The Freeform Fabrication of Structurally Optimized and Complexly-Shaped Metal Tubular Components

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Abstract

The service conditions of many structural frames composed of tubular metal components would ideally warrant the use of high strength-to-weight ratio components with shapes and internal geometries that respond to context-specific structural requirements. Commercially available and emerging solid freeform fabrication technologies can be utilized to indirectly or directly manufacture metal tubular structural components with optimizing features that cannot otherwise be manufactured. The results of prototyping experiments demonstrating the viability and potential of this application of additive manufacturing will be presented. This presentation will discuss successful prototype 356 aluminum and 316 stainless steel internally reinforced freeform tubular components manufactured indirectly using expendable patterns made by selective laser sintering and 3D printing. The application of laser and metal powder based freeform fabrication technologies that provide superior material properties will also be discussed, especially in terms of requirements for multi-axis deposition and sophisticated path planning software, and the implications of voxel- or layer-based functionally gradient materials.

1.0 Introduction

The term tube is conventionally understood to refer to a hollow lineal component with a constant cross-sectional shape and size. Constant cross-sectional configuration, however, is not inherent in the definition. Complex hydroformed automotive chassis components, for example, are referred to as being tubular, and are created by deforming conventional metal tubes.

Conventional roll-formed or extruded metal tubes can be considered to exhibit generally optimized strength-to-weight ratios achieved by a combination of hollowed simple cross-sectional geometry and particular material properties.

1.1 Classifying Structural Optimization

The author has defined two general classes of structural optimization as it pertains to components utilized in structural frames. Externally optimized components are those that generally maximize strength-to-weight or strength-to-material usage ratios with features that are visible on the exterior of the component. Rolled steel sections produced to industry standards such as angles or 'I' beams are common examples exhibiting simple cross-sectional geometry. Non-hollow extrusions also fall into this category. Examples of much more complex externally optimized components include subtractively formed bulkheads such as those found in aircraft fuselage frames: such components can feature a wide variety of complex product-specific web, flange, and rib configurations. A few research and/or commercial organizations are presently developing hybrid additive and subtractive methods for making complex externally optimized components such as bulkheads. AeroMet Corporation, for example, has developed gantry-configured 3-axis deposition of titanium onto webs that are pre- (or post-) cut from titanium sheets. This deposition process forms ribs and flanges, and required surface accuracy is achieved by CNC machining the deposited material.

Internally optimized components are those that generally maximize strength-to-weight or strength-to-material usage ratios using features that are formed internally and/or are not visible on the exterior of the component, except possibly at open ends or via external shape, as with a hydroformed member. Conventional tubes are very basic internally optimized components in that their hollowness is not visible unless holes or perforations have been created. Extrusion is frequently used to manufacture much more complex internally optimized components, and many of these components, such as those found in aluminum building fenestration systems or in the chasses of manufacturing equipment, can feature highly complicated cross-sectional geometry. The extent, however, to which complex internally optimized components such as extrusions can obtain maximum strength-to-weight ratios and respond to context-specific service conditions, is limited by formal constraints inherent in available manufacturing methods. Additive processes, especially direct metal deposition methods, have significant potential to circumvent these constraints and enable further optimization of metal structural frame components.

The general constraints on product form inherent in established manufacturing processes are listed below. A taxonomy of all available manufacturing processes for making metal structural components is presented in Figure 1. This taxonomy conventionally classifies manufacturing processes as mass-conserving or mass-reducing, but then sub-classifies processes based on the geometric constraints they impose on product design.

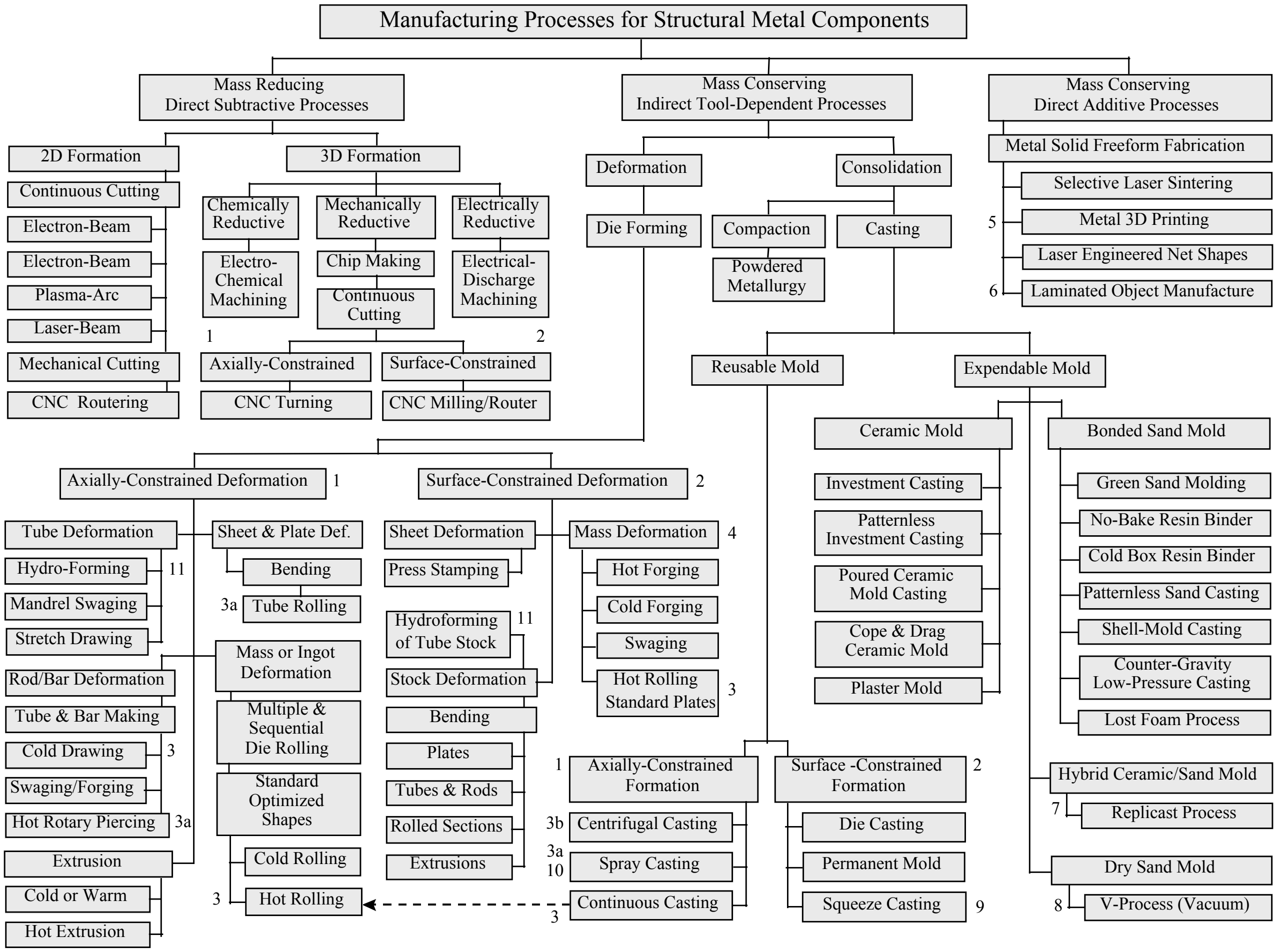
1. Equipment-based constraints. The formal output (e.g. possible product size) of a given manufacturing process is limited by at least one piece of available required equipment.

2. Motion-based constraints:

- *Rotational Motion* results in axially-constrained product geometry.
- *Lineal Motion* (centralized applied force) results in products with a constant cross-sectional configuration (e.g. extrusion, rolling).
- *Surface Distributed Lineal Motion* (distributed applied force) can only produce parts without undercut or re-entrant features (e.g. stamping and forging).
- *Multi-Axis Motion* cannot access or create significant internal features when utilized in conjunction with subtractive manufacturing methods.

3. Tooling-based constraints. The need to remove mandrels, re-usable patterns, dies, re-usable molds, and required fixtures, as well as the components (products) formed with these tools, significantly limits the potential geometry of products, or, in other words, the extent to which optimizing features can be incorporated into designs.

4. Process Based Constraints. Workpiece access and material removal requirements (e.g. removal of expendable cores, internal expendable molds, support powder or support stuctures from internal cavities) can constrain the extent to which product designs might be fully optimized.



1. Axially-Constrained Formation or Deformation Processes are those that create products with axial or rotational motion. Processes that extrude or roll material through dies or molds generate products that are both axially constrained and constant in cross section. Subractive turning processes create axially-constrained products, but these may vary significantly in cross section.

2. Surface-Constrained Formation and Deformation processes are those that form material within the constraints of part-specific surfaces. Indirect Tool-Dependent Processes form parts within the external surfaces of the component or the internal surfaces of its tooling. In subtractive formation, material is removed up to the external surfaces. Surface-Constrained processes are also limited (constrained) by the need for surface-oriented fixturing or jigs (subractive processes) or die and mold parting surfaces.

3. Fundamental manufacturing process for making industry standard structural metal materials and stock products (e.g. sheets, plates, rolled sections, tubes).
3a. A process by which standard tubular products are made.
3b. Centrifugal Casting is used to make standard tubular products, but it is more often used to make manufacturer-specific products.

4. Mass Deformation refers to the deformation of a preformed and component-specific ingot containing a pre-determined quantity of metal in a pre-engineered configuration. Hot Rolling of plates and sheets is, like the production of rolled sections, often directly linked to a continuous casting operation.

5. Metal 3D Printing is being developed by the ProMetal Divison of ExtrudeHone Corporation, licensee of MIT's 3D Printing patent. It is commercially viable as a rapid tooling system for injection molding and other tools requiring complex internal passages that cannot be made by conventional methods (e.g. for conformal cooling). ProMetal is developing larger build volume machines that will make the production of structural components technically viable for some applications, although it will likely be many years before the process is commercially viable for architectural structures.

6. Research into the use of metal sheets in Laminated Object Manufacturing is ongoing at Helisys, Inc. and The Warwick Manufacturing Group (UK). Metal LOM is not presently commercially viable and should be considered a process in R&D. The most significant technical obstacles are removal (de-cubing) of metal from cavities and the surface dimensional accuracy resulting from aliasing (stair-stepping). While research into variable cutting angles per or within a given layer (metal sheet) is ongoing, resolution of this issue will still result in products with a degree of surface abstraction which will necessitate finish machining operations for many applications.

7. The Replicast Process, invented simultaneously at The Castings Development Centre (UK) and Waukesha Foundry (WI), combines the dimensional and surface accuracy of Investment Casting with the size capacity of bonded sand molding processes. A relatively thin ceramic shell mold is positioned in a flask which is then filled with a sand/binder mixture, vibrated and compacted, and placed under a vacuum during metal pouring.

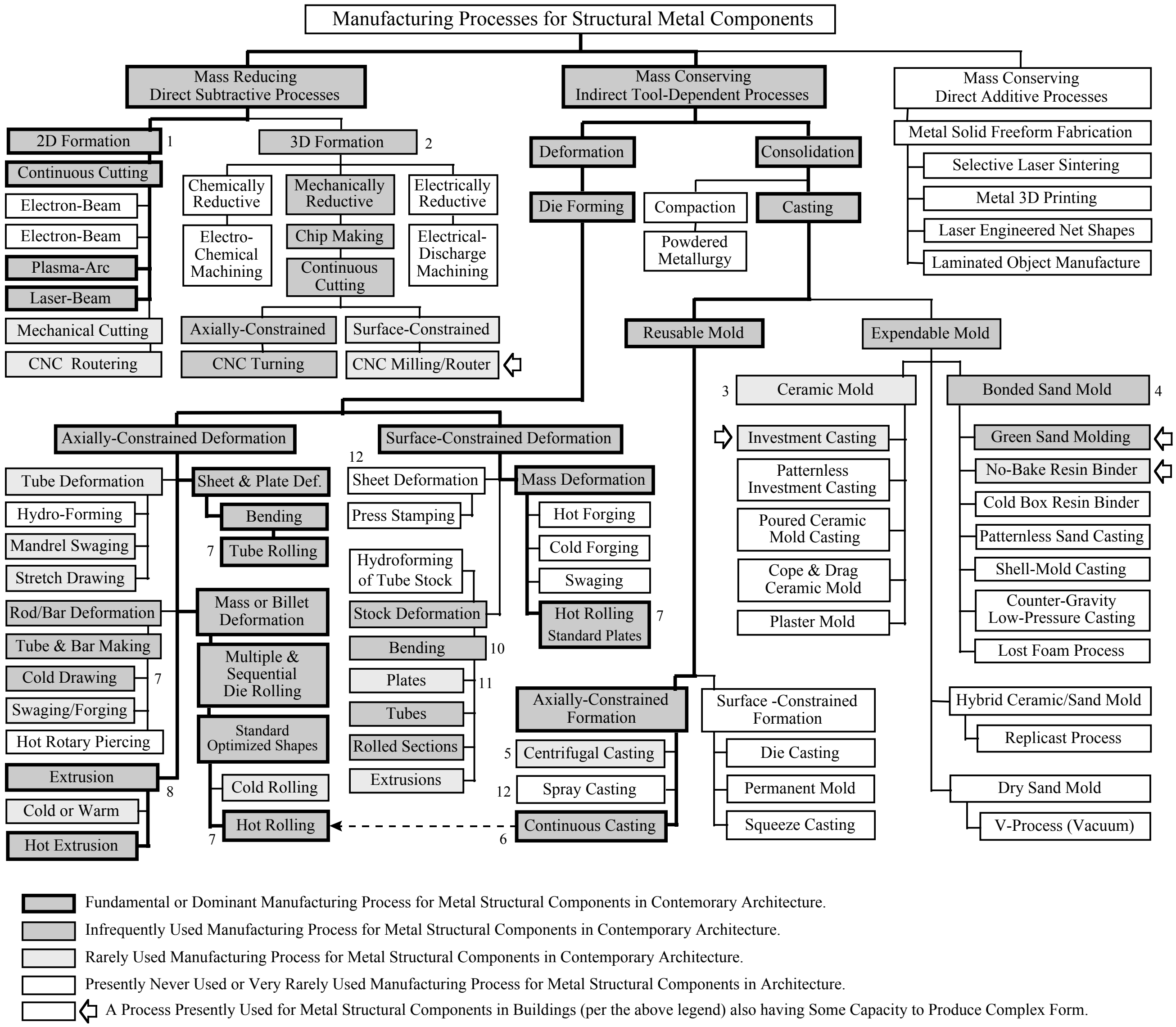
8. The V-Process was invented in Japan for making architectural products such as gratings and ornamental panels. It is now largely used for making mechanically and or structurally functional components as well as housings.

9. Squeeze Casting, which is also known as Semi-Solid Forging, is a hybrid process combining the metallurgical advantages of forging with the greater design freedom permitted by casting. Molten metal solidifies under pressure in metal molds and the casting is then ejected in a manner similar to injection molding.

10. In Spray Casting, which is also known as the Osprey Process, molten metal is sprayed onto a rotating mandrel as it passes through a controlled chamber. The process is used to manufacture seamless tubes and pipes.

11. Hydroforming operations can be either axially-constrained or surface constrained.

Fig. 1. Taxonomy of Manufacturing Methods for Producing Structural Metal Components[1]



Notes:

1. Plasma-Arc and Laser Cutting are commonly used for producing job-specific components such as custom plates or web members for metal fabrications.
2. Continuous Mechanical 3D Cutting is generally only used for making small components and connectors in tensile structures or fenestration support structures, and, of these, axially-constrained formation is much more common. More complex versions of such small structural parts are sometimes investment cast.
3. Structural Investment Castings are generally only used in architecture for small connectors (e.g. glazing bosses) or brackets in job-specific secondary structural systems such as those supporting a window wall. Manufacturers of specialty glazing systems sometimes provide system-standard investment castings.
4. While job-specific structural Sand Castings (mostly iron) were used extensively in the latter half of the 19th century for components in compression (e.g. columns), their use rapidly declined with the advent of stronger standard rolled sections. The use of sand castings for both primary and secondary structural components in buildings , while still not common, has increased significantly in the past approximately fifteen years, especially in the United Kingdom.
5. Centrifugal Casting was used more frequently in architectural structures in the 19th Century. It is sometimes used as an alternate means of producing stock or job-specific tubular (typically column) components. Centrifugal castings are much denser than statically-poured castings and are conseqently stronger (but not as strong as rolled tubes).
6. Continuous Casting is a basic ingot-producing process. Continuous Castings are typically fed directly into hot rolling operations to produce standard optimized sections.
7. Fundamental process for making standardized steel products for the construction industry.
8. Extrusion is not typically used for making components for primary structural systems in buildings because it cannot compete economically with hot rolling for steel products (higher temperatures increase die cost and wear). It is, however, the dominant technology for making aluminum structural frames for fenestration assemblies.
9. Mandrel Swaging of tubes is occassionally used for making tapering ends for larger tubular steel structural components.
10. The two-dimensionally-constrained bending of standard optimized structural sections for job-specific steel frame components is fairly common in architecture.
11. Three-dimensional bending of plate products is quite rare in architecture, although commonplace in the marine industry.
12. Sheet products are generally accepted to be those less than 6mm (1/4”) thick and plate products to be 6mm or greater in thickness. While planar stamping of sheet products is a common means of manufacturing architectural cladding components, in other industries sheetmetal is frequently stamped into complexly-shaped structural frame components as well as protective enclosures, as is the case with unitized automotive structures.

Fig. 2. Analytical Taxonomy: Manufacturing Metal Architectural Structural Components.

2.0 Current Design Context

At present, the majority of structural metal frame components are designed, specified, or selected from standard configurations to accommodate areas of maximum stress or loading. The other portions of a given member are therefore inherently over engineered and/or sub-optimally designed. For example, the cross sectional size and configuration of an aluminum extrusion used as a beam is determined by the portions of its length that will transfer the most significant structural loads. Other portions of the same component may experience much smaller loads or transfer different types of forces. These portions would ideally have a different configuration, but the component's overall geometry is dictated by more critical loads incurred elsewhere.

While this relationship between design and manufacturing is to varying degrees universally true, it is especially true in architectural and civil applications where most structural frames are one-off configurations composed of industry-standard component members. Unlike other industries where production volumes can justify product-specific tooling costs, architects, civil and structural engineers frequently have to design custom context-specific structural frame solutions using components whose tooling and production costs are distributed via standardization across multiple related industries. Figure 2 is an analytical taxonomy of manufacturing processes for making structural metal components, with those methods presently used in architectural and civil applications highlighted. Mass customization enabled by large scale indirect and direct metal solid freeform fabrication has the potential to enable the circumvention of design constraints that are presently universal in the building design and construction industry.

3.0 Classifying Internal Structural Optimization

For the purposes of this research it was necessary to assess all extant processes for manufacturing metal structural components in terms of their capacity to produce structurally optimized and complexly-shaped tubular components. It also became necessary to qualify and classify the extent to which some of these processes possess such a capacity. The results of this assessments and classifications are presented in Figure 4. The varying extent to which those manufacturing processes with a capacity to produce internally-reinforcing features could produce such features resulted in distinct categories of internally-reinforced free-form tubes:

1. *Freeform tubes with no internal reinforcing*. Either additive or subtractive methods can be used to make expendable patterns or reusable tooling for the indirect manufacture of free-form tubes with variable or constant wall thickness. Expendable patterns are used in conjunction with various expendable ceramic mold casting processes. (Examples are shown in Figure 7b.) Hard tooling is utilized, for example, to hydroform complexly-shaped tubes.
2. *Freeform tubes with limited internal reinforcing*. These are freeform tubes with internal reinforcements that do not bridge between opposing tube walls, or, in other words, internal surface reinforcements that can be formed within the constraints of reusable pattern removal requirements (e.g. as with bonded sand mold casting). Such surface reinforcement or ribbing is common on non-tubular components and housings, and could be introduced on the inner (or outer) surfaces of expendable or reusable patterns for freeform tubes.
3. *Freeform tubes with extensive internal reinforcing*. This class of freeform tubes highlights the type of optimization that it was hypothesized could be achieved using additive

technology to directly (utilizing laser (or electron beam) and metal powder based deposition processes) manufacture such a component, or to indirectly manufacture it using an expendable pattern casting process. The specific features that can be incorporated into the design of a complexly-shaped and internally reinforced tube are:

a) Complex corrugated tube walls.
b) Internal bracing that bridges between opposing external furrows or surfaces, in some cases via a core that follows the tube's curvilinear trajectory.
c) Curvilinear openings within the internal braces that demonstrate the possibility of improved strength to weight ratios in these features.
d) Relatively thin walls that demonstrate the possibility of improved overall strength to weight ratios with the use of internally-reinforcing features enabled by additive formation.

4.0 Indirect Manufacture of Structurally Optimized and Complexly-Shaped Metal Tubular Components with Solid Freeform Fabrication

A variety of experimental prototypical freeform tubes with extensive internal reinforcing were designed in ProEngineer with the features enumerated in item 3 above. All of these features, as well as connective features and the overall composition of the tubes were parametrically variable so that these computer models could be readily modified in response to various structural and manufacturing simulation analyses. The indirect manufacture of these prototypical shape optimized internally reinforced tubes was then tested: pattern components were created using 3D printing (Z Corporation Z402 machine) and selective laser sintering (both Castform™ and Trueform™ materials). These self-registering pattern components were then glued together and transported to aerospace foundries where gating and other pattern features were added. These prototypes were successfully investment cast in both 356 aluminum and 316 stainless steel. They received various heat treatments in order to maximize their strength. Two of these prototypes are 1820 mm in curvilinear length, but most are approximately 600 mm in curvilinear length, such as the one shown below in Figure 3.

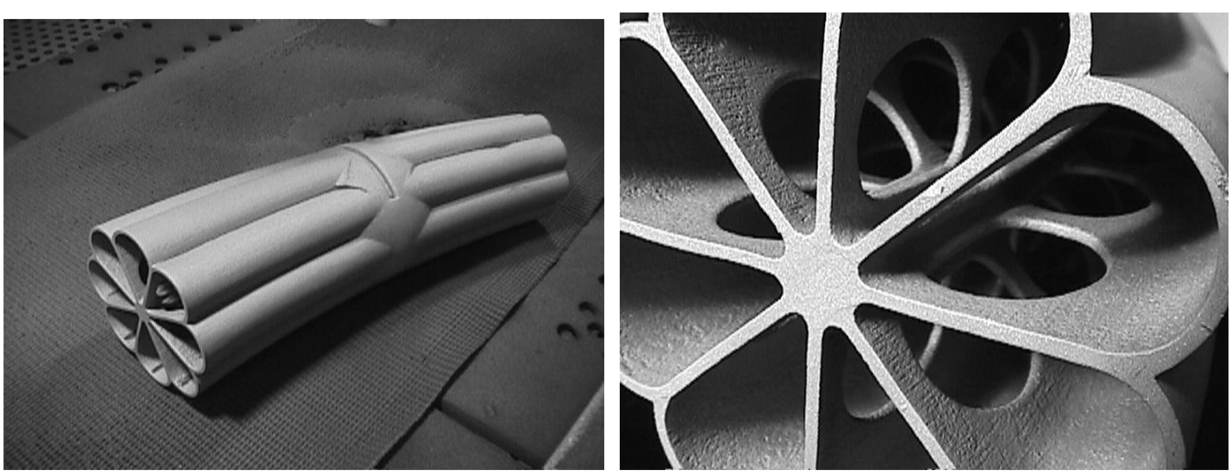
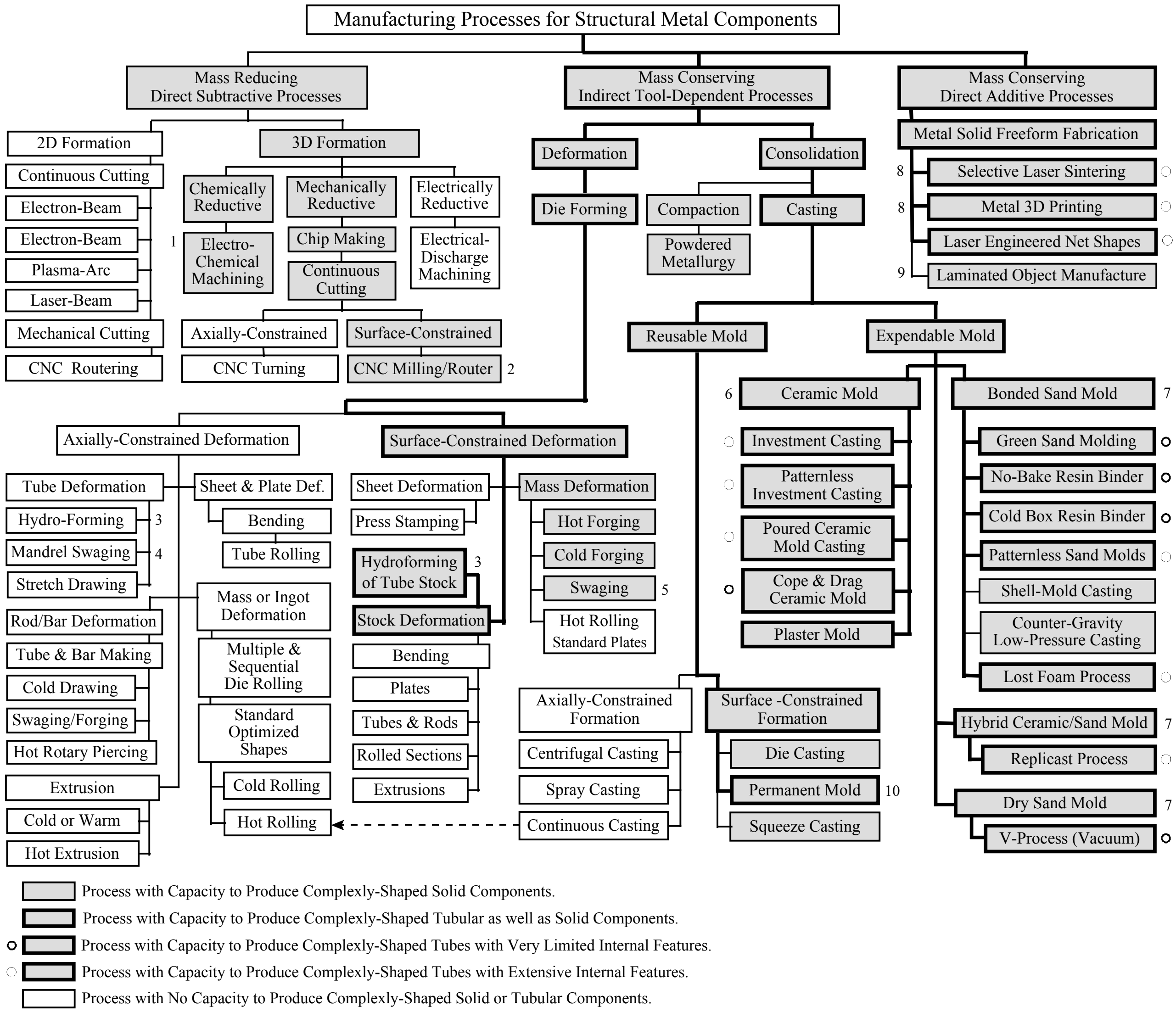


Fig. 3a & 3b. Portion of an A356 structurally optimized and complexly-shaped tube with extensive internal reinforcing features. Investment cast from 3D printed patterns.



1. Electro-Chemical Machining (ECM) is used to machine forging dies from high-strength alloys and to form complex cavities in aerospace components. ECM technically has the capacity to produce complex solid and tubular forms, but these would be limited in size by the work range of the machine set-up (typically for small parts) and expensive: Part-specific tooling requires significant production volume or peformance criteria for the process to be economically viable .

2. Multi-Axis Mechanical CNC Milling can easily produce solid complexly-shaped metal parts, but complex tubes of any significant depth (beyond 2 times the depth of the bit - and chuck depending on opening size) cannot be produced unless they are longitudinal "halves" for making complex tubes as welded or assembled fabrications.

3. Standard tubular products can be hydroformed into either axially-constrained or complexly-shaped variable cross section tubes, the later being increasingly used in the making of automobile chasis components. Equipment and tooling costs are high.

4. The use of Swaging to make variable section tubular components is inherently constrained by the need to remove the required mandrel after formation.

5. Swaging operations can utilze either all rotating dies (inherently axially constrained) or the combination of a stationary and a rotating die, which permit the formation of non-axial complexly-shaped solid parts, although this is less common.

6. All Ceramic Mold casting processes can produce complexly-shaped tubular components with internal (and external) features if necessary shell bridges and access holes are accommodated, and especially if patterns are generated by Solid Freeform Fabrication technologies. However, Poured Ceramic and Plaster Mold processes are generally used only for small components, and designs for use with Patternless Investment Casting must accommodate the build volumes of SLS machines or assembly from SLS mold components. The size capacity of Investment Casting has increased significantly in recent years and parts up to 60" or 80" are now successfully cast.

7. Bonded Sand Molds, Dry Sand Molds and the Replicast Process can be used to make complexly-shaped tubes with internal (and external) features, but these processes are significantly limited relative to Ceramic Mold Casting processes for two reasons: a). Pattern removal during mold making will not accommodate undercuts, and; b). Patterns are typically made using multiple-axis CNC machining/routering which would require subdividing the pattern into many components (discreet machining operations) to accommodate significant internal complexity. Even then it would be difficult or impossible (depending on the design) to match the capability of Solid Freeform Fabrication.

8. Process can inherently make complexly-shaped tubes with internal features, but the design must accommodate the removal of unsintered or unbound powder, and products are very limited in size by the build volumes of various machines.

9. Research into the use of metal sheets for LOM is ongoing at Helisys, Inc. and The Warwick Manufacturing Group (UK). The process could make some complexly-shaped tubular designs, but its potential is very limited by the need to remove (de-cube) internal material.

10. Permanent Mold Casting can produce complexly-shaped tubular parts if sand cores are used. This practice is fairly common.

Fig. 4. Analytical Taxonomy: Manufacturing Complexly-Shaped Metal Components

5.0 Architectural Applications of Complexly-Shaped and Structurally Optimized Metal Tubular Components

Complexly-shaped and structurally optimized metal tubular components are being designed by the author's architectural practice, Freeform Design & Manufacturing Research Studio, and manufactured for use in full size architectural structures. The components shown in Figures 6 and 7, for example, are prototypes for the conservatory structure shown in Figure 5. This structure was designed as an assembly of discreet parametrically-variable components in ProEngineer, and these components were in turn subdivided as required into self-registering pattern components that will be manufactured both subtractively (CNC milled from high density foam) and additively using 3D printing. The pattern components will then be assembled and bonded together with foundry glue prior to being manufactured using a variety of hybrid sand and ceramic mold casting processes. The components were digitally analyzed both structurally and in terms of castability (i.e. with MAGMA), and modified as required (i.e. per stress analysis, metal flow, and shrinkage). The model shown in Figure 5 was also designed as a kit of parts in ProEngineer, and these parts were made with stereolithography, urethane castings made from RTV tools and stereolithography patterns, and laminated object manufacture.

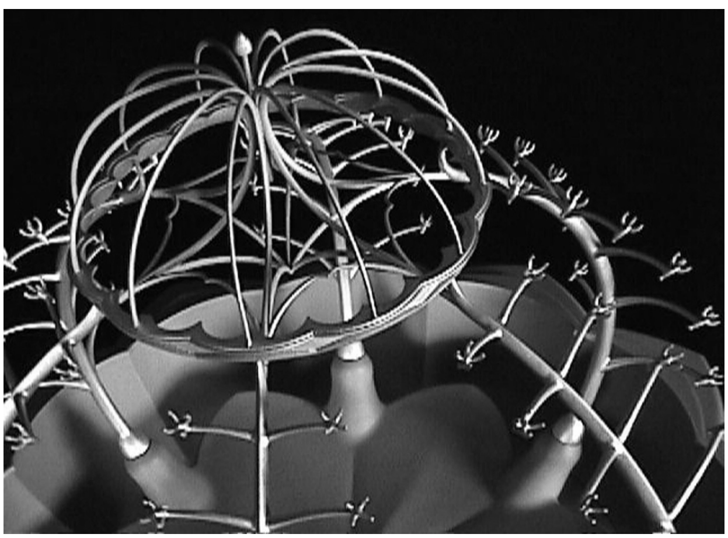


Fig. 5. Structural Model of a Conservatory

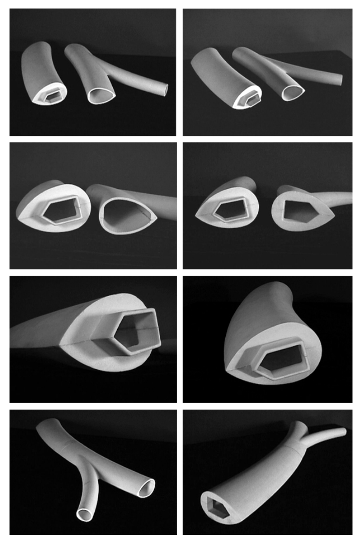


Fig. 6. Component Patterns

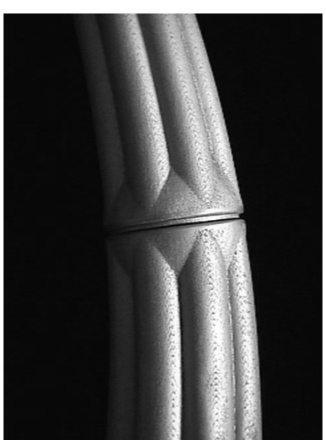
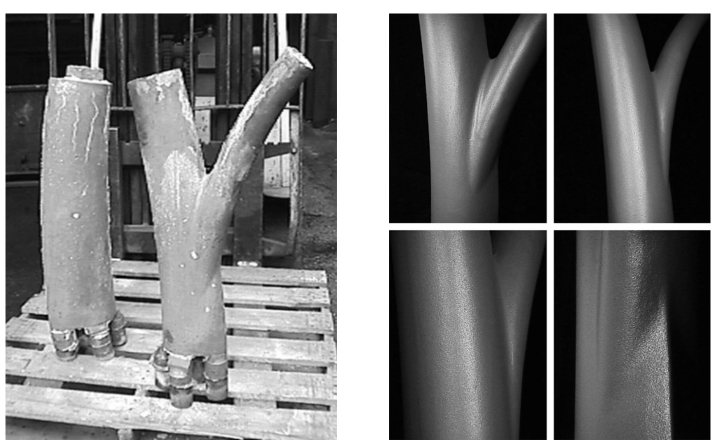


Fig. 7a. A356 Prototype



7b. 316 Stainless prototypes, as cast and powder coated.

6.0 Notes on Biomimetic Structural Form

The notion of optimizing the strength-to-weight ratio and/or strength-to-material usage ratio of a tubular structural component by optimizing its geometry (design) per anticipated product-specific service conditions can be considered a biomimetic approach to structural design enabled by solid freeform fabrication. This is because such an approach attempts to replicate some of the material efficiencies found in biologically generated structures. The author has defined two fundamental classes or approaches to biomimetic design:

1. The direct imitation of biologically generated structural efficiencies can be considered a *scientific approach* that includes:
    - replicating structural composition, which is always relative to other biological functions and naturally occurring service conditions;
    - imitating material efficiency by minimizing and functionally varying or distributing material usage
    - generally maximizing overall strength to weight ratio per natural precedent.
2. Aesthetically-driven or interpretive organic structural form, which is in part or whole an *artistic approach* to biomimetic design.

Design for commercial products (as opposed to performance specified, entirely non-aesthetic products) involves the reconciliation of the scientific and artistic approaches to interpreting natural structures. The balance can vary greatly, especially in architecture, and indeed this is reflected in the conservatory design shown here. However, the research introduced in this paper (e.g. per Figures 3a and 3b above) is focused solely on maximizing engineered "biomimetic" structural efficencies, not only for architectural purposes, but for a wide variety of small and large scale applications.

6.1 Cautionary Notes on Biomimetic Structural Form

1. Nature is generally highly efficient (i.e. economical). But, there is a distinction between natural economy and human economy. After satisfaction of service conditions (including embedded safety factors), economic efficiency (cost) governs most commercial design (e.g. the retail warehouse is a high strength-to-weight ratio construct maximizing enclosed volume whilst generally minimizing material usage – while a more efficient structure might be possible, the cost of manufacturing the required components does not add sufficient value).

2. The higher the degree of material efficiency relative to function, the greater the extent to which a structure might be considered "biomimetic," regardless of its form.

3. The distinction between natural economy and human economy exists because nature has more sophisticated manufacturing (material forming) processes. SFF (especially in conjunction with FGM) and the emerging capacity to manufacture biologically (i.e. grow components and materials) are major steps in the ever-increasing human capacity to replicate nature. The commercialization of this increasing capacity is (as it always has been) constrained by cost benefit realities: the value added by new means of achieving conventional or previously impossible solutions must be sufficient to justify increased cost.

7.0 Concluding Discussion

Free-form tubular components with extensive internal reinforcing have been successfully indirectly manufactured using a variety of expendable mold casting methods and expendable patterns made with 3DP & SLS. These prototypes range up to 1820 millimeters in curvilinear length. In addition, a wide variety of internal and external "biomimetic" geometric configurations have been developed. The quantification (measurement) of strength-to-weight ratio improvements possible with these geometries is ongoing, and benchmark geometric configurations are being developed for experimental prototyping and comparative analysis using a variety of direct metal processes. Powder based direct metal SFF processes that utilize surrounding powder for support (SLS & 3DP/ProMetal) can presently best accommodate complex biomimetic tubular designs. The only major constraints on design with these processes are the need to remove powder from internal cavities and the limited (but improving) achievable tensile strengths.

Current research is focused on small scale applications, and assumes the capacity to manufacture complex internal features while also matching or exceeding the properties of wrought alloys. This assumption recognizes the fact that many of the possible benefits of structurally optimized and complexly-shaped metal tubular components cannot be fully realized utilizing casting processes, even though expendable patterns with the required geometries can be produced using SFF: the limitations of achievable material properties, especially tensile strength, even with appropriate heat treatments, can result in failure to fully capture the benefits of improved geometry, especially for service conditions requiring tensile performance.

Various laser or electron beam and metal powder based deposition methods, including LENS™ and other proprietary processes, can presently best satisfy the material strength requirements of the designs. These processes, however, must address other significant issues and limitations in order for the manufacture of structurally optimized and complexly shaped tubular components to become truly viable. These issues include:

1. Circumvention of the need for support structures in inaccessible areas via controlled multi-axis deposition.
2. Most path planning software for direct metal deposition processes cannot presently accommodate complex geometric configurations. This is a very significant hurdle.
3. Accuracy and surface quality must be improved. Surface roughness can lead to fatigue cracking and catastrophic structural failure. Some service conditions will require CNC milling of surfaces to eliminate this potential. Internal surfaces are therefore problematic and suggest the need for hybrid metal deposition and subtractive processes. The path planning requirements for such conditions are a significant hurdle.
4. Capturing the full benefits of biomimetic designs for freeform metal tubes is ultimately dependent on realization of significant capacity to achieve functionally-graded materials – controlled local deposition of alloys via at least layer-based FGMs, but preferably voxel-based material specification and voxel-cluster material delivery.

[1] The term Laser Engineered Net Shaping is used in Figures 1,2 and 4 to generically describe laser or electron beam and metal powder deposition processes.