which, based on the user's needs, it is advisable to use nozzle smaller than 0.3 mm of diameter with lower print speeds at 30 mm/s.

Likewise, the determination of profiles with inclination, as well as elements with dimensional variation generated by narrowing of the geometry, can be analyzed with the use of cones. The present investigation uses two truncated components to identify the effects caused by angular variation. Despite the use of a commercial diameter nozzle and the dimensions considered in the design of the cones, the component was able to print without defects. However, it should be considered that the inclination of the component is an important factor that is associated with the angle used. The result of a smaller angle is a consequence of a stepping between the layers.

A relevant part is a function of the number of vertices and faces that define the component, which affect both the quality of the finish and the resistance that the component can offer different types of efforts. As it is presented in Table 2, simple geometries have better performance when their construction angle is parallel to the "X" axis of printing; however, complex components have a better performance in terms of fewer vertices when 60° orientations are performed or 30° of the component regarding the printing axis "X." The possibility is left open to experiment with lower angle ranges for future experiments.

Finally, it is convenient to mention that in the history of the FFF, the development of research works has been focused on the analysis of the capacity of reproduction of components, the development of materials, analysis of mechanical properties of the printed elements, quality of the component, and the effect of the printing parameters on the control variables of the equipment. However, the recommendations of orientation of objects formed by the basic geometries have been discarded, which detonate the quality of any component printed in FFF, because a component is designed from cubes, spheres, cylinders, cones, and inclined planes. Therefore, the possibility of performing an effect analysis of the several printing factors against the orientations of basic geometric elements could define a standard of printing orientation for components, which are printed through FFF technology; therefore, it is finally left open for further research.

Finally, here is important to mention some limitations in our research, because due to characteristics associated to the filament printing equipment used, the final quality of analyzed components was limited to the characteristics reproduced by the height of the layer and the thickness of the shields, especially in geometries with cylindrical and spherical characteristics. Likewise, the orientation of components with respect to the impression plate represents a limitation in this project, because only four orientations were considered (0°, 30°, 60°, 90°). In addition, the use of the Cura® software limits the specialist in the object preparation, restricting variables of interest such as the orientation and separation of the filling patterns.

So, based on that limitations, future works are intended to replicate the experiment using different 3D printer equipment. Also, it is intended to modify and reprogram the objects, with orientation angles, as well as the characteristics associated with the raster angle, raster width, and air gap.

Author contributions Julian Israel Aguilar Duque: conceptualization, investigation and project administration, visualization and supervision, software, writing—original draft preparation and writing—review and editing; Jorge Luis García-Alcaraz: software, investigation, methodology, validation, formal analysis, and writing—original draft preparation; Juan Luis Hernandez Arellano: software, writing—review and editing, conceptualization, methodology, software, and data curation.

Data availability Does not apply.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

Code availability Does not apply.

References

1. DDDrop (2020) What are the advantages of the FDM technology? https://www.dddrop.com/fdm-technology/. Accessed 02.05.2020 2020
2. Rylands B, Böhme T, Gorkin R, Fan J, Birtchnell T (2016) The adoption process and impact of additive manufacturing on manufacturing systems. J Manuf Technol Manag 27(7):969–989. https://doi.org/10.1108/JMTM-12-2015-0117
3. Rayna T, Striukova L, Darlington J (2015) Co-creation and user innovation: the role of online 3D printing platforms. J Eng Technol Manag 37:90–102. https://doi.org/10.1016/j.jengtecman.2015.07.002
4. Oettmeier K, Hofmann E (2016) Impact of additive manufacturing technology adoption on supply chain management processes and components. J Manuf Technol Manag 27(7):944–968. https://doi.org/10.1108/jmtm-12-2015-0113
5. Weller C, Kleer R, Piller FT (2015) Economic implications of 3D printing: market structure models in light of additive manufacturing revisited. Int J Prod Econ 164:43–56. https://doi.org/10.1016/j.ijpe.2015.02.020
6. Knight L, Meehan J, Tapinos E, Menzies L, Pfeiffer A (2020) Researching the future of purchasing and supply management: the purpose and potential of scenarios. J Purch Supply Manag:100624. doi:https://doi.org/10.1016/j.pursup.2020.100624
7. Belman E, Jiménez J, Hernández S (2020) Comprehensive analysis of design principles in the context of industry 4.0. RIAI Rev Iberoam Autom Inform Ind 1:16. https://doi.org/10.4995/riai.2020.12579
8. Wirth M (2020) What the 3D printing community teaches us about innovation. The crest of the innovation management research wave, vol Series in Innovation Studies. Vernon Press, Malaga
9. Nikitakos N, Dagkinis I, Papachristos D, Georgantis G, Kostidi E (2020) Economics in 3D printing. In: 3D printing: applications in medicine and surgery. Elsevier Inc., pp 85-95. doi:https://doi.org/10.1016/B978-0-323-66164-5.00006-4
10. Heemsbergen L, Daly A, Lu J, Birtchnell T (2019) 3D-printed futures of manufacturing, social change and technological innovation in China and Singapore: the ghost of a massless future? Sci Technol Soc 24(2):254–270. https://doi.org/10.1177/0971721819841970
11. Zhang L, Luo X, Ren L, Mai J, Pan F, Zhao Z, Li B (2020) Cloud based 3D printing service platform for personalized manufacturing. SCIENCE CHINA Inf Sci 63(2):124201. https://doi.org/10.1007/s11432-018-9942-y
12. Wang L, Du W, He P, Yang M (2020) Topology optimization and 3D printing of three-branch joints in treelike structures. J Struct Eng 146(1):04019167. https://doi.org/10.1061/(asce)st.1943-541x.0002454
13. Goyanes A, Fina F, Martorana A, Sedough D, Gaisford S, Basit AW (2017) Development of modified release 3D printed tablets (printlets) with pharmaceutical excipients using additive manufacturing. Int J Pharm 527(1–2):21–30. https://doi.org/10.1016/j.ijpharm.2017.05.021
14. Armoo AK, Franklyn-Green L-G, Braham AJ (2020) The fourth industrial revolution: a game-changer for the tourism and maritime industries. Worldwide Hospitality and Tourism Themes 12(1):13–23. https://doi.org/10.1108/WHATT-10-2019-0063
15. Frandsen CS, Nielsen MM, Chaudhuri A, Jayaram J, Govindan K (2020) In search for classification and selection of spare parts suitable for additive manufacturing: a literature review. Int J Prod Res 58(4):970–996. https://doi.org/10.1080/00207543.2019.1605226
16. Ghaffar S, Mullett P Commentary: 3D printing set to transform the construction industry. In: publishing i (ed) Proceedings of the Institution of Civil Engineers-Structures and Buildings, London, 2018. vol 10. ice, pp 737–738. doi:https://doi.org/10.1680/jstbu.18.00136
17. Khan MS, Sanchez F, Zhou H (2020) 3-D printing of concrete: beyond horizons. Cem Concr Res 133:106070. https://doi.org/10.1016/j.cemconres.2020.106070
18. Sanjayan JG, Nematollahi B (2019) 3D concrete printing for construction applications. 3D concrete printing technology. Elsevier Inc, Butterwoth. doi:https://doi.org/10.1016/C2017-0-02407-2
19. Choi JW, Kim N (2015) Clinical application of three-dimensional printing technology in craniofacial plastic surgery. Arch Plast Surg 42(3):267–277. https://doi.org/10.5999/aps.2015.42.3.267
20. Soriano-Heras E, Blaya-Haro F, Molino C, de Agustin Del Burgo JM (2018) Rapid prototyping prosthetic hand acting by a low-cost shape-memory-alloy actuator. J Artif Organs 21(2):238–246. https://doi.org/10.1007/s10047-017-1014-1
21. Salmi M, Tuomi J, Paloheimo KS, Björkstrand R, Paloheimo M, Salo J, Kontio R, Mesimäki K, Mäkitie AA (2012) Patient-specific reconstruction with 3D modeling and DMLS additive manufacturing. Rapid Prototyp J 18(3):209–214. https://doi.org/10.1108/13552541211218126
22. Vanderploeg A, Lee S-E, Mamp M (2017) The application of 3D printing technology in the fashion industry. Int J Fash Des Technol Educ 10(2):170–179. https://doi.org/10.1080/17543266.2016.1223355
23. McCormick H, Zhang R, Boardman R, Jones C, Henninger CE (2020) 3D-printing in the fashion industry: a fad or the future? In: Technology-driven sustainability. Springer, pp 137–154. doi:https://doi.org/10.1007/978-3-030-15483-7_8
24. Sun D, Valtasa A (2019) 3D printing in modern fashion industry. J Text Sci Fash Technol 2(2):4. https://doi.org/10.33552/JTSFT.2019.02.000535
25. Nachal N, Moses J, Karthik P, Anandharamakrishnan C (2019) Applications of 3D printing in food processing. Food Eng Rev 11(3):123–141. https://doi.org/10.1007/s12393-019-09199-8
26. Sun J, Peng Z, Fuh J, Hong G, Chiu A (2015) A review on 3D printing for customized food fabrication. Proc Manuf 1:308–319. https://doi.org/10.1016/j.promfg.2015.09.057
27. MarketWatch (2019) Additive manufacturing market industry 2019 global growth, size, demand, trends, insights and forecast 2023. MarketWatch. https://www.marketwatch.com/press-release/additive-manufacturing-market-industry-2019-global-growth-size-demand-trends-insights-and-forecast-2023-2019-09-18. Accessed 2020.01.07 2020
28. Kalpakjian S, Schmid SR (2014) Manufacturing, engineering and technology [In spanish: Manufactura, ingeniería y tecnología]. 7th edn. Pearson educación, New Jersey
29. Srivatsan TS, Sudarchan TS (2016) Additive manufacturing. Innovations, advances, and applications. Vol 1, 1 edn. Taylor & Francis, Boca Raton, Fl, USA. First published
30. Petch M (2018) 3D printing industry jobs board launches. 3D printing industry. https://3dprintingindustry.com/news/3d-printing-industry-jobs-board-launches-130004/. Accessed 2020.01.15 2020
31. Liu C-S, Lin L-Y, Chen M-C, Horng H-C (2017) A new performance indicator of material flow for production systems. Proc Manuf 11:1774–1781. https://doi.org/10.1016/j.promfg.2017.07.311
32. Soltesz J, Rutkofsky M, Kerr K, Annunziata M (2016) The workforce of the future: advanced manufacturing's impact on the global economy. http://www.ge.com
33. Khajavi SH, Partanen J, Holmström J (2014) Additive manufacturing in the spare parts supply chain. Comput Ind 65(1):50–63. https://doi.org/10.1016/j.compind.2013.07.008
34. Hamidi F, Aslani F (2019) Additive manufacturing of cementitious composites: materials, methods, potentials, and challenges. Constr Build Mater 218:582–609. https://doi.org/10.1016/j.conbuildmat.2019.05.140

35. Shanmugam S, Naik A, Sujan T, Desai S Developing tobust 3D printed parts for automotive application using design for additive manufacturing and optimization techniques. In: INCOSE International Symposium, 2019. Wiley Online Library, pp 394–407. doi:https://doi.org/10.1002/j.2334-5837.2019.00694.x
36. Bogdanov D (2019) 3D printing technology as a trigger for the fourth industrial revolution: new challenges to the legal system. Perm U Herald Jurid Sci 44:238–260. https://doi.org/10.17072/1995-4190-2019-44-238-260
37. Weng Y, Li M, Liu Z, Lao W, Lu B, Zhang D, Tan MJ (2019) Printability and fire performance of a developed 3D printable fibre reinforced cementitious composites under elevated temperatures. Virtual Phys Prototyping 14(3):284–292. https://doi.org/10.1080/17452759.2018.1555046
38. Arivarasi A, Kumar A (2019) Classification of challenges in 3D printing for combined electrochemical and microfluidic applications: a review. Rapid Prototyp J 25(7):1328–1346. https://doi.org/10.1108/RPJ-05-2018-0115
39. Herzberger J, Sirrine JM, Williams CB, Long TE (2019) Polymer design for 3D printing elastomers: recent advances in structure, properties, and printing. Prog Polym Sci:101144. doi:https://doi.org/10.1016/j.progpolymsci.2019.101144
40. Chougan M, Ghaffar SH, Jahanzat M, Albar A, Mujaddedi N, Swash R (2020) The influence of nano-additives in strengthening mechanical performance of 3D printed multi-binder geopolymer composites. Constr Build Mater 250:118928. https://doi.org/10.1016/j.conbuildmat.2020.118928
41. Woodson T, Alcantara JT, do Nascimento MS (2019) Is 3D printing an inclusive innovation?: an examination of 3D printing in Brazil. Technovation 80-81:54–62. https://doi.org/10.1016/j.technovation.2018.12.001
42. Flynn EP, Bach C Integrating advanced CAD modeling simulation, 3D printing, and manufacturing into higher education STEM courses. In: 2019 IEEE Technology & Engineering Management Conference (TEMSCON), 2019. IEEE, pp 1–5. doi:https://doi.org/10.1109/TEMSCON.2019.8813627
43. Ford S, Minshall T (2019) Invited review article: where and how 3D printing is used in teaching and education. Addit Manuf 25: 131–150. https://doi.org/10.1016/j.addma.2018.10.028
44. Garretson IC, Mani M, Leong S, Lyons KW, Haapala KR (2016) Terminology to support manufacturing process characterization and assessment for sustainable production. J Clean Prod 139:986–1000. https://doi.org/10.1016/j.jclepro.2016.08.103
45. Buchanan C, Gardner L (2019) Metal 3D printing in construction: a review of methods, research, applications, opportunities and challenges. Eng Struct 180:332–348. https://doi.org/10.1016/j.engstruct.2018.11.045
46. Avrutis D, Nazari A, Sanjayan JG (2019) Industrial adoption of 3D concrete printing in the Australian market: potentials and challenges. In: 3D concrete printing technology. Elsevier, pp 389-409. doi:https://doi.org/10.1016/B978-0-12-815481-6.00019-1
47. Esposito Corcione C, Palumbo E, Masciullo A, Montagna F, Torricelli MC (2018) Fused deposition modeling (FDM): an innovative technique aimed at reusing Lecce stone waste for industrial design and building applications. Constr Build Mater 158:276–284. https://doi.org/10.1016/j.conbuildmat.2017.10.011
48. Ford S, Despeisse M (2016) Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. J Clean Prod 137:1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150
49. Coporation DSS (2017) Solidworks. 2017 SP2 edn., Waltham,MA, U.S.A.
50. Austodesk (1982) AutoCad. 2020 edn., San Rafael, CA, U.S.A
51. Co. H-WG (2018) Repetier. 2.0.5 edn., Willich, Germany
52. B.V. U (2018) Ultimaker Cura Software. 4.1 edn., Geldermalsen, Netherlands
53. Industries M (2009) MakerBot. 2020 edn., New York, U.S.A.
54. Qi K (2020) Filament compositions for fused filament fabrication and methods of use thereof. USA Patent
55. Mu M, Ou C-Y, Wang J, Liu Y (2020) Surface modification of prototypes in fused filament fabrication using chemical vapour smoothing. Addit Manuf 31:100972. https://doi.org/10.1016/j.addma.2019.100972
56. Taha MM, Jumaidin R, Razali NM, Kudus SIA (2020) Green material for fused filament fabrication: a review. In: Implementation and evaluation of green materials in technology development: emerging research and opportunities. IGI Global, pp 1-27. doi:https://doi.org/10.4018/978-1-7998-1374-3.ch001
57. Taylor RM, Niakin B, Lira N, Sabine G, Lee J, Conklin C, Advirkar S Design Optimization, fabrication, and testing of a 3D printed aircraft structure using fused deposition modeling. In: AIAA Scitech 2020 Forum, 2020. p 1924. doi:https://doi.org/10.2514/6.2020-1924
58. Zhang X, Zheng Y, Suresh V, Wang S, Li Q, Li B, Qin H (2020) Correlation approach for quality assurance of additive manufactured parts based on optical metrology. J Manuf Process 53:310–317. https://doi.org/10.1016/j.jmapro.2020.02.037
59. Merrill P (2014) The new revolution. ASQ. http://asq.org/quality-progress/2019/10/innovation-imperative/be-ready.html. Accessed 01.15.2020 2020
60. Tanenbaum M, Holstein W (2019) Mass production. Encyclopædia Britannica, inc. https://www.britannica.com/technology/mass-production. Accessed 04.15.2019
61. Weeren RV, Agarwala M, Jamalabad V, Bandyopadhyay A, Vaidyanathan R, Langrana N, Safari A, Whalen P, Danforth S (1995) Ballard C Quality of parts processed by fused deposition. In: 1995 International solid freeform fabrication symposium, Austin. The University of Texas at Austin
62. Bähr F, Westkämper E (2018) Correlations between influencing parameters and quality properties of components produced by fused deposition modeling. In: CIRP (ed) Conference on Manufacturing Systems, Stutgart, Germany. vol 1. CIRP, pp 1214–1219. doi:https://doi.org/10.1016/j.procir.2018.03.048
63. Jiang J, Xu X, Stringer J (2018) Support structures for additive manufacturing: a review. J Manuf Mater Process 2(4):64. https://doi.org/10.3390/jmmp2040064
64. Minetola P, Calignano F, Galati M (2020) Comparing geometric tolerance capabilities of additive manufacturing systems for polymers. Addit Manuf:101103. doi:https://doi.org/10.1016/j.addma.2020.101103
65. Boschetto A, Bottini L (2015) Roughness prediction in coupled operations of fused deposition modeling and barrel finishing. J Mater Process Technol 219:181–192. https://doi.org/10.1016/j.jmatprotec.2014.12.021
66. Boschetto A, Bottini L, Veniali F (2016) Finishing of fused deposition modeling parts by CNC machining. Robot Comput Integr Manuf 41:92–101. https://doi.org/10.1016/j.rcim.2016.03.004
67. Dong G, Wijaya G, Tang Y, Zhao YF (2018) Optimizing process parameters of fused deposition modeling by Taguchi method for the fabrication of lattice structures. Addit Manuf 19:62–72. https://doi.org/10.1016/j.addma.2017.11.004
68. Kovan V, Altan G, Topal ES (2017) Effect of layer thickness and print orientation on strength of 3D printed and adhesively bonded single lap joints. J Mech Sci Technol 31(5):2197–2201. https://doi.org/10.1007/s12206-017-0415-7
69. Hart KR, Wetzel ED (2017) Fracture behavior of additively manufactured acrylonitrile butadiene styrene (ABS) materials. Eng Fract Mech 177:1–13. https://doi.org/10.1016/j.engfracmech.2017.03.028
70. Durakovic B (2018) Design for additive manufacturing: benefits, trends and challenges. Period Eng Nat Sci 6(2):179–191

71. Alsoufi MS, Elsayed AE (2018) Surface roughness quality and dimensional accuracy—a comprehensive analysis of 100% infill printed parts fabricated by a personal/desktop cost-effective FDM 3D printer. Mater Sci Appl 9(1):11–40. https://doi.org/10.4236/msa.2018.91002
72. Harikrishnan U, Soundarapandian S (2018) Fused deposition modelling based printing of full complement bearings. Proc Manuf 26:818–825. https://doi.org/10.1016/j.promfg.2018.07.102
73. Dabbour LM (2012) Geometric proportions: the underlying structure of design process for Islamic geometric patterns 1 (4):380–391. doi:https://doi.org/10.1016/j.foar.2012.08.005
74. Salazar-Martín AG, Pérez MA, García-Granada A-A, Reyes G, Puigoriol-Forcada JM (2018) A study of creep in polycarbonate fused deposition modelling parts. Mater Des 141:414–425. https://doi.org/10.1016/j.matdes.2018.01.008
75. Gautam R, Idapalapati S, Feih S (2018) Printing and characterisation of Kagome lattice structures by fused deposition modelling. Mater Des 137:266–275. https://doi.org/10.1016/j.matdes.2017.10.022
76. Balderrama-Armendariz CO, MacDonald E, Espalin D, Cortes-Saenz D, Wicker R, Maldonado-Macias A (2018) Torsion analysis of the anisotropic behavior of FDM technology. Int J Adv Manuf Technol 96(1–4):307–317. https://doi.org/10.1007/s00170-018-1602-0
77. Mellor S, Hao L, Zhang D (2014) Additive manufacturing: a framework for implementation. Int J Prod Econ 149:194–201. https://doi.org/10.1016/j.ijpe.2013.07.008
78. Sood AK, Ohdar RK, Mahapatra SS (2009) Improving dimensional accuracy of fused deposition modelling processed part using grey Taguchi method. Mater Des 30(10):4243–4252. https://doi.org/10.1016/j.matdes.2009.04.030
79. RepRap (2012) Prusa I3. U.S.A Patent
80. Song Y-A, Park S (2006) Experimental investigations into rapid prototyping of composites by novel hybrid deposition process. J Mater Process Technol 171(1):35–40. https://doi.org/10.1016/j.jmatprotec.2005.06.062
81. Locker A (2019) Teh best 3D design/3D modeling programs [In spanish: Los mejores programas de diseño 3D/modelado 3D]. https://all3dp.com/es/1/mejores-programas-diseno-3d-software-modelado-3d-gratis/. Accessed 2020.01.05 2020
82. Organization AIS (2010) Geometrical product specifications (GPS)—ISO code system for tolerances on linear sizes—part 1: basis of tolerances, deviations and fits. USA
83. Mohamed OA, Masood SH, Bhowmik JL (2015) Optimization of fused deposition modeling process parameters: a review of current research and future prospects. Adv Manuf 3(1):42–53. https://doi.org/10.1007/s40436-014-0097-7
84. Moylan S, Slotwinski J, Cooke A, Jurrens K, Donmez MA (2012) Proposal for a standardized test artifact for additive manufacturing machines and processes. In: Scholar S (ed) Proceedings of the 2012 annual international solid freeform fabrication symposium, Austin, TX, NIST, pp 6–8
85. Bourell D, Stucker B, Espalin D, Arcaute K, Rodriguez D, Medina F, Posner M, Wicker R (2010) Fused deposition modeling of patient-specific polymethylmethacrylate implants. Rapid Prototyp J 16:164–173. https://doi.org/10.1108/13552541011034825
86. Montero M, Roundy S, Odell D, Ahn S-H, Wright PK (2001) Material characterization of fused deposition modeling (FDM) ABS by designed experiments. http://ode11.com/publications/sme_rp_2001.pdf. Accessed 13552540210441166 10
87. Pennington R, Hoekstra N, Newcomer J (2005) Significant factors in the dimensional accuracy of fused deposition modelling. In: SAGE (ed) Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, Singapore. vol 1. pp 89–92. doi:https://doi.org/10.1243/095440805X6964
88. Cheng B, Chou K (2015) Geometric consideration of support structures in part overhang fabrications by electron beam additive manufacturing. Comput Aided Des 69:102–111. https://doi.org/10.1016/j.cad.2015.06.007