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DIRECT MANUFACTURING

3D PRINTING & ADVANCED MANUFACTURING

GETTING THE MOST OUT OF METAL 3D PRINTING: UNDERSTANDING DESIGN & PROCESS CONTROLS FOR DMLS

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GETTING THE MOST OUT OF METAL 3D PRINTING

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Metal 3D printing is the ideal alternative to complex designs that machining or casting can't achieve. It offers the mechanical properties of aerospace standard materials and the design freedom of 3D printing.

The impact of metal 3D printing on the manufacturing landscape has become significantly more measurable within the last decade. Materials developments and concentrated research into producing fully dense additive metal parts has led to recent widespread adoption of the technology for end-use production. This paper will cover metal 3D printing design constraints and freedoms, available metal materials, quality and process controls, surface finishes, and heat treatment methods that truly empower metals to overcome conventional manufacturing challenges and deliver incredible parts impossible to achieve through other production means.

Metal 3D printing overcomes conventional manufacturing challenges to deliver incredible designs.

While metal 3D printing has a variety of monikers, there are mainly two contrasting technologies with which to 3D print metal parts: Direct Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM). Additional metal 3D printing processes include metal extrusion and a cold spray technology. According to the Wohlers Report 2015, DMLS comprises the largest installed base of metal 3D print systems worldwide. It has perhaps warranted the most attention from R&D departments; therefore we'll solely focus on DMLS in terms of design considerations, post-processing techniques and mechanical properties. By leveraging the mechanical properties of DMLS parts through optimized designs and post-processing treatments we'll see the best results out of metal 3D printed parts.

HOW IT WORKS

Direct Metal Laser Sintering (DMLS) begins with a design in the form of a 3D CAD file. A high-powered laser melts powdered metal layer by layer to build up one or multiple designs. The process is comparable to welding with a very fine and precise laser. Parts are printed in an enclosed build chamber infused with argon gas. A Yb-fibre laser focused via dynamic mirrors selectively melts the design's cross section through a computer-determined scan path. The fine-tuned laser, powder and layer additive process combine to form a powerful design freedom triad. DMLS metals offer similar properties that aerospace, medical and energy industries have come to rely heavily on for production.

MATERIALS FOR METAL ADDITIVE MANUFACTURING

Similar to metal injection molding, DMLS powders are created via atomization. Previously, powders for additive manufacturing comprised a very small sampling of the overall market for metal powder. However, the demand for metal 3D printing has significantly increased and pushed development towards tailored metal powder compositions. Today, a collaborative effort between the quality measures of metal powder suppliers and additive manufacturing service providers is speeding development in the manufacturing of additive metal alloys. At Stratasys Direct Manufacturing, we verify material chemistry, powder morphology, and particle size. Then we test a variety of printed mechanical properties, including tensile, hardness, and microstructure, before making them available to customers. Through tests and customer interfacing, Stratasys Direct Manufacturing is in a unique position to function as a catalyst for further materials advancements.

METALS AND ALLOYS AVAILABLE FOR METAL 3D PRINTING:

i. Steel
ii. Stainless steel
iii. Titanium – pure
iv. Titanium alloys
v. Aluminum alloys
vi. Nickel-based alloys
vii. Cobalt chrome alloys
viii. Copper-based alloys

Metal 3D printing materials are familiar and widely used in the aerospace sector. However, just as aluminum cast parts differ from aluminum machined parts, metal 3D printed parts differ in properties from machined and cast metals. Understanding these differences is key to realizing your 3D printed design in metal.

3D printed metal parts are similar to cast parts in terms of density and strength right off the machine. An as-built DMLS part is roughly 99.5% dense before post-processing. After heat treatments, DMLS parts will greatly surpass metal injection molded parts in terms of porosity. The industry standard for a metal injection molded part is 2% to 5% porous whereas DMLS parts exhibit less than 0.5% porosity. Stratasys Direct Manufacturing has performed significant materials tests to study post-processing treatments that can further strengthen DMLS part properties. Before we discuss those treatments, it's important to understand how design affects the mechanical performance of your DMLS part and how to design with these details in mind to get the most out of manufacturing with DMLS.

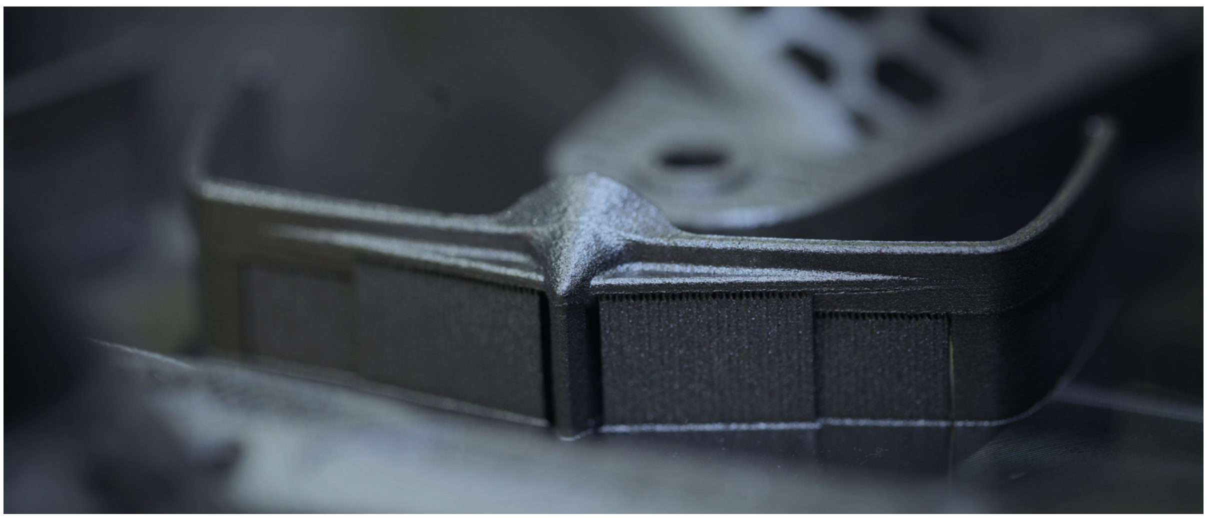


Figure 1: DMLS parts are anchored to the build platform during printing.

DESIGN AFFECTS PERFORMANCE

DMLS parts are built anchored to the build platform. A buffer zone of supports (~6mm) helps achieve clean part removal via machining (Figure 1). As mentioned earlier, DMLS uses a very powerful laser to melt powdered metals. The laser is powerful enough to cause delicate, unsupported features to burn and distort. Burn occurs when a downward facing unsupported surface of a part cannot survive the laser. This section explains how to factor in supports and angles to minimize support structures and optimize your design for DMLS manufacturing.

Angles

Support structures are automatically generated through STL editors and then manually refined within the part file prior to building. Support material is the same metal as the final part and can require extensive labor to remove. With DMLS, features below 45 degrees and delicate unsupported features will experience burn and therefore require support structures. 60 degree angles are ideal and will not suffer from ablation.

Consider the simple design below. In Figure 2, the open box design (left) is intended to allow ample cooling for interior components. It has a large and flat downward facing surface. Due to the nature of metal 3D printing, its downward facing surface will warp or burn out without extensive support structures (shown right in blue). This simple design might work well for machining, but it isn't taking advantage of DMLS.

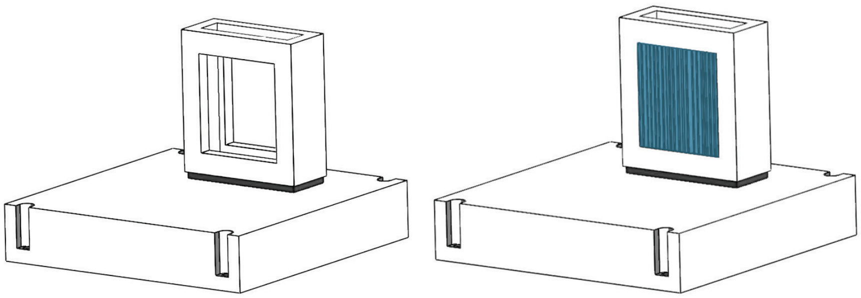


Figure 2: The left-hand figure shows the original design. The right-hand figure reveals the extensive supports required in blue.

One solution to minimize supports: Exchange the flat downward facing surfaces for an angled, saw-blade configuration. In Figure 3, the saw-blade design reduces supports by offering a surface with degree variances that aid in the sintering process. The new design cuts support removal time in half which reduces overall build time. In the next section, we'll discover how to further optimize the design for metal 3D printing.

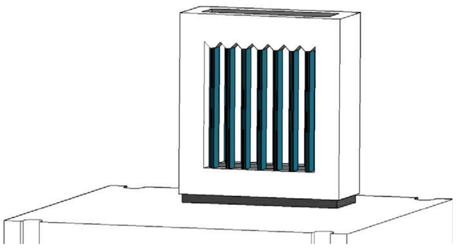
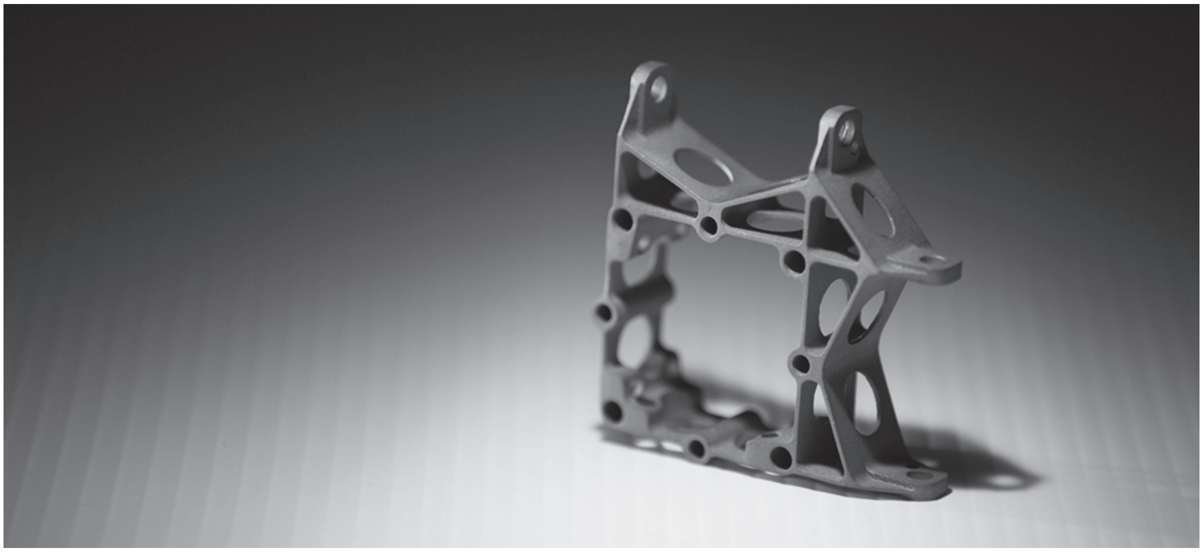


Figure 3: By adding a saw-tooth design to the figure, support structures (in blue) are decreased.



Self-Supporting Features

DMLS is fundamentally minimalistic in material usage. Compared to machining, which subtracts from a pre-existing block of metal, DMLS forms parts one layer at a time, welding material only where it is needed, leaving excess metal powder untouched. Such a manufacturing approach encompasses unique design opportunities.

For example, the redefined self-supporting structure in Figure 4 may appear more involved than our original model, but to DMLS Figure 4 is as easy to execute as our original open box design because it's a matter of melting or not melting material. In fact, because the columns in Figure 4 eliminate the need for support material, Figure 4 is easier for DMLS to produce when factoring in labor. Additionally, because the original intent of the square frame was to provide interior objects breathing for cooling, the simple addition of columns maintains this function while enhancing the structural integrity of the design. Therefore this seemingly more complex column configuration results in a stronger part by taking advantage of DMLS capabilities.

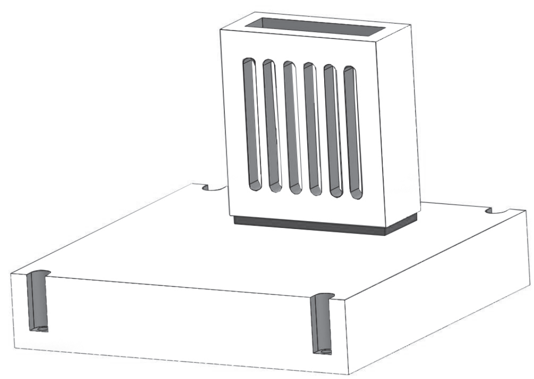


Figure 4: Self-supporting features are ideal with DMLS.

DMLS builds internal channels and no-access features directly into a part.

No-Access Features

While DMLS is favored because it can build no-access features, enclosed designs may still require support structures which can become trapped within a part. However, a few simple design rules for DMLS can actualize critical internal features without the addition of supports.

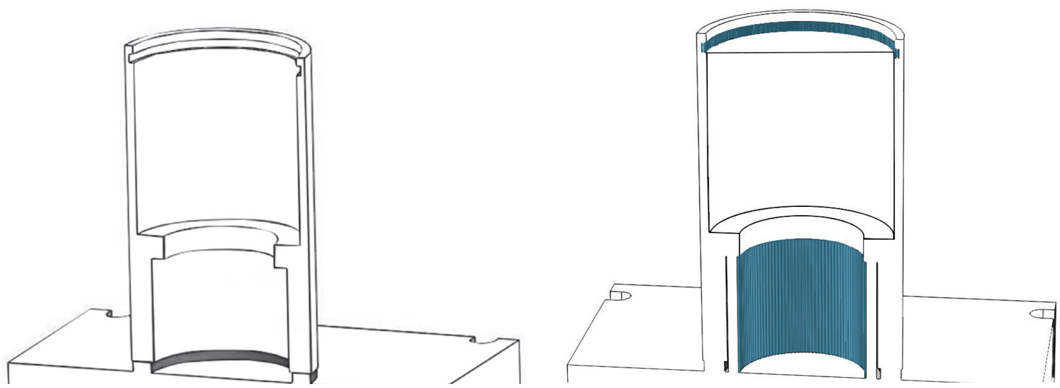


Figure 5: The internal angles featured in this cross-sectional view (left) result in trapped supports (right, supports in blue).

Figure 5 shows a cross-sectional view of a part with sharp internal angles (left). These internal angles require supports that become trapped inside the part (right). One solution for this design is to change the angled features into feature gradations. Rather than an abrupt change from flat surface to overhanging feature, allowing these features a fluid movement at gradations above 45° eliminates trapped supports that would be difficult or impossible to remove.

Design Tip: Wall thickness is geometry dependent, however a ratio of 8:1 between wall thickness and wall height is recommended.

In Figure 6, we've incorporated a fillet to smooth out the abrupt angle in the center, and a chamfer at the top. Now, the design achieves internal no-access features machining or casting would be hard pressed to imitate while reducing material consumption and eliminating internal support structures.

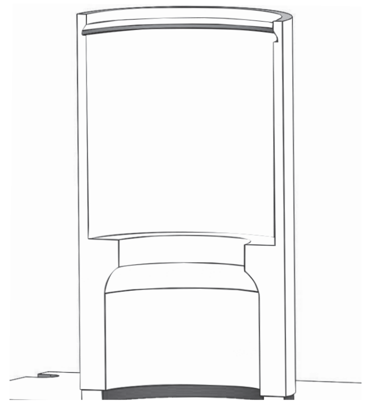
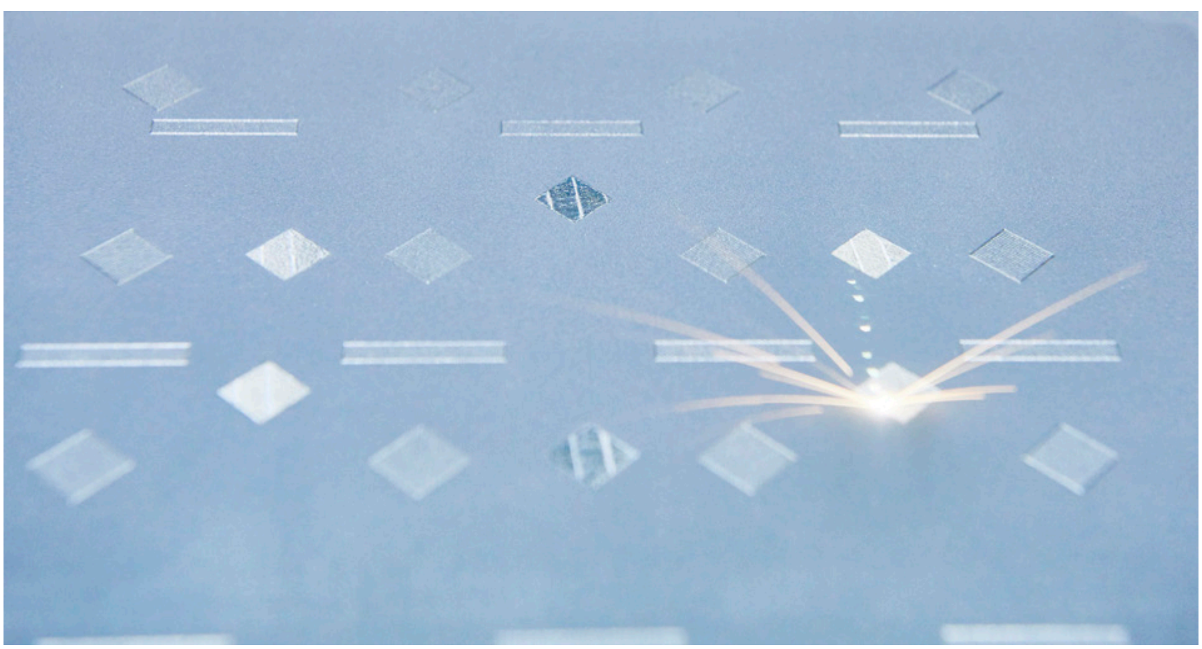


Figure 6: An added chamfer and fillet optimize this design for DMLS

In conventional manufacturing, less involved geometries are preferable. By contrast, DMLS turns complexity into an asset.

These design tips will influence the strength of your part, especially when it comes to malleability, by complementing the post-process stress and heat treatments DMLS parts must undergo to achieve full density. Stress relief and heat treatments aid in a DMLS part's ability to perform excellently under testing and avoid the cracking or fracturing of the metal throughout its lifetime. Stratasys Direct Manufacturing has carefully studied DMLS heat treatment measures internally, as detailed in the next section.



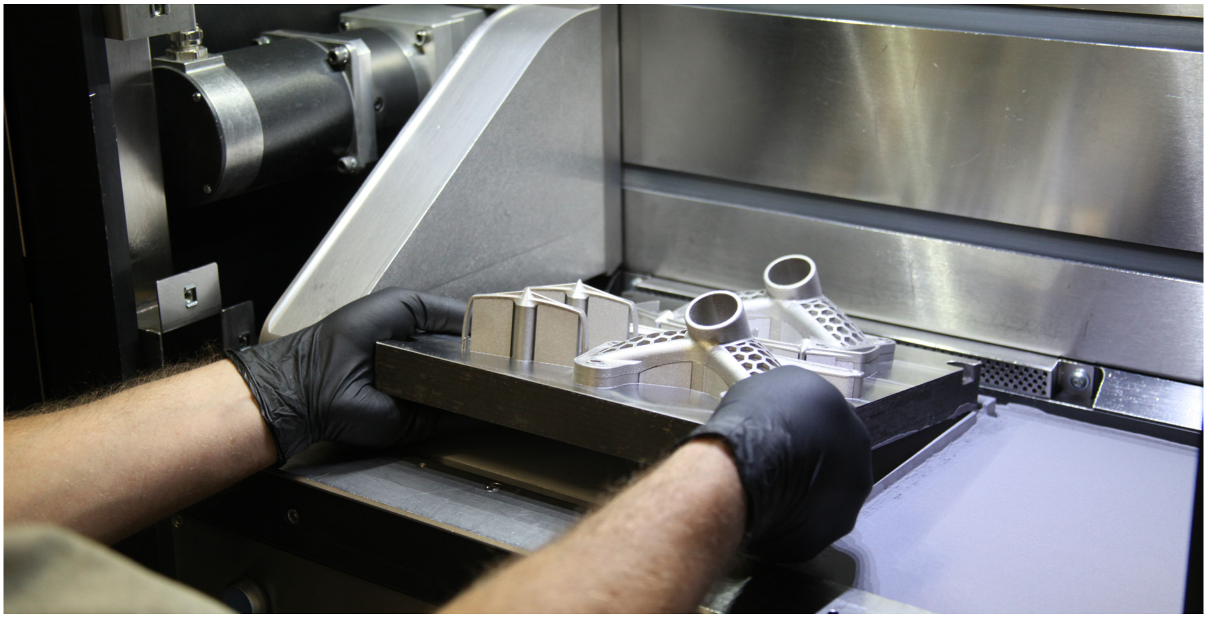
Sparks fly as the laser fuses the powder together during DMLS 3D printing.

PREVENTING FRACTURES IN AM PARTS & IMPROVING DENSITY

Fractures or cracks in a DMLS part occur due to three factors: 1) internal stress exceeding the yield strength of the material 2) stress risers in the design or 3) long term component use. Cracks are easily removed during post-processing, but fractures can be prevented from occurring during the lifespan of a component through heat treatment processes.

Stress Relief

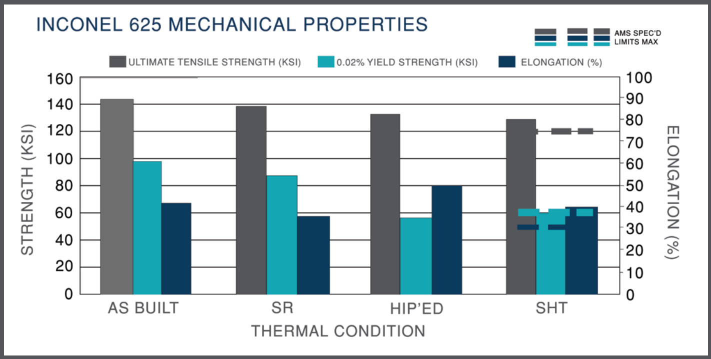
All DMLS parts are subjected to stress relief prior to removal from the build platform to avoid deformation. Stress relief cycles at Stratasys Direct Manufacturing vary from alloy to alloy but are typically performed at 1950°F for 1.4 hours and air cooled at room temperature. Depending on the metal alloy and part design, stress relief may be performed at 1725 – 1850°F and then cooled. Through stress relief the metal returns to an annealed state.

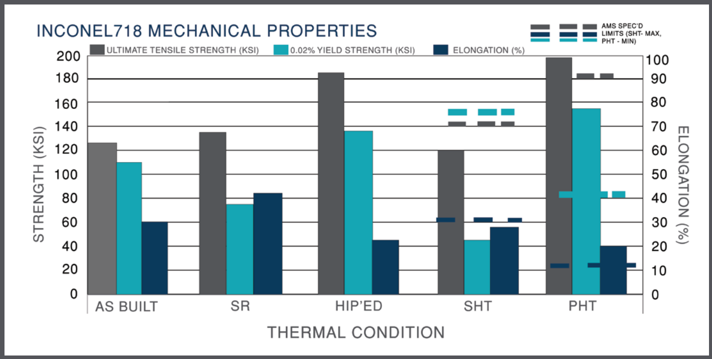


Fractures are prevented from occurring during the lifespan of a DMLS part through tough heat treatment processes.

HIP, SHT and PHT

Secondary heat treatments such as HIP (hot isostatic pressing), SHT (solution heat treatment), and PHT (precipitation hardening treatments) can result in stronger parts with properties closer to wrought metals. These treatments have repeatedly proven to enhance density from ~95.5% as-built to 100% density. At Stratasys Direct Manufacturing, we subjected our Inconel 625 and Inconel 718 to heat treatment processes to measure the effectiveness of heat treatments on 3D printed metals and determine whether a 3D printed metal can achieve industry relevant mechanical properties. We built 20 tensile bars in both materials and recorded their properties. Then, we machined the bars to ASTM standards and subjected the bars to thermal conditioning. Conditioning included HIP SHT, and PHT treatments. We discovered DMLS metals can be brought to the same standards of AMS spec'ed aerospace alloys through HIP SHT and PHT treatments.





Finishing

On top of these strengthening treatments, DMLS parts can be hand polished to result in ideal surface finishes and machined to meet critical engineering tolerances. The surface of a DMLS part as-built is ~350 Ra µinch. Glass bead blasting will smooth surfaces to 98-236 Ra µinch while a tumbled finish will further ameliorate surfaces to 32-124 Ra µinch. Hand polishing is more ideal for one-off unique parts that require a very specific surface quality.

INDUSTRIES USING DMLS TODAY

DMLS is renowned for its advancements in aerospace, particularly in the creation of gas turbine engine parts placed in the high temperature high pressure environments of the engine. However DMLS is a production solution for energy, medical and consumer applications and has been further penetrating these markets as material options continue to expand.

DMLS APPLICATIONS

Aerospace: Injectors, combustor liners, rocket engine manifolds, research efforts, functional prototypes

Energy: Rotors, stators, mud motors, turbine prototyping and research, bridge applications

Medical: Dental devices, surgical tools, orthopedic implant devices and prototypes, educational models, training tools

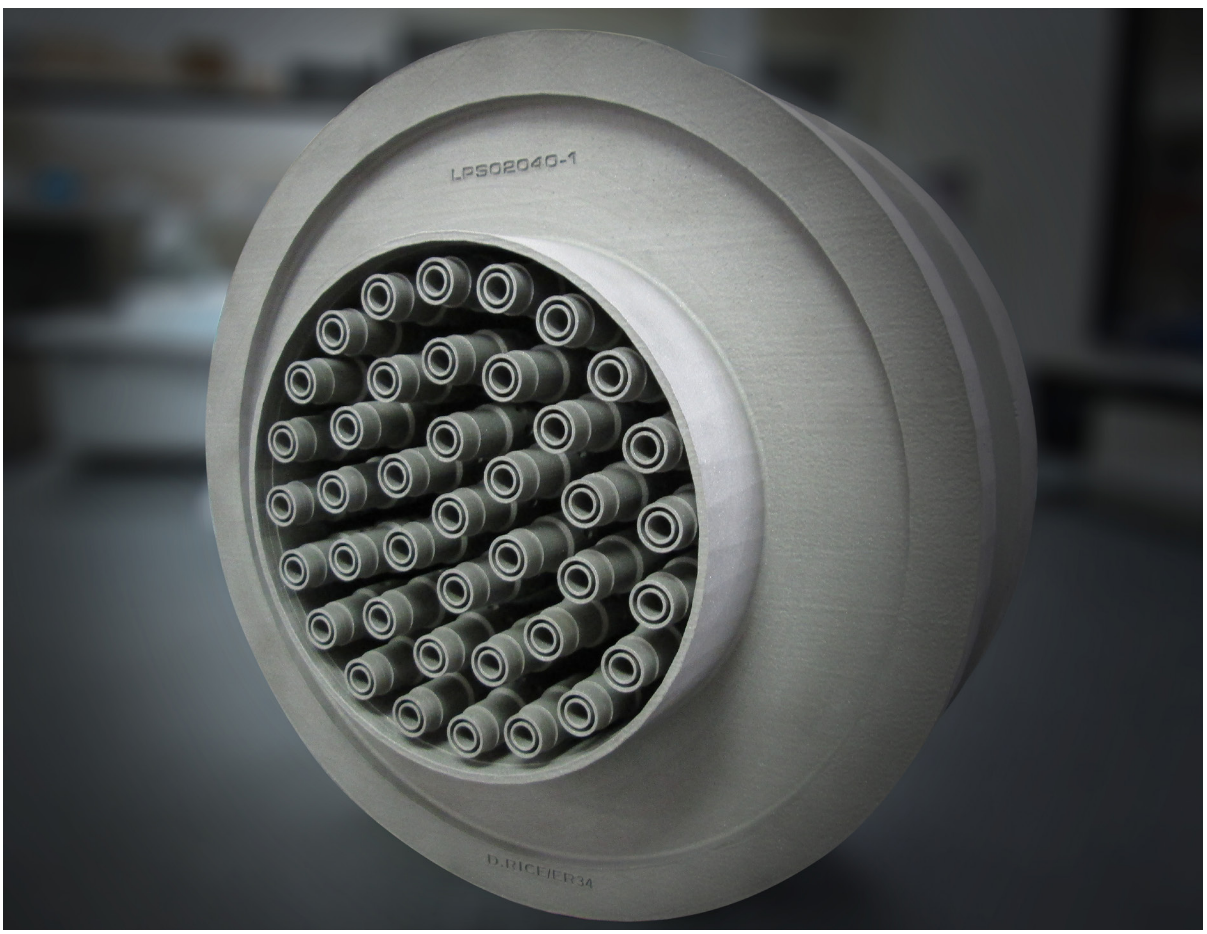
Industrial: Prototype tooling, manufacturing fixtures, low volume production

The most tangible benefit of DMLS when compared to die or investment casting, metal injection molding or machining is time, as illustrated in our research and development case study with NASA's Marshall Space Flight Center.

CASE STUDY: DMLS FUEL INJECTOR

The intention of the 3D printed metal fuel injector Stratasys Direct Manufacturing built for Marshall Space Flight Center revolved around reducing part count, manufacturing time, and aiding Marshall in vetting out DMLS for aerospace applications. Stratasys Direct Manufacturing worked to combine design features for an optimized DMLS configuration. What began as a 150+ piece machined unit was transformed into a two-part 3D printed unit that eliminated extensive touch labor. While the original part took months to build, the 3D printed unit was built in just 10 days and has undergone multiple hot fire tests, proving DMLS 3D printing can offer a 90-95% decrease in turnaround time and is viable for high intensity applications.

PROCESS	TIME
CNC Machining & Conventional Manufacturing	~4 – 6 months
DMLS 3D printing	10 Days



FUTURE OPPORTUNITIES: REFINING PROCESS CONTROLS

As a layer additive process, DMLS could offer finite control over the material properties of a part. Research and development today is based heavily around measuring the properties of each individual layer of the material. In five to ten years, DMLS operators will have complete layer control over the melt pool for each passing of the laser across the build. Build control on a layer by layer basis could mean achieving perfect melt and density by altering melt temperatures. It could mean multi-material printing as well. While the capability is a ways off from automation, studies today show significant promise of a program entering the mainstream within the next decade.

PRODUCTION OF THE FUTURE, HAPPENING TODAY

DMLS is the ideal alternative to complex designs that machining or casting can't achieve. It offers the mechanical properties of aerospace standard materials and the design freedom of 3D printing. As further industries adapt to the technology, we'll see metal 3D printing overtake healthcare through medical devices and tools, aerospace through consolidation and lightweight solutions, energy through fine-tuned complex mechanisms and many other industries. It may transform applications we haven't even dreamed up just yet.