Minisurf – A minimal surface generator for finite element modeling and additive manufacturing

Meng-Ting Hsieh a,∗, Lorenzo Valdevit a,b

a Mechanical and Aerospace Engineering Department, University of California, Irvine, CA 92697, USA
b Materials Science and Engineering Department, University of California, Irvine, CA 92697, USA

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ABSTRACT

Triply periodic minimal surfaces (TPMSs) have long been studied by mathematicians but have recently garnered significant interest from the engineering community as ideal topologies for shell-based architected materials with both mechanical and functional applications. Here, we present a TPMS generator, Minisurf. It combines surface visualization and CAD file generation (for both finite element modeling and additive manufacturing) within one single GUI. Minisurf presently can generate 19 built-in and one user-defined triply periodic minimal surfaces based on their level-set surface approximations. Users can fully control the periodicity and precision of the generated surfaces. We show that Minisurf can potentially be a very useful tool in designing and fabricating architected materials.

1. Introduction

For decades, scientists and engineers have been striving to design and fabricate new multiphase materials with controlled phase topologies – often termed “architected materials” or “metamaterials” – with unprecedented and tunable combinations of properties; architected cellular materials, where one phase is void, are the most notable examples. In terms of mechanical behavior, significant efforts have focused on designing architected materials that are stiff, strong and...
tough at very low density, by optimizing the topology of the material phases. Traditionally, topologies have largely been limited to beam-based structures, such as honeycombs in 2D [1–7] and octet lattices in 3D [8–14]. More recently, interest has shifted to shell-based topologies with minimal surface characteristics, such as triply periodic minimal surfaces (TPMS) [15–20] and isotropic stochastic spinodal minimal surfaces [21–23]; while more challenging to fabricate, these topologies are devoid of nodes and other stress intensification regions, which results in improved strength and toughness [21,24–26] as well as efficient fluid transport at low pressure drops [27–29]. Many studies of these minimal surface topologies have been motivated by the development of superior additive manufacturing (AM) technologies that enable their fabrication, and generally employ finite element modeling (FEM) for calculation of their mechanical and functional response; as a consequence, there is an increasing need for quick and accurate generation of computer-aided design (CAD) files for periodic cellular materials based on TPMS topologies, to be employed both for numerical analysis and additive manufacturing.

In this article, we present an efficient software application called “MiniSurf”, which combines surface visualization and CAD file generation (for both FEM and AM) within one single graphical user interface (GUI). We briefly describe and illustrate the main software features. In addition, we highlight the impact of this package on current and potential applications in the field of architected materials design. Finally, we discuss the software limitations and future improvements.

2. Description and features

MiniSurf is a software package that runs on Matlab Runtime (a freely accessible Matlab compiler) for visualization and generation of triply periodic minimal surface CAD files (with .inp extension for FEM through Simulia Abaqus and/or .stl extension for AM). The software package has a sleek and simple GUI consisting of two panels: a control panel (left) and a visualization panel (right), as shown in Fig. 1. The control panel allows users to select from the built-in library of minimal surfaces, as well as to type in the custom level-set equation of any desired surface. To facilitate generation of periodic architected materials, users can adjust the number of unit cells $N_i$, with $i = x, y, z$, along the x, y and z-directions, to produce specimens of different aspect ratios and number of unit cells, as shown in Fig. 2(a) and (b). In addition, the precision of the generated surfaces, governed by number of composing facets, can be fine-tuned by changing the number of mesh grid points $P_i$ (with $i = x, y, z$) along the x, y, and z-directions. The generated minimal surfaces will be shown in the visualization panel in either non-mesh or mesh mode, as illustrated in Fig. 3(a) and (b).

MiniSurf currently has 19 built-in minimal surfaces. All these minimal surfaces are generated by meshing their implicit level-set approximations $f(x, y, z) = c$, where c is a constant and x, y, and z represent the location of $P_i \times P_j \times P_k$, grid points in a 3D volume of size $N_x \times N_y \times N_z$; equations for all built-in surfaces are reported in Table 1. The meshing is executed via the Matlab built-in function isosurface, that discretizes the minimal surfaces into many triangular facets, thus
These studies are recent and the interest of the mechanics community in truss-based lattices in terms of specific strength and toughness [41–43].

Additional ones frequently added) and automatically creates CAD files providing information on the facet-vertex connectivity. Information on the connectivity is then subsequently used to write CAD files in .inp format.

Table 1

<table>
<thead>
<tr>
<th>TPMS</th>
<th>Level-set equation for the TPMS $f(x, y, z) = c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schwarz P [30,31]</td>
<td>$\cos(x) + \cos(y) + \cos(z) = 0$</td>
</tr>
<tr>
<td>Double Primitive [32]</td>
<td>$0.5(\cos(x) \cos(y) + \cos(y) \cos(z) + \cos(z) \cos(x)) + 0.2(\cos(2x) + \cos(2y) + \cos(2z)) = 0$</td>
</tr>
<tr>
<td>Schwarz D [31,33]</td>
<td>$\sin(x) \sin(y) \sin(z) + \sin(y) \cos(x) \cos(z) + \cos(x) \sin(y) \cos(z) + \cos(x) \cos(y) \sin(z) = 0$</td>
</tr>
<tr>
<td>Complementary D [33]</td>
<td>$\cos(3x + y) \cos(z) - \sin(3x - y) \sin(z) + \cos(x + 3y) \cos(z) + \sin(x - 3y) \sin(z) + \cos(x - y) \cos(3z) - \sin(x + y) \sin(3z) = 0$</td>
</tr>
<tr>
<td>Double Diamond [30]</td>
<td>$0.5(\sin(x) \sin(y) + \sin(y) \sin(z) + \sin(z) \sin(x)) + 0.5 \cos(3x) \cos(y) \cos(z) = 0$</td>
</tr>
<tr>
<td>Gyroid [30,33]</td>
<td>$0.5(\cos(x) \cos(y) \cos(z) + \cos(y) \sin(x) \sin(z) + \sin(x) \sin(y) \sin(z)) - 0.5(\sin(2x) \sin(2y) + \sin(2y) \sin(2z) + \sin(2z) \sin(2x)) = 0.2$</td>
</tr>
<tr>
<td>G' [30]</td>
<td>$\sin(2x) \cos(y) \sin(z) + \sin(2y) \cos(z) \sin(x) + \sin(2z) \cos(x) \sin(y) = -0.32$</td>
</tr>
<tr>
<td>Double gyroid [32]</td>
<td>$2.75(\sin(2x) \sin(2y) + \sin(2y) \sin(2z) + \sin(2z) \sin(2x)) \cos(x) - (\cos(2x) \cos(2y) + \cos(2y) \cos(2z) + \cos(2z) \cos(2x)) = 0.95$</td>
</tr>
<tr>
<td>Karcher K [30]</td>
<td>$0.1(\cos(x) + \cos(y) + \cos(z)) + 0.3(\cos(x) \cos(y) + \cos(y) \cos(z) + \cos(z) \cos(x)) - 0.4(\cos(2x) + \cos(2y) + \cos(2z)) = -0.2$</td>
</tr>
<tr>
<td>O, CT-O [30]</td>
<td>$0.6(\cos(x) \cos(y) + \cos(y) \cos(z) + \cos(z) \cos(x)) - 0.4(\cos(x) + \cos(y) + \cos(z)) = -0.25$</td>
</tr>
<tr>
<td>Lidinoid [33,34]</td>
<td>$0.5(\sin(2x) \cos(y) \sin(z) + \sin(2y) \cos(z) \sin(x) + \sin(2z) \cos(x) \sin(y)) - 0.5(\cos(2x) \cos(2y) + \cos(2y) \cos(2z) + \cos(2z) \cos(2x)) = -0.15$</td>
</tr>
<tr>
<td>Neovius [30,31]</td>
<td>$3(\cos(x) \cos(y) + \cos(y) \cos(z) + \cos(z) \cos(x)) + 4 \cos(x) \cos(y) \cos(z) + \cos(2x) \cos(2y) = 0$</td>
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<tr>
<td>I-WP [31,33]</td>
<td>$2(\cos(x) \cos(y) + \cos(y) \cos(z) + \cos(z) \cos(x)) - (\cos(2x) + \cos(2y) + \cos(2z)) = 0$</td>
</tr>
<tr>
<td>Fisher-Koch S [32,33]</td>
<td>$\cos(2x) \cos(3y) \cos(3z) + \sin(x) \sin(y) \sin(z) + \sin(2x) \cos(y) \cos(z) = 0$</td>
</tr>
<tr>
<td>Fisher-Koch C(9) [33]</td>
<td>$\cos(2x) + \cos(2y) + \cos(2z) + 2(\sin(3x) \sin(2y) \cos(x) + \cos(x) \sin(2y) \sin(3z)) \sin(2x) \cos(y) \cos(z) + \cos(x) \sin(2y) \cos(z) = 0$</td>
</tr>
<tr>
<td>Fisher-Koch Y [33]</td>
<td>$\cos(x) \sin(y) \cos(z) + \sin(x) \sin(y) \sin(z) + \sin(2x) \sin(y) \sin(z) + \sin(2y) \sin(z) \sin(2x) \cos(y) = 0$</td>
</tr>
<tr>
<td>Fisher-Koch CY [33]</td>
<td>$-\sin(x) \sin(y) \sin(z) + \sin(2x) \sin(y) \sin(z) + \sin(2y) \sin(z) \sin(2x) - \cos(2x) \cos(y) \cos(z) + \sin(2x) \cos(y) \cos(z) + \cos(2y) \sin(y) = 0$</td>
</tr>
<tr>
<td>P-RD [30,32,33]</td>
<td>$4 \cos(x) \cos(y) \cos(z) - (\cos(2x) \cos(2y) + \cos(2x) \cos(2z) + \cos(2y) \cos(2z)) = 0$</td>
</tr>
</tbody>
</table>

These studies are recent and the interest of the mechanics community in the structural performance of TPMS-based materials is only expected to grow. MiniSurf will certainly support a number of future projects in this field. As examples, MiniSurf is currently used in two ongoing projects in our research group: (i) Mechanical properties of 3D printed interpenetrating phase composites with shell-based reinforcements [44]. MiniSurf is used to generate CAD files for Schwarz P surface shell-based reinforcements for interpenetrating phase composites. These composites can be readily fabricated by multi-material jetting in VeroWhite (a hard polymeric material for reinforcement) and Agilus (a soft elastomeric material for the matrix) using a Connex 3D printer. The effect of the matrix/reinforcement interpenetration on the mechanical properties of the composites are subsequently investigated both experimentally and numerically (for the numerical studies, MiniSurf-generated meshes are used in finite elements analyses of deformation and damage of the composites). (b) Architected materials designs for long bone implants [45]. In this effort, we are investigating the performance of minimal surface-based porous materials as implants for long bone repair. Schwarz P CAD files are generated using MiniSurf for the purpose of surface area calculations and finite element modeling. The results are then used to draw comparisons among different topological designs and identify optimal topologies.

At the same time, we expect MiniSurf to have a broad impact on multidisciplinary studies far beyond the solid mechanics field. The
interest of the engineering community in TPMS shell-based materials is documented in several recent studies where TPMS-based architected materials are manufactured and investigated for their multifunctionality, including (1) thermal properties (e.g., thermal conductivity [46,47], coefficient of thermal expansion [48] and heat exchange [49–51]), (2) acoustic properties (e.g., sound absorption and acoustic band gaps [52,53] and audible coloration [54]) and (3) electrochemical properties (e.g., electrical conductivity [55,56]).

4. Limitations

Despite being user friendly and freely accessible to all researchers and engineers, MiniSurf has three main limitations:

(1) **Suboptimal mesh**

In general, meshing in Matlab is done through the Delaunay triangulation algorithm [57,58], which connects a given set of discrete points. Although such algorithm tends to avoid triangular facets with acute angles, meshing of highly curved minimal surfaces – based on the initial user-defined 3D uniform grid points – still results in many triangular facets with bad aspect ratios (thin and long).

(2) **Zero-thickness surface**

MiniSurf generates minimal surfaces composed of many facets without any physical thickness. Postprocessing to thicken these surfaces is often required. Fortunately, many commercial finite element packages (for example, Simulia Abaqus) or additive manufacturing software (for example, Geomagic Design X) have such postprocessing ability.

(3) **Nonparallel computing**

Currently, MiniSurf can only execute calculations with one single-core processor, although it can still efficiently generate highly meshed surfaces (300 × 300 × 300 initial mesh grid points) under one minute.

5. Conclusion and future improvements

In this paper, we presented a software package, MiniSurf, that efficiently produces CAD files of shell-based architectural materials consisting of periodic arrays of minimal surface unit cells, for additive manufacturing and finite element modeling. The surface description is provided via implicit level-set equations. Currently, the software library has 19 built-in minimal surfaces, but any user-defined level-set surface is also allowed. Despite the limitations discussed in Section 4, we expect the software package to be impactful, given the profound interest of the engineering community in TPMS shell-based materials across a wide range of multidisciplinary fields.

In the future, we plan to further improve MiniSurf by focusing on its remeshing algorithm, its thickening functionality (triangular facets to triangular prisms), and a parallel computing implementation. Furthermore, we will keep adding new minimal surfaces to our existing library.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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