

REDUCTION OF COMPLEX OBJECTS INTO MANUFACTURABLE ELEMENTS USING THE SHELL-SLICE APPROACH

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ABSTRACT

Software tools for generating a parting surface around a molded part have been available for many years and could be of use for additive fabrication of complex objects. This paper explores the use of software tools such as Materialise Magics Tooling™ and SolidWorks® software to assist in reducing complex objects, such as a lattice structure, into sub-elements free of undercuts and hidden internal geometry. The objective of the proposed Shell-Slice approach is to decompose an object into elements that can be readily machined and created via hybrid fabrication processes. The appeal of hybrid fabrication combined with an automated Shell-Slice approach, is the machinability of each sub-element parting-surface and the remarkable build-speeds and surface-finishes that may be attainable.

1. INTRODUCTION

Purpose

During efforts to develop strategies to improve part quality and reduce the build-time of complex lattice structures, a new method for “decomposing” CAD models was realized -the “*Shell-Slice*” approach. The goal of this approach is to simplify complex objects, such as a lattice structure, into two independent sets of elements, “support-phase elements” and “part-phase elements,” each containing no undercuts or hidden geometry, in a form that can be readily machined with 3-axis machining by a hybrid fabrication process. A standing challenge of all Additive Manufacturing (AM) processes has been in speeding up deposition rates while maintaining or improving surface-finish quality. With layer-based processes, the primary penalty for improved surface finish is reduced build rate. The reverse is true as well; with improvements in build speed, surface quality can be penalized. The purpose of this research effort was to experimentally assess the feasibility of the Shell-Slice approach in successfully decomposing a complex object into a minimal number of manufacturable elements suitable for hybrid fabrication. This paper has been prepared to provide the SFF community with an introduction to the Shell-Slice approach. The Shell-Slice approach is being proposed for the production of complex objects via hybrid fabrication processing whereby material is added, slightly beyond the CAD boundary for that element, followed by a material removal process to bring upward facing surface within CAD tolerance. Methods for reducing complex objects into sub-elements are described in addition to explanation of how free-form surfacing can be used for generating complex mold parting surfaces.

Scope

Sketching, CAD modeling, and experimentation were key to the visualization and understanding of the requirements of the Shell-Slice approach as it evolved. Simple models were considered early-on, including a 2-D side-view of a lattice structure; a 3-D sphere and torus with a primitive core geometry within; a 3-D lattice sub-section with nested undercuts; and, a sphere with multiple nested cores. At the time of the work, .stl’s were anticipated to be the primary format of build files; so, both Materialise Magics Tooling™ and SolidWorks® software were used. Later research efforts leveraged the capabilities of Rhinoceros™, a 3-D CAD modeling software. As part geometry becomes more complex, the ability to see a method for sub-dividing an object becomes unclear and the time required verifying a “success”

increases significantly. Though somewhat labor-intensive, the direct, hands-on approach to create CAD models has provided an important learning opportunity, and helped in visualization of the complex sub-elements and some of the unique challenges. Structures of great complexity will require additional process automation (including software and hardware advancement) and are beyond the scope of this paper, but will be considered in future efforts.

Background

Optimized Lattice Microstructures

The direction of research on optimized lattice structures has been to develop a process to integrate optimization of a structural component's shape and topology with optimization of the composite material within, by treating the component's inner skeleton as part of the design domain. Rather than a solid cast component with optimized outer shape, one can produce a component with an inner skeleton – or microstructure – designed to maximize, minimize or vary stiffness, thermal conductivity, strength, or other properties (1) (2). Figure 1 illustrates lattice structures found in nature as well as a computer generated lattice structure. Lattice structures with ligament (rod-element) counts approaching one million or more are anticipated and feature sizes down to 100 microns or lower are desired. Unlike a typical plastic injection molded or CNC-machined component having somewhat accessible surfaces, optimized lattice structures inherently have significant undercut or hidden-surfaces and “nested undercuts” in almost all cases.

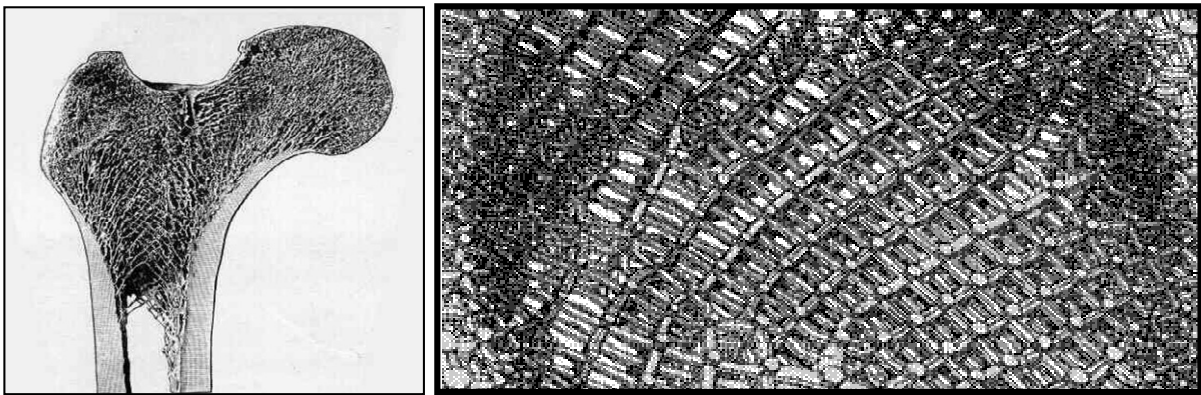


Figure 1. Cut-away view of Femur (left) and computer generated optimized lattice structure (right).

Additive manufacturing appears to be the only option available for generating such complex lattice structures. Currently available AM processes, though improving steadily, have a number of limitations for efficiently growing lattice structures at a level of quality and reasonable price to permit widespread use. Several AM direct and indirect options are available for producing lattice structures including Layered Manufacturing (LM), LM-pattern based casting, and several non-layer-based hybrid processes. Ultimately, structures produced in a range of materials are desirable, particularly metal alloys such as titanium, super-nickels, and chrome-copper.

Layered Manufacturing:

The majority of commercial LM processes first subdivide a solid object into layers, which are reconstructed using one of a number of additive methods. Layers of material are cured, sintered, fused or bonded to reproduce a cross-sectional slice of the object being fabricated. These layers are stacked and joined to the previous layer to eventually form the complete object. It is well known by the additive manufacturing community that objects of virtually any shape or form can be produced by these methods so long as sufficient support structure is available for the object of interest and the process provides sufficient resolution in the X, Y, and Z axis. Some efforts to improve efficiency have led to advanced slicing techniques whereby layers with more vertical change (shallower slope) can have finer layers and those with a constant Z profile (infinite slope) can be grown in thicker layers, making the process more

efficient. Polymer-based LM processes have achieved superior resolution and surface finish when compared to metals. With regard to producing metal lattice structures via LM, processes such as Electron Beam Melting (EBM), Selective Laser Melting (SLM), and Direct Metal Laser Sintering (DMLS)

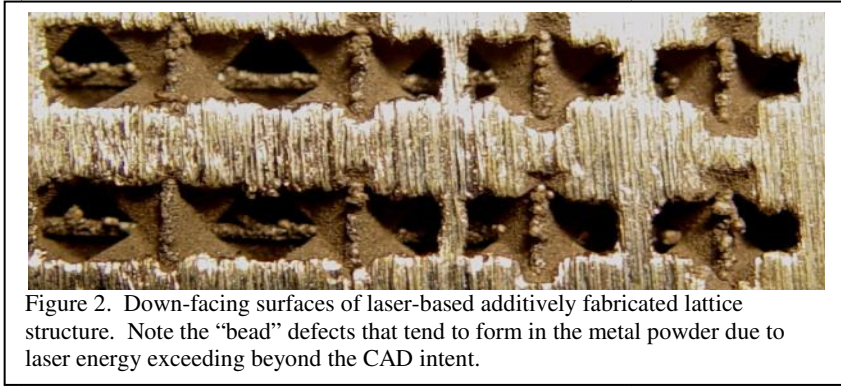


Figure 2. Down-facing surfaces of laser-based additively fabricated lattice structure. Note the “bead” defects that tend to form in the metal powder due to laser energy exceeding beyond the CAD intent.

offer opportunities and challenges. One opportunity is the refined grain structure and superior mechanical properties achieved by the rapid-freezing of the melt-pool as the laser traces each layer. One challenge of many LM processes is warpage, reduced in some cases by rigid supports. Another common LM problem is the poor surface finish achievable with laser-based and E-beam-based processing, especially on down-facing surfaces such as that shown in figure 2. Undesirable beading is clearly visible on the down-facing ligaments of this lattice structure produced using DMLS (offered by EOS). Also visible here is the *cut-off* face from where this lattice structure was removed from the precision ground *expendable* steel plate it was grown on. Much has been done to improve upon LM processes for metals to push them to their limit but some of these challenges clearly have points of diminishing returns.

LM-Pattern Based Casting:

Fairly complex lattice structures can be produced via LM-pattern based casting processes such as the radially gradient lattice structure illustrated in figure 3. Other processes capable of casting very fine features such as those common with lattice structures include centrifugal casting (3) and counter-gravity casting (4). Two specific challenges do exist as lattice-structure designs become more complex. The first is illustrated in SolidCast™ solidification simulation model shown in figure 4. Filling molten metal into a lattice structure within a ceramic mold is fairly straight-forward, given sufficient mold temperature, melt-superheat, and head-pressure. The challenge that can only be overcome by component design-change is the trapped volumes of molten metal lacking *feeders* during solidification. As lattice ligaments freeze off these volumes of molten metal can only become porous as they cool, shrink and freeze. Depending on the form of the porosity, they could become the “weakest link” in a lattice structure or even a missing link. A second significant challenge of the metal casting approach to lattice structures is the removal of ceramic without damaging the structure as mechanical or chemical mold removal techniques are employed. Flash formed in cracks further complicates ceramic removal in complex lattice castings. As lattice structures approach 10’s and 100’s of thousands of ligament

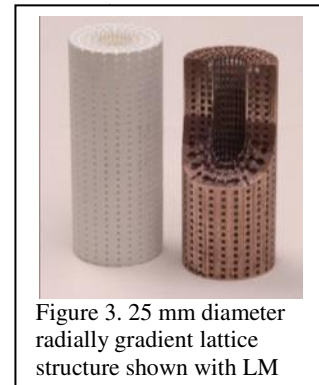


Figure 3. 25 mm diameter radially gradient lattice structure shown with LM

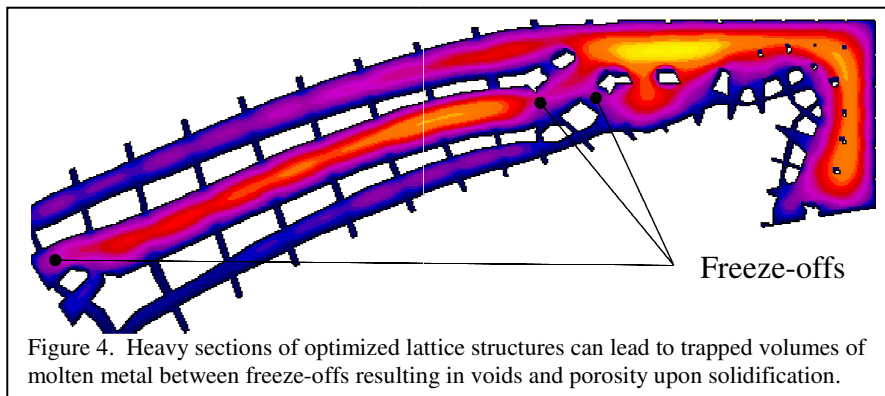


Figure 4. Heavy sections of optimized lattice structures can lead to trapped volumes of molten metal between freeze-offs resulting in voids and porosity upon solidification.

elements, these two challenges become increasingly insurmountable. When compared to LM-based metal processes an advantage of LM-based pattern casting is the lower cost of producing metal parts.

Non-layer-based Additive Processes:

Another group of processes include those non-layer-based approaches that additively produce an object, section by section. Several examples include Shape-Deposition Manufacturing (SDM), and laser Engineered Net Shaping (LENS). With these approaches parts are typically decomposed into simple elements that can be readily machined with CNC Milling. After material is deposited or positioned, the unwanted material is removed down to the upper-most CAD geometry of that up-facing stack of elements. Much has been done to decompose simpler objects into manufacturable elements. Some of the early work in this area has leveraged mold-making know-how, as well as mold-making software tools available to mold designers. One example is an early paper describing a method for recognizing undercut features in molded parts (5). Here, the software goes through a part B-rep model to identify undercut features. Another paper looks at designing the mold for an object consisting of primitive shapes (6). A decomposition-based approach (7) describes a method to minimize support contact area and volume when constructing a larger assembly of elements in foam, which are adhered together to make a larger object. Other efforts have targeted minimizing the number of sub-elements such as that described by Hu (8) claiming fewer layers are possible. Goel describes a method for decomposing objects into undercut-free elements based on undercut edges (9). All of these papers are very helpful in seeing options for approaching the challenge of decomposing lattice structures; but, unfortunately it is unclear if any of the approaches will fully address the challenges of generating undercut-free elements for a complex lattice structure along with the outer, mold-like support structure, as is the goal of the authors.

The Shell-Slice Algorithm:

The “Shell-Slice” algorithm is capable of reducing a complex CAD surface representation of a lattice structure into “line-of-sight” (LOS) elements, and providing the data required for reassembling the object, one region at a time, until the complete part, encased within “mold” volume, is created.

To date the approach used to better understand the requirements of the Shell-Slice algorithm and “see” through the complexity has involved much CAD modeling, manual core extractions, and hand sketching. Simple models were considered early on with primitive core geometry. As part complexity increases the ability to verify that the Shell-Slice approach is valid quickly becomes obscured. The Shell-Slice algorithm considers the surface of the part geometry as well as the extents volume, or “negative” of the part, rather than the solid region of the part itself. This approach is introduced in the following sections of this paper.

2. More about the “Shell-Slice” Algorithm

The “Shell-Slice” algorithm is intended to reduce a complex CAD surface representation of a lattice structure (in addition to other challenging geometries) into LOS-elements and provide required data for reassembling the object, one region at a time, until the complete part, encased within a “mold (or support)” volume, is created. A simplified flowchart of the Shell-Slice algorithm is shown in figure 5. The Shell-Slice algorithm first identifies the “least-core” of a desired part. The *least-core* is then used to reduce all other cores and part sub-sections into LOS-elements. The LOS-elements are combined in a manner to minimize the total number of elements while maintaining machinability. The Shell-Slice

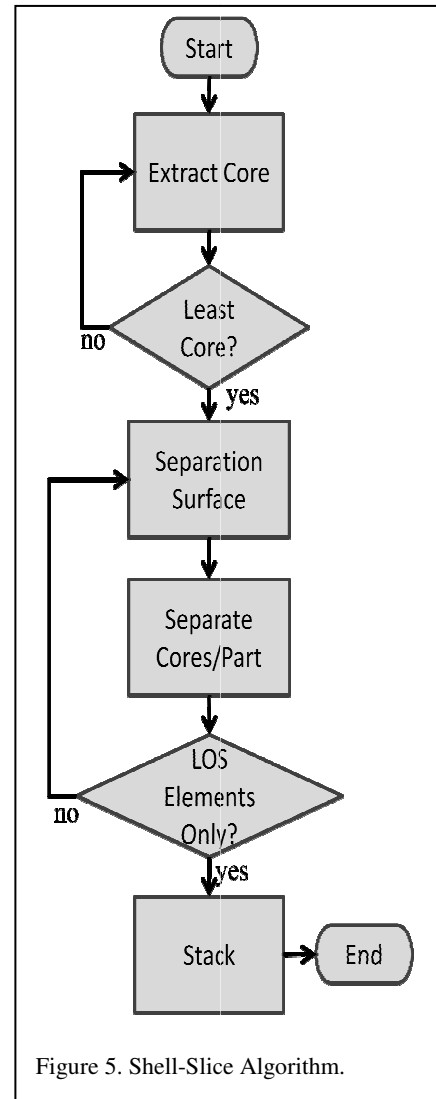


Figure 5. Shell-Slice Algorithm.

approach combines core extraction techniques and parting-surface generation to create the alternating subunits of support phase and part phase required for hybrid-fabrication processes. Similar techniques are employed when reducing an object such as an engine block or manifold into its cores and mold components capable of forming internal oil and coolant passages. This has typically been a labor-intensive process. The Shell-Slice approach is aimed at automating this task while being able to address components with a much more advanced level of complexity. The Shell-Slice procedure is described in the following subroutines.

Least-Core Subroutine

As mentioned above, the first step is to reduce the object, or “shell” of interest to the “least core.” This is accomplished by extracting hidden, undercut core geometry from each subsequently extracted core until an LOS-element is reached (figure 6). The extraction process is applied to part and support materials alike.

- Input: A model of a connected 3-D object; the LOS (line-of-sight) direction
- Processing: If the object has a hidden core, use LOS processing to construct a new 3-D object that models the core. Repeat if necessary with the new object, until an object with no hidden cores is reached— also called an LOS object
- Output: Models of all cores found, up to and including the least core, which has no hidden surfaces

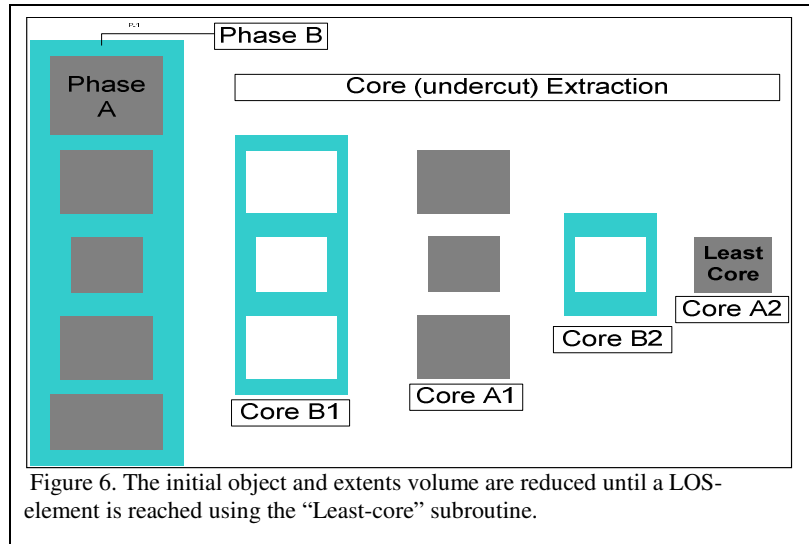


Figure 6. The initial object and extents volume are reduced until a LOS-element is reached using the “Least-core” subroutine.

Separation Surfaces Definition Subroutine

Starting with the *least core* and the extents volume of the support structure a parting surface is defined (figure 7). The parting surface is ideally designed to be a normal to the *least core* geometry, undercut free, and extending to the extents volume. The parting surface is generated by using mold design tools such as those offered by Materialise Magics Tooling™ software.

- Input: A model of a 3-D object that has no hidden cores; the LOS direction
- Processing notes: There are multiple correct parting surfaces, with some having especially desirable properties. The initial implementation will make a simple choice. The next generation will be designed to use the CNC-friendly subroutine (below)
- Output: A separation surface looking from the LOS direction (This can be modeled as a “displacement map” in graphics terms – or a “2.5-D” surface in machining terms)

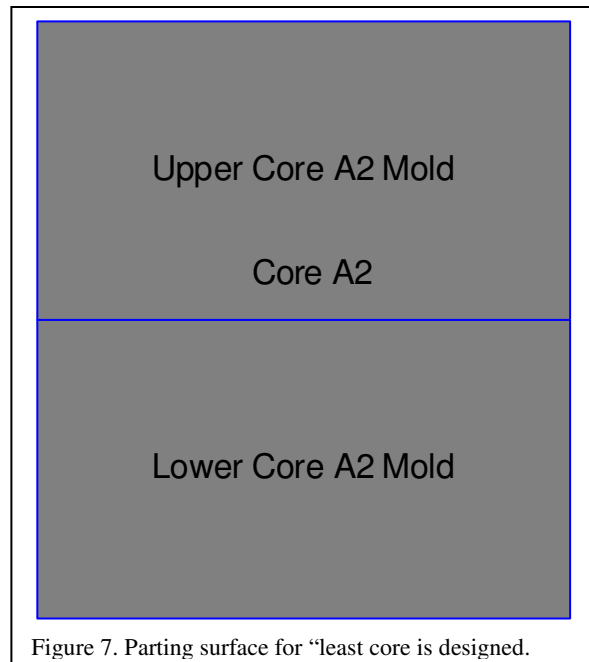


Figure 7. Parting surface for “least core” is designed.

LOS-Element Boolean Operations Subroutine

Using the lower mold half (or ideally the parting surface) from the previous subroutine the next step is to sub-divide the second-to-last core to eliminate the undercut geometry. Shown in figure 8, Core B2 is divided into Core B2a and B2b. The two new cores are LOS-elements, and are used to generate the next parting surfaces for the next core geometry. Figure 9 illustrates this operation. This process is repeated until all core geometry, including the original “part” and “mold,” have been completely subdivided into LOS-elements.

- Input: core and separation surface
- Processing : The preceding core is subdivided using the separation surface
- Output: 2 LOS elements

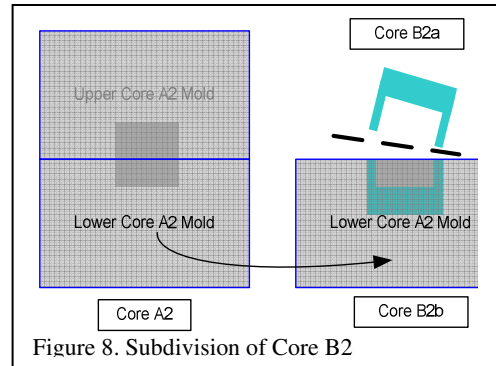


Figure 8. Subdivision of Core B2

Stacking Subroutine

After all cores have been reduced to LOS-elements the next step is to recombine many of the LOS-elements in a logical, machinable manner to reduce the total number of elements. Figure 10 illustrates the process of combining the 17 LOS-elements to the more manageable number of 11.

- Input: a complete selection of “sub-cores” for a particular phase of the object
- Processing: Combine all sub-cores that fall within the same parting surface boundaries and consisting of the same phase
- Output: An optimized set of cores for the input phase. These cores are what must be physically realized to actually manufacture the object using the 2S2P-Hybrid process

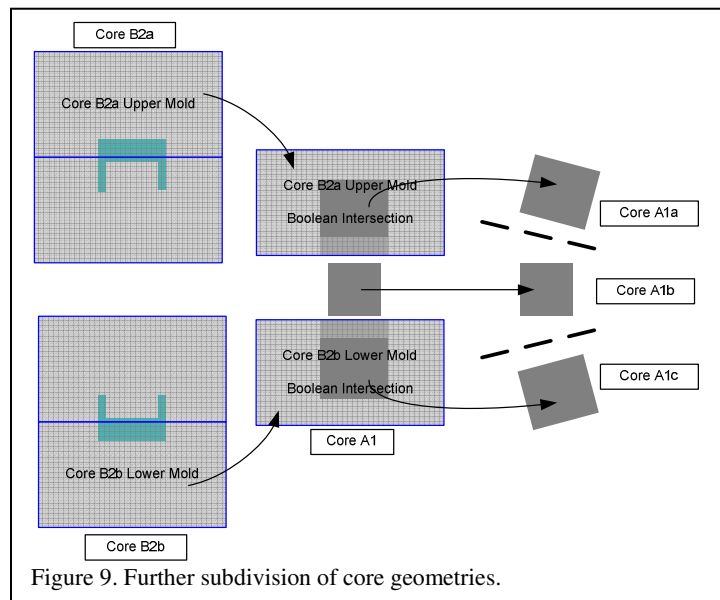


Figure 9. Further subdivision of core geometries.

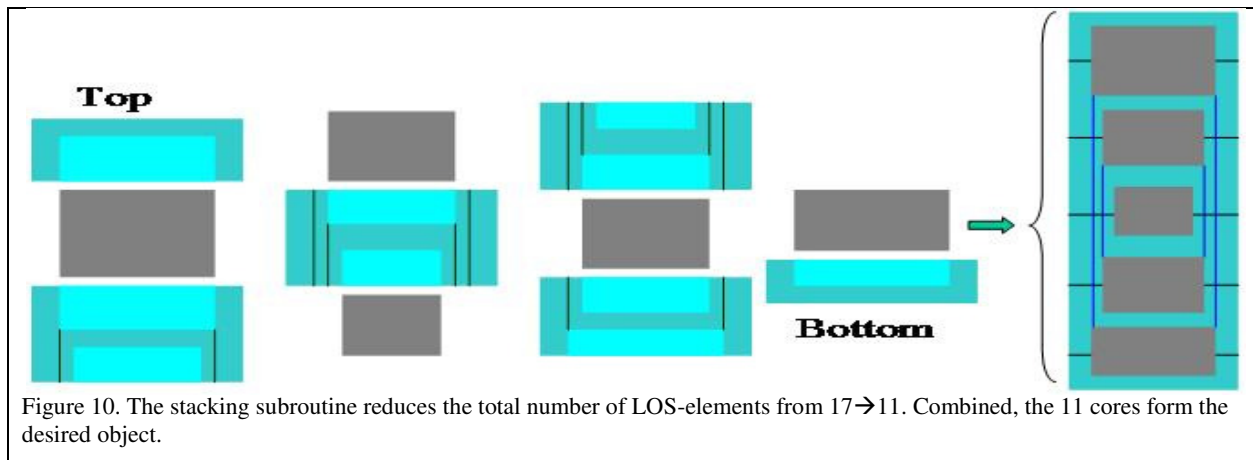
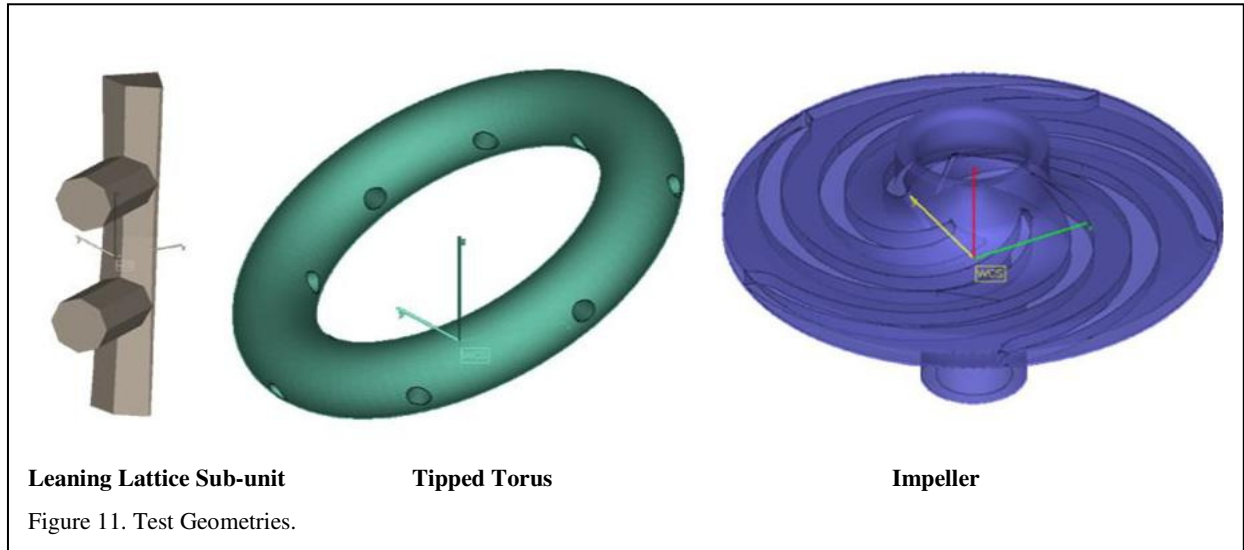


Figure 10. The stacking subroutine reduces the total number of LOS-elements from 17→11. Combined, the 11 cores form the desired object.

3. Test Geometries

Figure 11 illustrates the three test parts used as the Shell-Slice approach evolved to its current state. A number of much simpler geometries were also used earlier in the procedure development process (not shown).



Lattice unit with nested cores

The leaning lattice unit was designed to include several key challenges including a nested undercut and a slightly tipped orientation. The lattice unit is cut from a more complex optimized structure generated using an optimization procedure.

Torus with through-holes

This part was used because it represents reasonable complexity and is a good example to point out the key characteristics of a good LOS component. It was tipped to make the geometry more challenging.

Impeller with core geometry

The Impeller geometry represents a somewhat challenging industrial component that would typically required more than a simple, coreless mold to produce.

4. Results & Discussion

Lattice unit with nested cores

Shown in figure 12 is the leaning lattice unit going through the main steps of the Shell Slice procedure. The first image shows the least core being extracted from the leaning lattice unit. The middle image shows the least-core being used to generate a parting surface followed by the parting surface being used to split the lattice unit into a LOS-elements and an upper portion which required further splitting. The last step shown is recombination of the LOS-elements followed by a graphical representation of the LOS-elements reconstructed using a hybrid fabrication process.

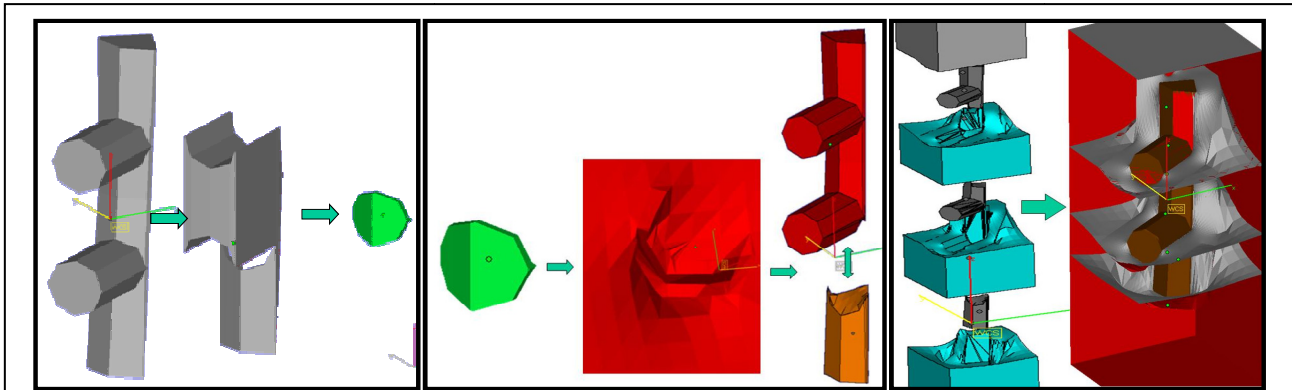


Figure 12. Shell-Slice Procedure applied to the “leaning Lattice Unit”

Torus with through-holes & Impeller with core geometry

The final hybrid-ready layers of the torus and impeller are shown in figure 13. The initial support layer is shown in the left-most image of the sequence for each geometry. Each subsequent (rightward) image shows the addition of more part and support features. The final (rightmost) image shows the final part. A closure support volume could be added as shown in the rightmost impeller image.

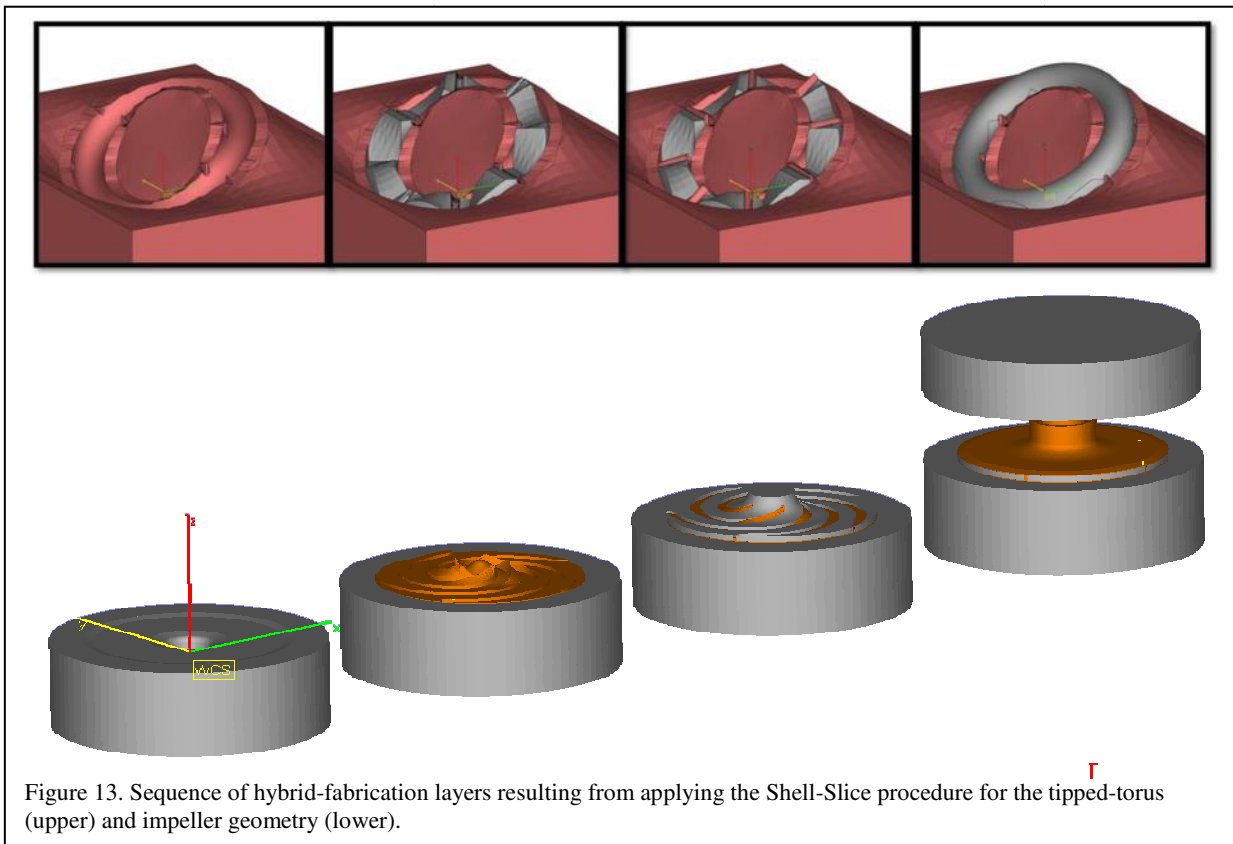


Figure 13. Sequence of hybrid-fabrication layers resulting from applying the Shell-Slice procedure for the tipped-torus (upper) and impeller geometry (lower).

Close visual inspection and an undercut-detection check of the resulting LOS-elements for all three test geometries did not reveal any undercuts, and, all three sets appear to be successfully prepared for hybrid fabrication. Enhancements could be made on the part layers to improve machinability, but, overall, the layers are free of undercuts, and are machinable with a 3-axis CNC mill.

5. CONCLUSIONS

- To simplify an object using the Shell-Slice approach the object must first be reduced to the *least-core*.
- The least core can be used in combination with parting surface methodology to further subdivide an object into undercut-free LOS-elements.
- LOS-elements can be recombined and stacked together to reduce the total number LOS-elements
- The Shell-Slice procedure was applied to a number of test geometries, including a lattice unit, torus, and impeller resulting in undercut-free LOS elements.
- Software advancements (and improved computing power) are required before the “Shell-Slice” procedure can be validated on parts of greater complexity.

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