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Application of Nonlinear Analysis in Evaluating Additive Manufacturing Process for Engineering Design Features: A Study and Recommendations

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Abstract:
In today's world, Additive Manufacturing (AM) is quickly becoming the dominant manufacturing technology. Massive development has occurred in recent decades, and it is occurring at a much faster rate. It has also progressed from simple prototype to actual end-use items and manufacturing tools. Various manufacturing processes, such as SLS, LENS, FDM, PolyJet, SLA, LTP, DMLS FDM, and binder jet printing, are produced using additive manufacturing techniques. Layer by layer material deposition/addition is a critical component in all these operations, which is why this technology is known as additive manufacturing. Rapid prototyping, 3D printing, digital manufacturing, and other such names are used. Automotive, Aerospace components, medical equipment parts, consumer goods and gadgets, fashion sector, jewelry, and other industries employ additive manufacturing.

Currently all designed parts can manufacture using either subtractive or additive manufacturing processes. However, distinct design elements established for production provide additional manufacturing obstacles in metal substation and metal addition manufacturing procedures. As the number of parts made directly utilizing additive manufacturing techniques grows, it is critical to compile a list of the best design for manufacturing principles applicable for various additive manufacturing procedures. This will assist the design community in ensuring that items are developed for additive manufacturing rather than generic strategy and produced.

The primary goal of this effort is to evaluate and comprehend the various additive processes and choose the optimal design for manufacturing procedures to be used. As a result, one should be prepared to select a suitable additive manufacturing process for printing based on the design aspects of the component to be produced.

Keywords: Additive Manufacturing Process, Design for Manufacturing (DFM), Design Features, Hole Feature.

1 Introduction

The additive manufacturing (AM) approach [1] is a promising technology that will be widely adopted in the major manufacturing industries around the world very soon. Colossal development has occurred in recent decades and is occurring at a far faster rate [2]. Additive Manufacturing technology has progressed from simple prototype to actual end-use items and manufacturing tools. Additive manufacturing techniques include selective laser sintering (SLS), stereolithography (SLA), fused deposition modelling (FDM), liquid thermal polymerization (LTP), polyjet (3DP), direct metal laser sintering (DMLS), binder jet printing (BJP), ballistic particle manufacturing (BPM), and laser engineered net shaping (LENS), among others [2-9].

The critical procedure in all these processes is layer by layer deposition of materials; thus, this technology is known as additive manufacturing. There are various equivalent words, such as 3D-Printing, Rapid Prototyping, and so on. Additive manufacturing is employed in a variety of industries, including automotive, aerospace, medical equipment parts and devices, consumer goods, the fashion sector, and jewelry [10-14].

Wohlers Report, 2017 shows percentage-wise use of Additive Manufacturing in a different domain as shown in Figure 1 [15].

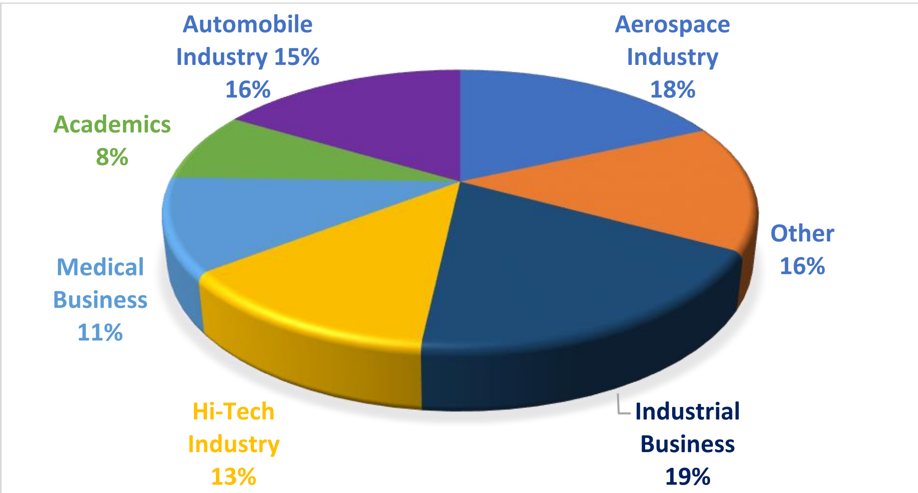

Figure 1: The use of additive manufacturing in many disciplines (Source: [15]).

According to the Wohlers Report, the April 2019 Additive Manufacturing technique is widely employed in the United States, subsequently followed by China and Germany [16]. Based on initial research and development investment and process adoption in the United States and China, other countries have adopted this technology. Figure 2 depicts possible future tread. According to Wohlers Report, August 2019, the utilization of Additive Manufacturing for end-use parts is increasing as compared to operational parts. This suggests that the additive manufacturing process is gradually moving towards stabilization and industry acceptance for operational rather than prototyping purposes [17].

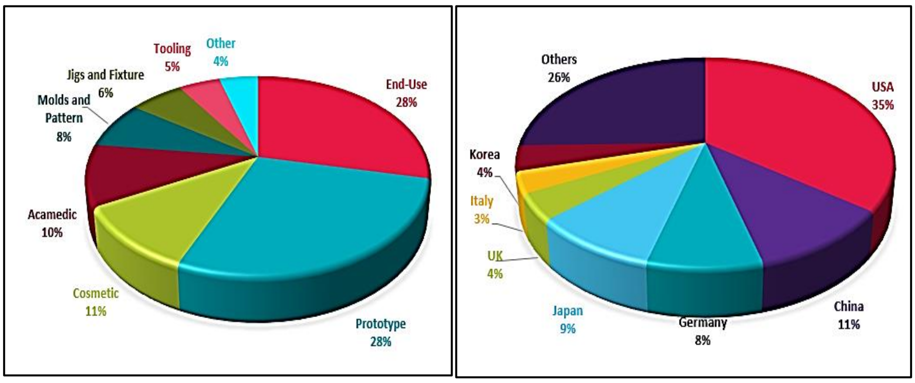

Figure 2: AM Research and development in many countries, as well as process adoption in various applications (Source: [16, 17]).

The primary cause for the slow adoption of Additive Manufacturing techniques is due to the following common problems. [18-20]:

- High initial setup cost and maintenance cost
- Raw material availability and cost
- Increased secondary processing cost and time.
- Layer by layer material deposition slows the component printing.
- Lack of Design for Additive Manufacturing Consideration
- 3D Printing knowledge database not available for reference.

Several 3D printing manufacturers are working on these difficulties in order to acquire the majority of the market opportunity. As projected by the present trend and progress of additive manufacturing, the first four hurdles will be overcome in the future years. To address the final two difficulties, researchers and industry R&D must join to collaborate and share their 3D Printing experience and knowledge. This would aid in the establishment of design standards for an additive manufacturing process as well as the promotion of greater adoption and use of this approach.

Another significant challenge is 3D-printing a final component in the first build. One must master the 3D-Printing of all parts, regardless of industry domain components. To overcome this obstacle, 3D-Printing practice and understanding of numerous elements are required to attain part quality and accuracy. Based on current 3D-Printing experience, it has been discovered that additional design features created on the Part to be printed produce distinct printing issues.

This research examines 3D-printing of Engineering design features, particularly hole features 3D Printing with various variables that impact in additive manufacturing processes and makes recommendations for best design recommendations.

2 Materials and Methods

For the 3D-Printing investigation of hole design features for additive manufacturing, different CAD software was employed to study.

These include- PTC - Creo Parametric 8.0 [21], Siemens - NX 2206 [22] & SolidWorks 2021 [23]

The CAD part with hole design features was modeled using above CAD Software and STL file created and part with different hole sizes are 3D printed with different cases for study purposes.

The following different additive manufacturing processes were employed for the 3D-Printing investigation of hole design features they are as follows:

Fused Deposition Method [1], Selective Laser Sintering [10], and Selective Laser Apparatus [4]

2.1 Design Requirements

To meet some functional requirements, design engineers perform component design first, followed by assembly design. Once a design is operationally ready, a prototype model is produced to test how the part/assembly performs. There is also the chance of changes to other components. It could be the aesthetic appearance, strength, or something else. Figure 3 depicts some of the aspects used in

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designing the component to meet the functional requirement. Traditional manufacturing procedures can also be used to create a variety of features.

Table 1 demonstrates some of the feature categories based on the traditional production method.

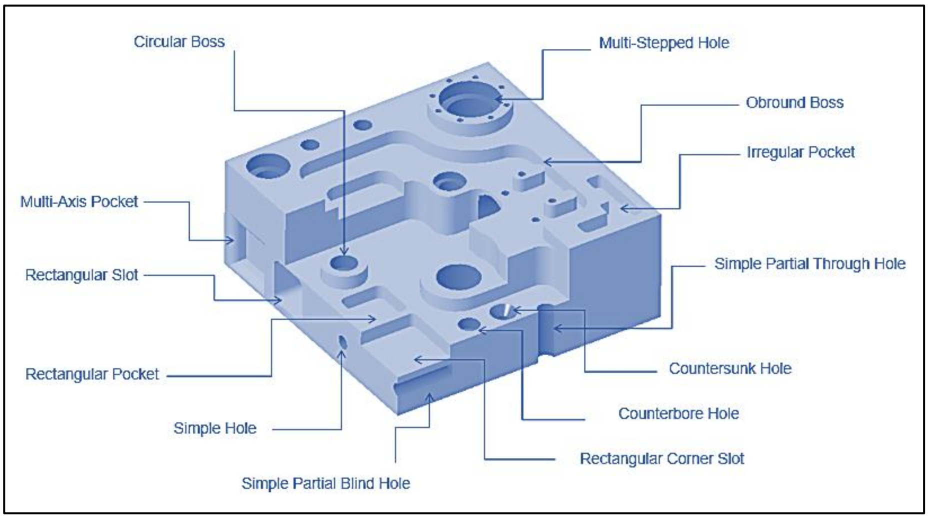

Figure 3: Unique features employed in the design of the component to meet the functional need for machining process.

Table1: Unique features standardized for different traditional manufacturing processes.

Injection Molding	**Machining**	**Sheet Metal**	**Forging**	**Casting**
Bosses	Holes	Bend	Webs	Cored Hole
Ribs	Cutouts	Holes	Ribs	Bosses
Pin	Pocket	Gusset	Fillets	Ribs
Holes	Slots	Emboss	Tapers	Corner Radius
Corners	Grooves	Hem	Corners	Draft
Wall Thickness	Side Radius	Curl	Bosses	Projections
Snap	Bottom Radius	Notch	Planes	Wall Thickness

The unique features listed in Table-1 for the various manufacturing processes are well practiced with the traditional manufacturing method. Standard design guidelines for different features are available to design such features specific to manufacturing process. Designers are making use of same traditional approaches for the additive manufacturing to 3D-printing the parts because of a lack of experience in manufacturing/printing components with additive manufacturing. Furthermore, there are no well-defined Additive Manufacturing design rules for creating the right parts and assemblies the first time. As a result, designers must comprehend the various additive manufacturing techniques and working principles. Furthermore, one must comprehend the benefits and drawbacks of each approach in terms of printing components and material, end application of the 3D printed components, and full life cycle in actual use of components.

2.2 Additive Manufacturing (AM) processes

Based on ASTM committee F42 for additive manufacturing, there are seven additive manufacturing techniques. [18, 25]

1. Powder Bed Fusion
2. Material Extrusion
3. Sheet Lamination
4. Binder Jetting
5. Material Jetting
6. Hybrid Technologies
7. Directed Energy Deposition or Laser Metal Deposition.

A typical strategy is to categories based on baseline technology, such as lasers, printer technology, extrusion technology, and so on. Another approach is to group processes together based on the type of raw material intake.

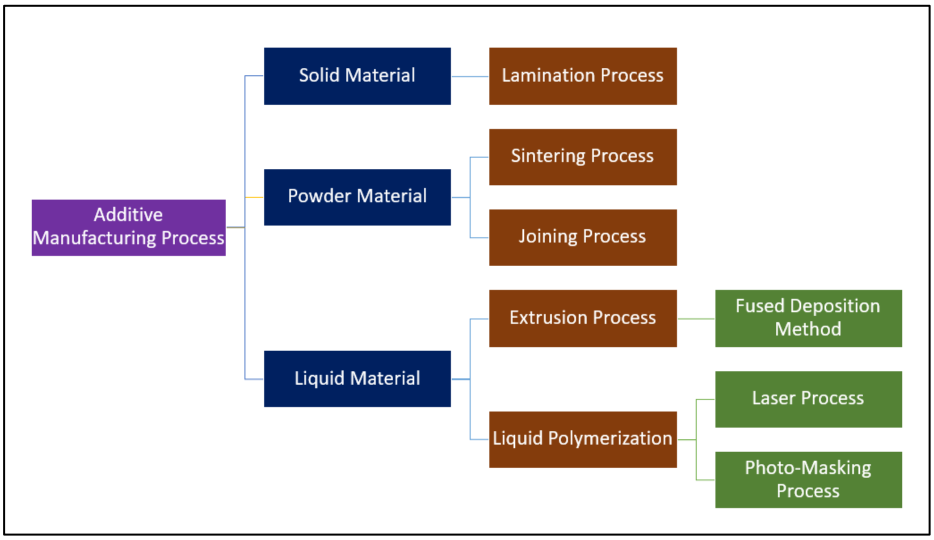

Figure 4: Methods for categorizing additive manufacturing (AM) technology based on different state of materials. (Source: [1]).

3 Results and Discussion

Challenges encountered with 3D printing engineering hole design features.

The results showed in the Figure 5 to 13, about the outcomes of 3D Printing study.

A thorough investigation was carried out to comprehend the behavior of various additive manufacturing processes when creating components with variable design features. The initial focus was on the hole features, and the additive manufacturing method may be more suited for printing holes. Hole features are commonly utilized in component designs such as injection molding, sheet metal, machining, plastic, die-casting, casting and so on. Depending on the accuracy required, conventional method of manufacturing produces most accurate hole feature using material removal process. In addition, hole features are formed throughout the casting and die-casting processes by employing cores. As a result, producing hole features on Part is difficult for the additive manufacturing process when accuracy is required.

3.1 Hole Features and Its Types

Depending on the functional needs, many types of hole features are generated on part design. The following are some of the most popular hole features accessible in CAD software as shown in figure 5.

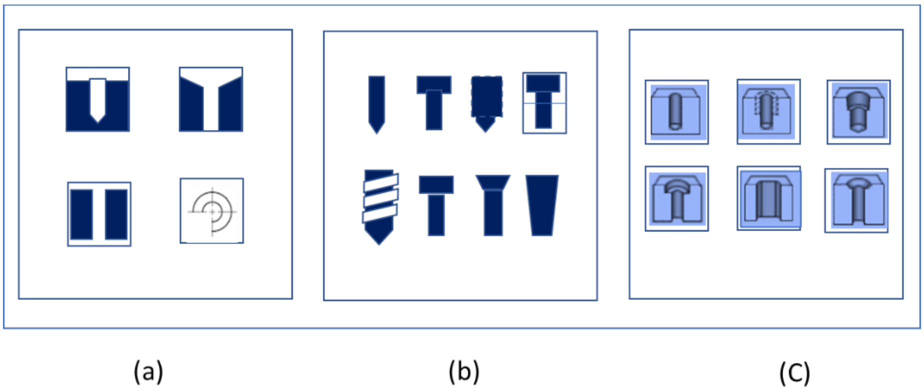

Figure 5: (a) Creo Parametric - Hole Features (Source: [21]), (b) NX- Hole Features (Source: [22]), and (c) SolidWorks- Hole Features (Source: [23]).

A simple hole feature is chosen for study purposes among other hole feature types. Investigation made to study the manufacturability challenges using an additive manufacturing process.

3.2 Simple hole feature

A hole feature is an opening into something, typically in a solid body. The hole features were discovered to be quite valuable for a variety of engineering and non-engineering reasons. Based on the functional needs, the hole feature can be designed as a through-hole or a blind-hole.

A blind-hole feature can be generated using drilling, reaming, or milling operation to a specific defined depth and not to the other side of the workpiece. Through-hole can made by using drilling, reaming, or milling holes throughout the reaming [26]. Following figure shows typical hole design feature for blind-hole and Through-holes.

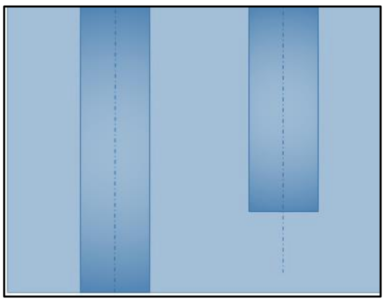

Figure 6: Types of simple holes -Through-hole and Blind hole,

Following factors impact on the accuracy of hole features.

i. Design for Manufacturing Approach
ii. Hole Axis concerning the Build Direction
iii. Impact of tensile load on printed part hole feature
iv. Tessellation Parameters used to generate the STL file.
v. Hole Size and Parameters

Design for Manufacturing Approach

i. Hole Size and Parameters: Smaller hole diameters have less accuracy than bigger diameters. However, because hole features are filled with printing material, achieving a hole size below a specific value is difficult as shown in figure 9. These capabilities vary depending on the additive manufacturing technology used.

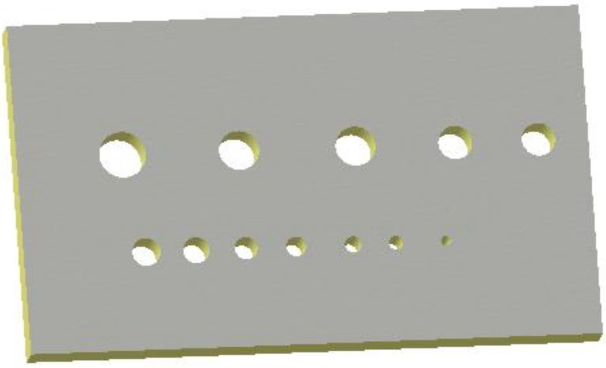

Figure 7: Hole Size Variation with CAD Model

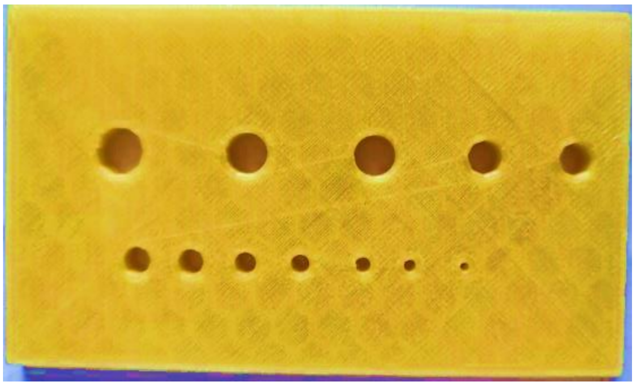

Figure 8: Photographs of Actual 3D-Printed Part

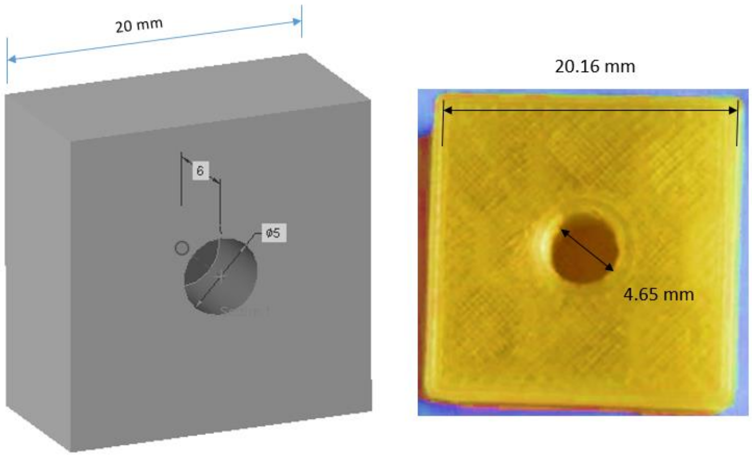

Figure 9: Test artifact Hole Size in CAD Vs. Actual 3D-Printed.

ii. Hole axis concerning the build direction.

Further observations were made in an experimental investigation for hole feature design, whether holes are parallel to build direction or perpendicular to build direction, as shown in following figure no.10.

(a) (b)

Figure 10: Photographs of the test artifact (a) CAD file with different Hole axis concerning the build direction, and (b) 3D-Printed Part to study the hole features.

Case A: Hole Axis Parallel to Build Direction (Smaller hole): In this scenario, the 3D-Printer constructs the Part as a series of layers stacked on top of one another. Part of this process provides relatively good quality holes since the prior layer supports the current layer.

Case B: Hole axis is Perpendicular to the Build Direction (Larger hole). In this case hole feature axis in the part is oriented perpendicular to the build direction. In such a hole feature, the support region structure is required in the SLA and FDM process, It is observed support material is wastage and additionally cycle time for 3D Printing is increased for building support structures.

As a result, the overall cost for holes perpendicular to the build direction will rise. Furthermore, the accuracy of the location is compromised. When the precision of 3D manufactured dilemmas in cases

A and B is compared, holes with axes parallel to build direction are more precise than holes with axes perpendicular to constructing demand.

iii. Impact of tensile load on 3D printed part with hole feature.

3D-Printing Layers direction impact directly on based on application load, tensile loading directions for layers are shown in figure 11. There are two tensile load possibilities: tension load normal to the layers as per case A, and the tensile load parallel to the layers as per case B. The tensile loading has the following effect on the layers:

A: Tension load normal to layers direction - Part is weak

B: Tension load parallel to layers direction - Part is strong

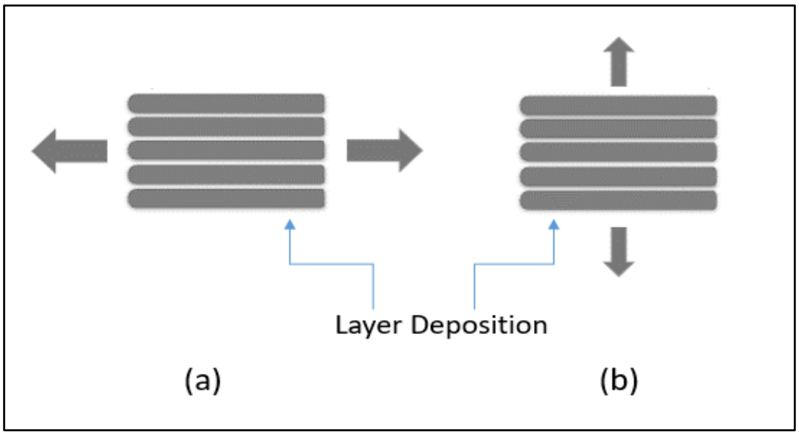

Figure 11: 3D-Printing- Layers Deposition Vs Tensile Loading Direction

Tessellation parameters of STL file

Standard Triangle Language (STL) file format is required as an input for Additive Manufacturing printer to 3D Print the part. After CAD design is created and ready for 3D Printing, the CAD file is translated into STL file format.

All major CAD software includes the ability to convert CAD files to STL file format. During the CAD file conversion, the entire model is tessellated into triangulation format, as illustrated in figure 12 (a), and the object's surface geometry shape information is saved in this file. STL files are universal file formats that are recognized as input files by all 3D printers that read the file and slice the 3D model into 2D layer information. This slicing information is also saved as G-code language for creating physical pieces.

Tessellation factors such as chord height, step size, and angle of contact are critical for 3D printing the intended part. Figures 12 (b), (c), and (d) show how tessellation size changes as the step size changes. The accuracy of hole size is observed to increase with suitable tessellation parameters such as step size, chord height, which should be as low as possible.

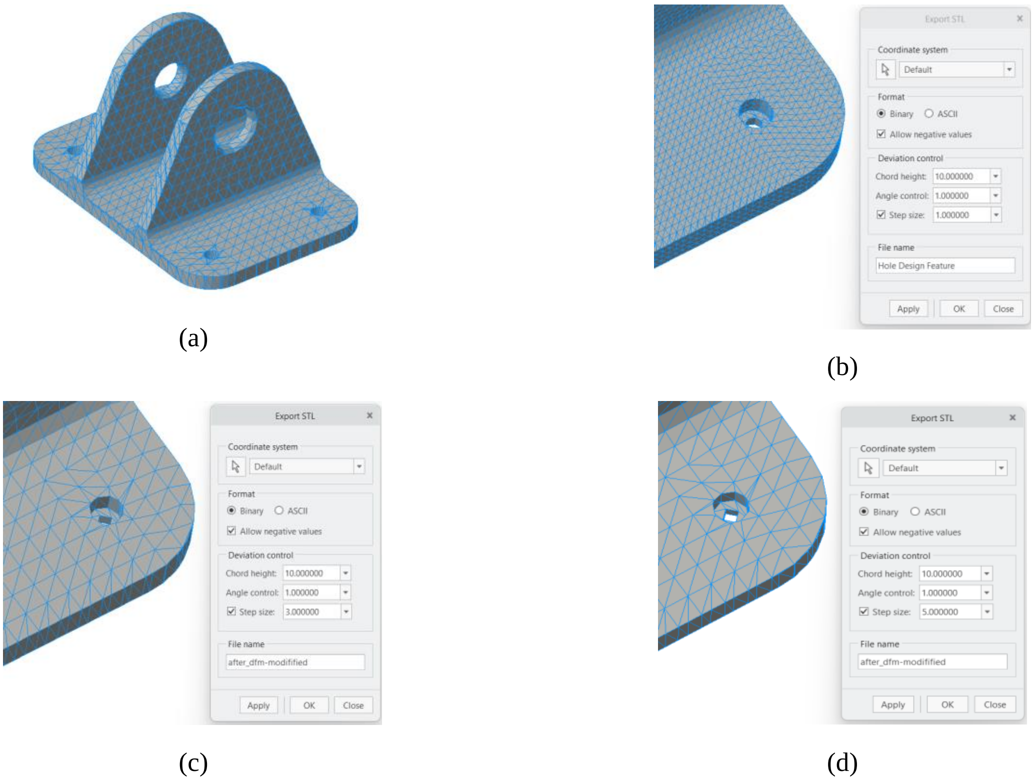

Figure 12: Screenshot of CAD Application for test artifact (a) Tessellated CAD file and (b), (c), and (d) Impact of Step Size on STL file.

Different sizes of hole feature designed to get it 3D Printed properly; it is recommended to design hole feature in appropriate size (more than 0.5 mm) to properly get 3D-Printed. The hole size should be larger than the minimum size stated in the machine's configuration specifications.

Avoid creating a hole design feature perpendicular to build direction. In case functionality does not allow to avoid creating a hole axis perpendicular to build direction, then modify the hole cross-section based on application into a pear or cone shape recommendation as shown below in figure 13.

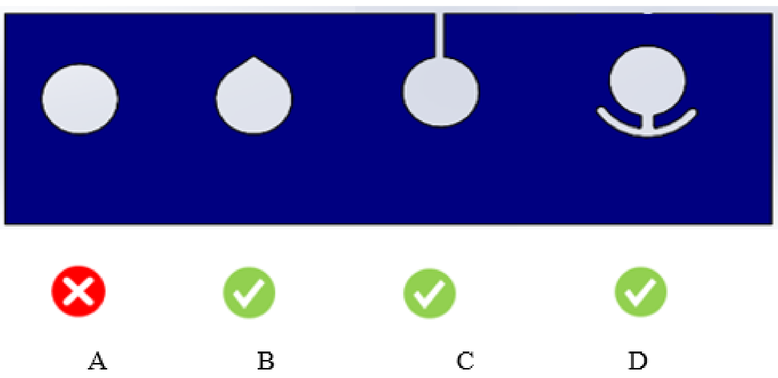

Figure 13: Recommendations to create hole features perpendicular to build direction.

As shown above figure, various methods for creating holes on vertical faces or holes with axis perpendicular to the build direction will aid in meeting the functional need. Even if the hole is made in a smaller or less precise size, such procedures will be effective in accommodating the functional need.

A – Non-preferred for hole preparation when precision is critical.

B, C and D are Preferred for preparing holes in 3D printed parts.

C & D - When other components must be assembled, this method is preferred.

B – Type hole is preferred when hole method versatility is limited, and precision of 3D Printed hole feature is critical.

4 Conclusion

Based on the research study, the following recommendations are made to improve the hole features of 3D-Printing. The hole feature should be reasonable in size to properly get 3D-Printed. The hole size should be larger than the minimum size stated in the machine's configuration specifications. It is best to avoid drilling a hole with an axis perpendicular to the build direction. If it is not possible to prevent making a hole with an axis perpendicular to the build direction, change the cross-section of the hole to a pear or cone shape, as shown in figure 13.

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B, C and D are Preferred for preparing holes in 3D printed parts.

C & D - When other components must be assembled, this method is preferred.

B – Type hole is preferred when hole method versatility is limited, and precision of 3D Printed hole feature is critical.

In comparison to other hole preparation procedures, there was no inaccuracy in the B kind of hole. As a result, the B technique is particularly useful for creating holes in 3D printed items.

The current study is extremely beneficial to researchers, academics, and persons working in the 3D Printing-based manufacturing arena.

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