

3D Printing File Format and Design for Creating Material compositions for Porous Structure

Ishaan Vasant, Arivarasi A, Anand Kumar R

Abstract—Nanoporous gold film detects the presence of heavy metal ions in water. Nanoporous gold film based sensor is fabricated by layering copper on silicon substrate with an intermediate titanium layer acting as an adhesive. This film is formed through electroless plating by spraying potassium gold cyanide on the copper. It is proposed to fabricate this sensor using 3D printing. Increased copper surface roughness increases the rate of formation of the film. This surface roughness can be achieved through lenient tolerances, curved triangles or porosity. Generating porosity is a superior method. STL, AMF and other file formats are compared for feasibility and optimality for this application. The slicer software and selected file format should be compatible. AMF file format is selected for the 3D printing of the nanoporous gold film based water sensor given that this format supports multiple materials and porosity in the layers.

Index Terms—file format, 3D printing, micro porous layer, multiple material

I. INTRODUCTION

3D Printing also known as Additive Manufacturing (AM), deals with additively building of 3D objects utilizing the 3D printing processes. Based on a software that designs, creates a 3D file format for specific allowable dimensions [1]. The information on a particular file format is sliced using slicer software having the compatibility of accepting the file format. As a result, the G-Code for provided model is generated and this printer executable instructions convert the material that is input, to a layer wise structure, of desired object.

The three main processes involved in 3D printing are *Modelling*, *Printing* and *Finishing* [8]. Models for 3D Printing can be made using CAD Computer Aided Design (CAD) software tools. A model can be an image from a digital

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Ishaan Vasant is an undergraduate engineering student of (Electrical & Electronics Engineering) BITS PILANI DUBAI CAMPUS, Dubai. P.O BOX 345055 Phone +971 04 420 0700 email f2013157@dubai.bits-pilani.ac.in

Arivarasi A is the PhD student of (Electrical & Electronics Engineering) BITS PILANI DUBAI CAMPUS, Academic city, Dubai. P.O. BOX 345055 Phone +971 04 420 0700 email p2014002@dubai.bits-pilani.ac.in

Dr Anand Kumar, Professor - Electrical & Electronics Department is with BITS PILANI DUBAI CAMPUS, Dubai. P.O.BOX 345055 Phone +971 04 420 0700 email akumar@dubai.bits-pilani.ac.in

camera or the scan of an image; this process of obtaining a model is termed as *reverse* engineering [24]. Any discrepancies in the models are corrected in the software itself before being fed to the printing mode. The procedure of viewing and making print ready information about the geometry is comparable to chiseling. Information is gathered about the appearance and basic shape of an object and is used to generate a computerized model for viewing. This is termed 3D Checking [6].

After the model is analyzed for mistakes and corrected, the model is printed from a file format. The vast majority of the CAD programming tasks create errors in the form of gaps, normals, confronts, self crossing points or complex manifold errors. These errors must be repaired to ensure accuracy in the model. 3D scanned models generally have a greater number of geometric errors: this is primarily due to the scanning methods used (these are mostly point to point securing).

The slicer divides the geometry of object into number of horizontal layers. The slicer software output is the Gcode that contains information for the printer about the directions in which to print the object. The 3D printer creates the object according the Gcode input [11]: the time required for printing depends on the strategy utilized and structure complexity.

For some applications, the printed object resolution is sufficient. But in other cases further processing is needed. Some of the printable polymers, for example, ABS, require enhancement with chemical vapor techniques. Not all AM methods can be used to print objects of *any* material; Examples include Selective Laser Sintering (SLM) and Electron Beam Melting (EBM). The larger part of metal printers includes the metal segment being cut off from the substrate after deposition [12].

There are numerous applications for AM technology in design, development, biotech, medicine and other areas. 3D printing is useful in research with its potential to customize and prototype specific geometries. Food printing is gaining momentum: chocolates and confectionaries are a few examples [10]. 3D printers are considered as a strategic tool for embedding stem cells equipped for creating new tissues and organs in living people [6]. 3D printed buildings, medicines, wearables and prosthetics are recent developments [10].

II. 3D PRINTING FILE FORMAT

A file format defines the way that information is encoded in order to store it electronically. It provides us information on how the encoding of bits is been done. Different 3D printing file formats are compatible with various types of slicer software and 3D printers. The available 3D printing file formats include Art of Illusion (AOI), Drawing Interchange Format (DXF), Data Working Group (DWG), G-Programming Language (G-Code), Initial Graphic Exchange Specification (IGES), Object File (OBJ), STereolithography (STL) [18], Standard for the Exchange of Product Model Data (STEP), 3D Manufacturing Format (3MF), SCAD and Additive Manufacturing Format (AMF).

A. Existing File formats

AOI extension is associated with art of illusion applications, which is a free and open source 3D modeling and rendering studio available for Microsoft Windows, Linux and Apple Mac OS X operating systems. This is better suited for animation developments. DXF is one of the most compatible vector file type and is used to exchange data between different CAD programs. Some of the dynamic blocks are not represented by DXF. The files tend to be larger. Line widths are not properly handled.

DWG contains meta data and vector image data describing the file contents. Previously, many binary variations of DWG format existed; recently, an ASCII based DWG format has been released. Only few non-CAD programs can operate DWG files. IGES was developed for the exchange of 3D/2D wireframe models, texts, and limited surface classes. But the data transfer is limited by the size of IGES files.

Standard for the Exchange of Product model data (STEP) defines all aspects of product like geometry, topology, materials, tolerances and exchanges product information. STEP files are more commonly used than IGES files. OBJ OBJ file formats are simple 3D models and hence supported by most 3D slicer and other non 3D printing software tools; but the large file size limits usage. Hewlett-Packard Graphics Language (HP/GL) is an existing standard data format for two dimensional graphic plotters.

G-Code files are in ASCII format and have the .gcode extension. G-Code has control information for 3D printer parts like the extruder head and stepper motor. Slice3r, Skeinforge or Cura tools create G-Codes for 3D printers. The slicer tools take a CAD model input, slice into layers, and output the G-Code required for each layer.

.3MF from Microsoft provides a consistent 3D printing background. .3MF file formats support 3D printing; additionally, they support subtractive manufacturing process like laser cutting. SCAD is the most popular and fully parametric file format for 3D printers and the generated files have a .scad extension. Designers use OpenSCAD to generate STL files from the .scad file. STereolithography (STL) file format defines the basic surface geometry of the object to be printed. Most of the design and modeling tools are compatible with STL files [9]. STL files are extensively used for Computer Aided Manufacturing (CAM) applications.

Additive Manufacturing File or Format (AMF) is text based; it is easy to read, write and parse using existing editing tools and is highly compressible. Different materials can be combined and various graded materials could be created. It is suitable for creating lattice and meso structures. In AMF file format, the proportion of red, blue and green can be specified to define a new color variation and add to the color palette.

The volumes are specified using triangular properties. Corresponding materials are defined by their properties. Consider the fabrication of a 10 cm diameter sphere with 10 μm precision. The compressed binary STL file for this sphere is 500 KB in size and contains 20,480 triangles. On the other hand, for the same sphere, the compressed AMF file size is only 10 KB in size and only contains 320 curved triangles. To fabricate a 1 m sphere with 1 nm precision, AMF can create the model with about 1 million triangles, but STL format might not support this resolution. AMF files are simple to implement. STL format is an approximation of CAD geometry. But AMF provides a more accurate representation of a 3D model with support for multiple materials, colors and complex geometries.

B. STL File Formats

A STL document triangulates the surface of the object. The resolution depends on the size and number of triangles. In constructing a triangle with a known (starting) coordinate, the next vertex is determined by the right hand rule [25]. The direction of the normal along an edge of a *straight edged* triangle does not change; but for a *curved edge* triangle, the direction of the normal will vary along the edge. The file format is defined in three dimensional Cartesian coordinates. There exists ASCII and binary formats of STL. Consider the STL code for a sample cube of 1cm x 1 cm x 1 cm: each face of the cube is divided into two triangles. Consider another cube of size 1 m x 1 m x 1 m; the STL code remains the same with only the triangle dimensions changing but not the number of triangles.

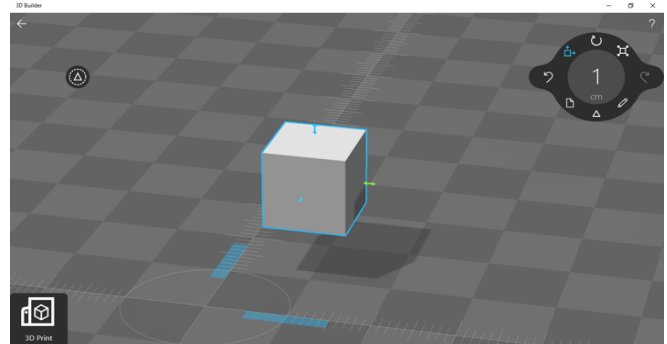


Fig. 1 – Cube created in COMSOL software to analyze the STL code. The normals to the six faces are shown. The STL code generated are same, except for the size of the triangles. There is no change in number of triangles.

Few of the problems faced are missing facets or gaps; degenerate facets; overlapping facets; non-manifold conditions (Non-manifold edge/point/surface). STL file is a facet model derived from precise CAD drawings and hence an approximate part model structure.

1. The STL file is many times larger than the original CAD data file for a given accuracy.
2. STL file carries redundant information, for example, duplicate edges, vertices.
3. Many commercial tessellation algorithms, which belongs to CAD vendors are not robust enough.
4. The repair software is required to correct the errors in file.
5. STL carries very limited information to represent color, material texture, substructure and other end product

properties.

6. The slicing of STL can, at times, take hours [14].
7. Tessellation of large curvature surfaces results in errors at the intersection between such surfaces. It results in gaps between edges.
8. Degenerated facets are created due to shell puncture algorithms.
9. Due to numerical round off errors, overlapping facets are generated, as the vertices are represented in floating point numbers. Thus the numerical round off will cause overlapped facets if tolerances are set to higher values.
10. The slicing algorithm causes 3D printing problems under non-manifold conditions even when valid tessellated solids are given as inputs to slicer software. The tessellated structure must be validated; if errors have occurred, the file must be repaired. Missing facets occur more frequently and here are algorithms to address such errors.

STL files does not support multiple materials. For example, if an object consists of two layers (each being a cubic structure) with each layer being of different materials, the difference in the material is ignored and the entire object is considered as one cuboid with a single material.

C. AMF File Formats

In 2009, the ASTM International Committee F42 on AM technologies was formed. This committee published Additive Manufacturing File (AMF) for part production of object with multiple metals using AM Technologies. STL format is classified under informal standards or defacto standard. AMF V1.1 is the new standard created under the collaboration between ASTM and ISO in 2014 [2]. An extensible markup language (XML) is used; this standard provides for tagging of information used. [20][21]. The five key element levels of AMF are *object*, *material*, *texture*, *constellation* and *metadata*. AMF has recently developed specifications for graded, mixed, lattice and random materials in a single file.

Object defines volume of each material. Each material has a *Material ID*. Each texture has a *Texture ID*; texture is provided for color and image definition. *Constellation* gathers the objects and places them in proper pattern. *Metadata* provides additional data for the model (e.g., name, author) or material (e.g., type). Multiple materials are specified using the *Material ID* parameter. Composite material can be homogeneous or non-homogeneous. A homogenous composition of different materials refers to equal proportions of the materials mixed. The composites are graded (in terms of material type) in vertical direction (z-axis). The grading of materials can follow periodic or non-periodic pattern, piecewise distribution or discontinuous blending functions (e.g., logical or step functions or modulus functions).

Material 5 is defined in XML format below as a homogenous mix of 30% water (with material id 1) and 70% Potassium Gold Cyanide (PGC) (with material id 2).

```
<material id = '5'>
<metadata type = "PGC">Medium Material</metadata>
<composite materialid="1">0.3</composite>
<composite materialid="2">0.7</composite>
</material>
```

Material 6 is defined in XML format below to be 10% resin (with material id 1) and 90% Titanium epoxy (with material id 2).

```
<material id = '6'>
<metadata type = "Ti">Medium Material</metadata>
<composite materialid="1">0.1</composite>
<composite materialid="2">0.9</composite>
</material>
```

International Standards Organization (ISO) and American Society for Testing and Materials (ASTM) 52921:2013, ASTM F2792-12a, ASTM F2971-13, ASTM F2924-14, ASTM F3001, ASTM F3056 are standards that define various material – process combinations [23].

The electrochemical sensor that detects the presence of heavy metal ions in water comprises of Silicon, Titanium and nanoporous gold (see Fig 2). The 3D printing process to fabricate this process is to print the composite of Resin and Titanium epoxy (this composite serves as an adhesive) on the Silicon substrate. Copper is then printed on the Resin/Titanium composite. The composite PGC is sprayed on the copper to form nanoporous gold through electroless plating and chemical reaction. The standards of material definitions should be compatible with the existing ISO / ASTM specifications [22]; AMF is best suited..

III. MODEL REQUIREMENTS & PROPOSITIONS

For an enhanced chemical reaction between Copper and PGC, the top surface of the copper layer should have a larger surface area; this increase in surface areas can be achieved by using a porous surface structure [3]. 3D printing a porous structure is complex requiring customization of the existing algorithm. Here, in AMF software, the options for creating different structures being facilitated, the required modifications are suggested.

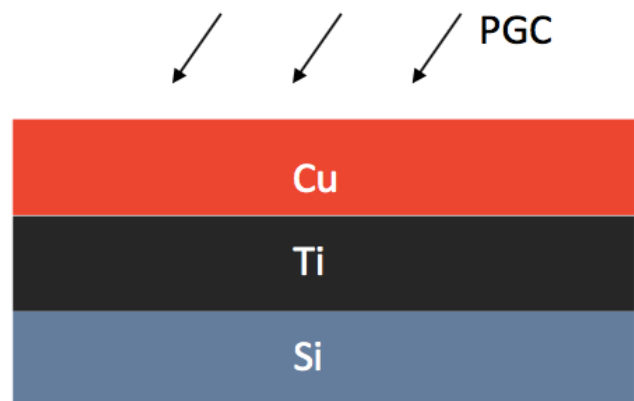


Fig. 2 –Sensor Structure to be 3D printed. The required materials are copper, Titanium, PGC. PGC reacts chemically with Copper to produce nanoporous gold film.

IV. CREATING SURFACE ROUGHNESS

Surface roughness can be created by lenient tolerances in the layer specification, curved edge triangular facets and porosity.

A. Lenient Tolerances

Unlike in Free CAD or STL, tolerances can be set in AMF; this tolerance setting appropriately tessellates an object. If tolerances for the top layer are set leniently, the round off errors exist and precise tessellation is not obtained. This leads to overlaps and gaps between triangle elements (facets).

B. Curved Edged Triangular Facets

The concept of curved edges is one method to generate a rough surface. Small projections on the surface could account for roughness. Existing facets can be modified to obtain curved and projecting facets. Using tangent vectors, the flat triangles can be made curved as illustrated in Fig. 4.

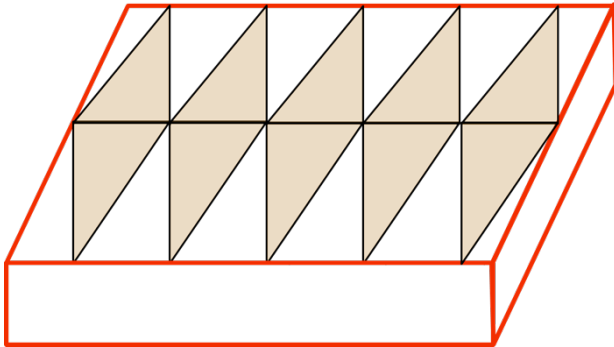


Fig. 3 –Flat triangular facets on copper surface

The XML code for curved edge is shown below; this code implements the curvature shown pictorially Fig. 4. v_1 and v_2 refer to two vertices of a triangle. $dx_1, dx_2, dy_1, dy_2, dz_1, dz_2$ are the normalized X,Y,Z components of the first and second edge direction vectors respectively. Roughness is determined by two parameters: thickness of layer and surface inclination relative to the incremental layers [19]; these parameters are used to model surface roughness. Viscosity of the metal material (e.g., PGC spraying) affects surface roughness during 3D printing [7].

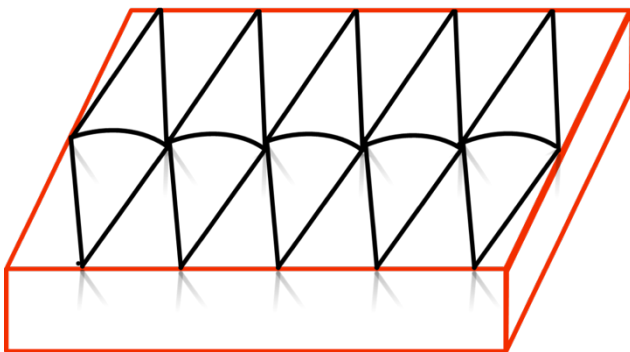


Fig. 4 – Curved edges are highlighted for sharp edge points to generate roughness, where the angle of inclination affects sharpness.

```
<edge>
<v1>0</v1>
<dx1>0.8</dx1>
<dy1>0.8</dy1>
<dz1>0.8</dz1>
<v2>1</v2>
<dx2>0.9</dx2>
<dy2>0.1</dy2>
<dz2>0.9</dz2>
</edge>
```

The edge points are described as per AMF usage using XML by defining the vertices with their normalized directional coordinate values.

The vertices and normalized directional co-ordinates are provided for two vertices and would extend for the extended co-ordinates. The edges are defined therein.

C. Void Composite using Porosity

Stochastic processes have a rich objects repository to explain the system randomness. Porosity generation stochastic algorithms are based on threshold Gaussian field techniques. Algorithms exist to generate random porous media. Li et al. [26] modified the algorithm proposed by Yang et al. [27] for a three dimensional sphere packing, a two step rearrangement technique, in order to generate random porous media. Network modelling provides a framework to describe the dynamic processes in a random medium [26]. For complex micro porous structure generation, CAD packages are not commonly used. The exception is if a voxel modeling technique or implicit functions are used to generate porous modeling. Porous surfaces can be modeled with Boolean functions having implicit functions. Porous structure is a specific type of solid having numerous pores [4]. Sintering in 3D printing is a process of production of porous metals in complex shapes. Granular material structure is used; the material is heated to a temperature close to melting point causing the particles to stick together in a porous fashion [5]. This porosity also strengthens the material. Force based algorithm creates regular porous structures, whereas random shifting is required for irregular porous surface creation [16]; both algorithms use *voxel* spacing for 3D structures. For sintered copper particles, the tolerance parameter, shrinkage and voxel spacing can be modeled for each pore size. Rather than regular porous structures, irregular porous structure modeling provides optimal solution increasing effectiveness and usefulness. Replication of porous structures reduces optimality as the reconstruction of modeling parameters creates a uniform environment which is not realistic [17]. Periodic porous structures might be easier to fabricate and model, but are also not realistic. 3D printing technique can provide a creative way for modeling and printing complex porous structures. Finite Element analysis is used to study porous flow and Navier-Stokes analysis to study fluid flow interactions; these analytical tools can be used with the irregular porous modeling of the rough surface required to enhance the chemical reaction rate between PGC and Copper.

Porous structure possesses numerous superior properties for sensing applications; pore parameters like size, shape, porosity and pore inter connection leads to diverse porous models. Yaohui et al. suggest a new approach for irregular porous structure based on centroid voronoi tessellation method [15]. Exhibiting a pore diversity becomes a major challenge. AMF supports implementation of porous structure through XML [19] in the file format generated for 3D printing.

Porous structures can be specified using the null material ID in random fashion. Either the material is completely present or is completely void. Fractional values can be generated although not currently supported in AMF. The fractional values are not allowed and will be interpreted as fully void. The function *rand* (x, y, z) returns a random value between 0 and 1 for the specified coordinates; this value is a measure the porosity. This function represents pseudo-random material structures.

The design of the heavy metal ion sensor is to divide the copper layers into two parts. The bottom part will be completely flat surface (without porosity) of copper in micro / nano thickness ranges. The top portion can be a composition of copper and void material in a checkerboard formation (see Fig. 5).

A sample code for the roughness schema shown in Fig. 5 can be implemented using material id combinations and creating composite material structures.

```
<material id = "1">
<metadata type="Name">Titanium epoxy</metadata>
</material>
<material id = "2">
<metadata type="Name">Nano Copper</metadata>
</material>
<material id = "3">
<metadata type="Name">PGC</metadata>
</material>
<material id = "4">
<metadata type="Name">Checkerboard</metadata>
<composite materialid="2">
floor((x+y+z%1)+0.5)</composite>
<composite materialid = "0">
1-floor((x+y+z%1)+0.5)</composite>
</material>
```



Fig. 5–Top layer of copper in checker board formation

Another way of using the same method is to have a single layer of composite material modeling. This layer would again be in a checkerboard formation, where one composite material is made to be of copper. The other composite material is a vertically graded mixture of copper and void material. A sample code structure for the roughness schema Fig. 6 is shown below.

```
<material id = "1">
<metadata type="Name">Titanium epoxy</metadata>
</material>
<material id = "2">
<metadata type="NanoCopper" </metadata>
</material>
<material id = "3">
<metadata type="PGC"</metadata>
</material>
<material id = "4">
<metadata type="Name">VerticallyGraded</metadata>
<composite materialid="2">z</composite>
<composite materialid="0">10-z</composite>
</material>
<material id = "5">
<metadata type="Name">Checkerboard</metadata>
<composite materialid="2">
```

```
floor((x+y+z%1)+0.5)</composite>
<composite materialid = "3">
1-floor((x+y+z%1)+0.5)</composite>
</material>
```



Fig. 6–Layer of copper in checkerboard formation. The copper layer is not partitioned as in Fig. 5.

Slicer software tools like Slice3r, Cura, MatterControl, G-Code generators and Skeinforge support AMF structure generated file formats.

V. CONCLUSION

The water requires multiple materials (Titanium composite, Copper and PGC composite). The electroless plating of nanoporous gold film requires chemical reaction between PGC and copper. This chemical reaction rate is enhanced with a rough copper surface. This roughness can be achieved by setting lenient tolerances for the layers, using curved edges with the triangular facets, or creating porosity (regular or randomly) in the copper layer. AMF is superior to STL in that it supports multiple materials to be printed. AMF can be adapted to print porous copper surface. The slicer tool selected should be compatible with AMF.

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