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<td>Author(s)</td>
<td>Rosen, David W.</td>
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ABSTRACT: Manufacturable ELements (MELs) are proposed as an intermediate representation to support Design For Additive Manufacturing (DFAM) and process planning. MELs are constructed to relate design features and geometric regions to manufacturing operations that are suitable to fabricate those features or regions. Such intermediate representations provide a validated parametric model that aids in the construction of as-fabricated part models for both engineering analysis and process planning. Viewed differently, MELs contain information with which designers can explore process-structure-property relationships of design features that capture manufacturing process characteristics. Examples are provided for vat photopolymerization and material extrusion processes.

KEYWORDS: manufacturing element, design for additive manufacturing, process-structure-property relationships, As-fabricated voxel model

INTRODUCTION

Design for manufacturing has typically meant that designers should tailor their designs to eliminate manufacturing difficulties and minimize costs. Additive Manufacturing (AM) technologies, on the other hand, provide the opportunity to explore new design concepts, complex geometries, novel material compositions and distributions, etc. during early design stages. Many companies are now pursuing production manufacturing using AM since they have determined how to take advantage of the unique capabilities of these technologies. At later design stages, the specifics of AM processes and materials must be considered to ensure well engineered products. For these later design stages, we propose the concept of Manufacturing Elements (MEL) to assist designers in analyzing the effects of AM processes and materials on their designs (Rosen 2007).

MELs relate design features and geometric regions to manufacturing operations that are suitable to fabricate those features or regions. A MEL contains information about the geometry or design feature of interest by a designer and the manufacturing information of a specific process and/or machine and material, including the important process variables for fabricating the design feature. MELs represent information enabling process-structure-property relationships of a material that is processed by a specific AM machine type to be computed. A MEL library is under construction that is hierarchically organized by design feature type and by manufacturing process and machine types. MELs at the lowest level of the hierarchy are intended to be instantiated with specific geometric regions in a part. Then, algorithms associated with the MEL library can be invoked to compute toolpaths and manufacturing plans, as well as mechanical properties using finite-element analysis on geometric models of the features and toolpaths.
The remainder of this paper introduces MELs in more detail and presents example MELs for vat photopolymerization (stereolithography) and material extrusion processes. Specific toolpath patterns are considered for struts in lattice structures fabricated by stereolithography. A more detailed example is presented next that is based on a novel material extrusion process for the design of an underwater robot. Conclusions are drawn briefly in the final section.

MANUFACTURABLE ELEMENTS

A Manufacturable Element (MEL) is a predefined, parameterized decomposition of a volumetric region of a part. A hierarchical collection of MELs is being constructed to serve as a MEL library that designers can select from when developing artifact designs. This hierarchy is organized by design feature and geometric region; then, each feature/region category is specialized by AM process. A subset of the MEL library is shown in Figure 1, which is a screencapture from the Protégé tool for constructing ontologies.

Figure 1. Part of the MEL hierarchy showing three types of geometric region types and two AM processes.

An information model for MELs consists of several structures starting with the overall MEL construct and including a structure for the toolpath and another for process variables.

MEL := <Name, char>
<Process, process_type>
<Geometry, geometric_model>
<Toolpath, Struct_Toolpath>
<Process Variables, Struct_ProcessVars>
<Material, material_type>

Struct_Toolpath :=<ToolpathPlan, toolpath_type>
<Num_contours, int>
<PathPoints, double_array>

Struct_ProcessVars := <ScanSpeed, double>, <LayerThickness, double>,
<SpecProcessVar1, double>, ... <SpecProcessVarN, double>

The main MEL structure includes fields for the MEL name, the AM process type, nominal or exemplar geometry, a toolpath structure, a structure for process variables, and the material type. Toolpath structures are meant to embody the specific toolpath geometry and any toolpath-specific variables. Toolpath geometry is computed using a standard algorithm that is parameterized by the various MEL and toolpath variables. The process variable structure includes two common variables, scan speed and layer thickness, and as many process-specific variables as is needed.
Material extrusion MEL

To illustrate the basic usage of the MEL information model, a simple MEL model for material extrusion will be presented. The MEL will be for a typical macro-scale geometric region with a standard toolpath pattern. The example below is given in the Matlab code that creates the Matlab structures for this MEL and creates the first of the ‘manufacturing_elements’ array of structures. This MEL is called ‘QuadRegion_MatlExt_MEL’ which indicates that it is for the material extrusion process and a simple 2D quadrilateral geometric region. The geometry is intended to be a 2D geometric face (indicated by the constant CAD_face_type). Nominal process variable values are given. The actual toolpath geometry (‘path_points’) will be computed after the specific part region has been identified and the entire MEL instantiated.

MEX_process_vars = struct('speed', 20, 'layer_thickness', 0.4, ...
    'road_width', 0.6, 'road_spacing', 0.6, 'fill_angle', 45);
MEX_toolpath = struct('contour_type', 'contour_serp', 'num_contours', 1, ...
    'path_points', []);
manufacturing_elements = struct('name', 'QuadRegion_MatlExt_MEL', ...
    'process', 'material_extrusion', 'geometry', CAD_face_type, ...
    'toolpath', struct(MEX_toolpath), ...
    'process_variables', struct(MEX_process_vars), 'material', []);

Vat Photopolymerization MEL

A more complex example will be given for a vat photopolymerization MEL for the design and fabrication of lattice structure, where the lattice struts have small diameters that are close to the resolution of the machine. A laser scanning stereolithography machine is assumed. Scan patterns and scan variables are associated with each strut in a unit cell. For each layer in the SL build process, the unit cell is sliced by a plane. For vertical struts, the intersection of the plane and the strut is a circle. For slanted struts, the intersection is an ellipse, while for horizontal struts, the intersection is a rectangle. Each case can be handled readily.

The MEL representation is given below. Scan speed is given by the name of a Matlab function that computes scan speed for laser-scanning stereolithography.

SL_process_vars = struct('speed', 'ScanSpeed_SL', 'layer_thickness', 0.05, ...
    'beam_diameter', 0.125, 'build_style', 'ACES', 'border_overcure', 0.02, 'hatch_overcure', 0);
SL_strut_toolpath = struct('contour_type', 'contour_SL', 'num_contours', 1, ...
    'path_points', []);
manufacturing_elements(2) = struct('name', 'LatStructStrut_SL_MEL', ...
    'process', 'stereolithography', 'geometry', CAD_face_type, ...
    'toolpath', struct(SL_strut_toolpath), ...
    'process_variables', struct(SL_process_vars), 'material', 'Accura ClearVue');

The cases for vertical and slanted struts are shown in Fig. 1 for several cases of small and increasing strut diameters. The notation is as follows: \( r \) = strut radius, \( W_0 \) = laser beam radius, \( \theta \) = strut angle, \( r_l \) = major axis of ellipse (with minor axis = \( r \)), and \( p = (p_x, p_y) \) = center of intersected circle or ellipse. The specific parameters in the cases were determined empirically and give reasonable results for typical SL resins and laser scanning speeds. For example, case a) \( r \leq 1.5 W_0 \)
is a reasonable limit for a point scan for a vertical strut. For slanted struts, cases b), c), and d) apply.

Using the standard SL exposure model (Gibson et al., 2015), the irradiation time for point scans and scan speeds for lines can be computed easily. For reasonably long scan vectors (more than \( \sim 3 \) times the laser beam diameter), the scan velocity, \( V_s \), to give a cure depth of 1.5 times the layer thickness is given in Eqn. 1a, while the time, \( T_c \), to cure a point of the same depth is in Eqn. 1b:

\[
V_s = \sqrt{\frac{2}{\pi}} \frac{P_L}{W_0 E_c} e^{-\frac{1.5 l}{D_p}} \tag{1a}
\]

\[
T_c = \frac{\pi E_c W_0^2}{2 P_L} e^{\frac{1.5 l}{D_p}} \tag{1b}
\]

where \( P_L = \) laser power [mW], \( D_p = \) depth of penetration [mm] (taken to be a constant measure of a resin’s sensitivity to laser energy), \( l = \) layer thickness. SL resins are assumed to be cured (form a solid) when they receive exposure that is equal to or greater than a certain amount, called the resin’s critical exposure, \( E_c \) [ml/mm²]. For a layer thickness of \( l = 0.1 \) mm, it is typical to cure the resin to a depth of 0.15 mm, or 1.5 times the layer thickness. This cure depth reaches a maximum along a scan’s centerline. Substituting reasonable values for a 3D Systems ProX 800 machine (\( P_L = 100 \) mW, \( W_0 = 0.065 \) mm, \( l = 0.1 \) mm) and ClearVue resin (\( E_c = 0.095 \) ml/mm², \( D_p = 0.1549 \) mm) yields a scan speed of about 4.9 m/s. At this speed, the width of a cured scan line is 0.091 mm for the numbers in this example, or about 70% of the laser beam diameter. The cure model presented briefly here has been implemented into a MEL for lattice unit cells fabricated using SL.

Figure 2. Scan pattern cases for sliced struts for a stereolithography MEL.
By adjusting scan speeds, it is possible to fine-tune a process plan such that lattice struts have appropriate sizes, which has been formulated as a parameter estimation problem and solved using nonlinear least-squares methods (Sager & Rosen, 2008).

**MATERIAL EXTRUSION EXAMPLE**

A new type of material extrusion process is being developed at SUTD that deposits liquid polymers, or other liquid materials, into a liquid matrix. This is suitable for embedding one type of material into PDMS, hydrogel, or other liquid material. The specific application for this example is a batoid (stingray type) robot that has flapping wings for propulsion and maneuvering (Valdivia, 2017). Experience has shown that the wings should have a certain stiffness distribution to provide suitable flapping motions (Viswanathan et al., 2016). Specifically for this example, wings should be approximately 5 times stiffer in the radial direction than in the angular direction. A plan view of a batoid robot schematic is given in Fig. 3a, while the side view of an actual robot is shown in Fig. 3b. This robot is approximately 350 mm long and 300 mm wide. The body and wings of the robot will be composed of PDMS with an elastic modulus of approximately 2.5 MPa and the stiffening material will be ABS with an elastic modulus of 2500 MPa.

To design the wing with the appropriate stiffness distribution, the QuadRegion_MatExt_MEL will be instantiated with the “Stiffened wing region” from Fig. 3a and some process variables adjusted. Using this MEL, the material extrusion deposition path will be designed. A serpentine deposition path will be used with 1, 2, or 3 contours. The road spacing (distance between depositions in the middle of the wing) is another design variable that will vary between 5 and 10 mm. Fig 4 shows an example toolpath with one contour and road spacing of 10 mm.

The design process proceeds with the enumeration of wing designs for the discrete design space defined by the number of contours and road spacing variables. In total, 18 designs were generated (3 number of contour values, 6 road spacing values). Structural finite element analysis was performed on each design with uniform loading in the X and Y directions. X and Y stiffnesses were estimated by dividing the load by the deflection times the wing thickness. The stiffness ratios ($Y/X$) were computed for each design and are plotted in Fig. 5. Careful examination shows that designs with 1 contour and road spacing of 7 or 8 mm provides stiffness ratios close to 5 (5.13 and 4.97, respectively). An alternative is 2 contours and a spacing of 6 mm (stiffness ratio = 5.22).

![Figure 3. Batoid robot example.](image-url)
CONCLUSION

Manufacturable ELEMENTS (MELs) were proposed as an intermediate representation to support DFAM and process planning. In principle, MELs contain information associated with representations of process-structure-property relationships that enable design exploration with a consideration of AM process and machine-specific capabilities and constraints. A library of MELs is under development for various design features and types of geometric regions. For each feature and region type, different MELs are constructed for different AM processes. Examples were provided for vat photopolymerization and material extrusion processes. Based on this work, MELs appear to be useful in helping designers understand AM capabilities and limits and in generating as-manufactured part models for engineering analysis, design, and manufacturing tasks.

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REFERENCES


