

## Pushing the Design Boundaries with Metal AM

By Ian Campbell and Terry Wohlers

Greater design freedom is recognized as one of the key benefits of using additive manufacturing (AM) for the final production of parts. Reducing the need for tooling and being able to more freely add and subtract material means that parts can be made with more geometric features and with much greater complexity. This has been exploited in many ways, with value being added to the product in one or more ways.

Value can come from reduced lifecycle costs, improved aesthetics, better ergonomics, and enhanced performance. A powerful example of enhanced performance is an automotive engine cylinder head made by FIT, a service provider with headquarters in Lupburg, Germany, using powder bed fusion of aluminum. Cylinder heads must function for gas flow (both intake and exhaust), water flow for cooling, and vibration damping. Also, these parts are load bearing, so they must be strong.

FIT was tasked with designing an improved version of race car's cylinder head and so an additional design requirement was reducing weight. The resultant design is the following figure. This part is a good example of how designing for AM maximizes AM's geometric freedom to enhance performance.



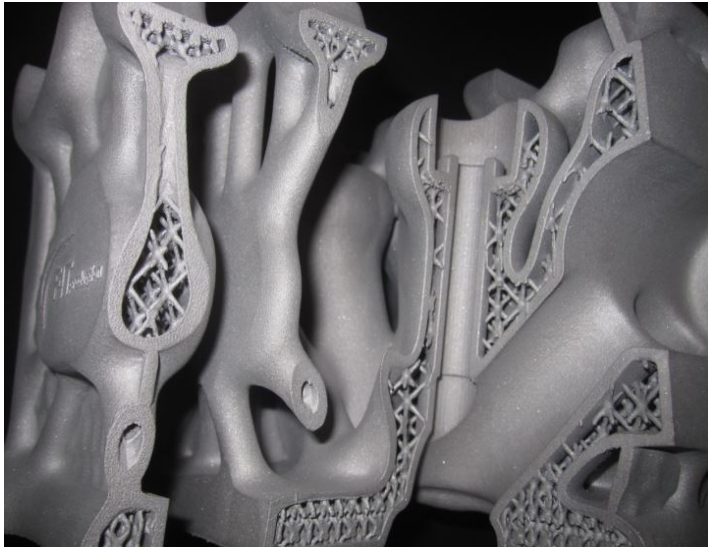
Optimized engine cylinder head, courtesy of FIT

### Design Opportunities

A key feature enabled by AM is gas flow optimization. The combustion chamber, intake tract, and exhaust tract design can be shape-optimized using computational fluid dynamics (CFD). However, the need to compromise an optimized design, due to manufacturing requirements, is much less with AM, compared to casting, which requires draft angle on the casting patterns.

Optimized coolant circulation is also permitted by AM. CFD can be used to optimize fluid flow to remove heat from the combustion chamber and exhaust tracts. AM offers a key advantage over casting because the water jackets and passage ways for coolant can include a lattice framework of complex structures. This results in increased surface area, and therefore, heat conduction. In the case of this cylinder head, the surface area increased from 823 cm<sup>2</sup> (50 in<sup>2</sup>) to 6,052 cm<sup>2</sup> (369 in<sup>2</sup>), which is more than seven times greater than the original design. Depending on the exact configuration of the lattice structure, it may also aid in creating turbulent flow —another aid to

improved cooling. This can give the added benefit of using a smaller water pump, thus reducing power loss from the engine.



Engine cylinder head with interior lattice framework, courtesy of FIT

Optimizing the weight of the cylinder head is another important way to benefit from AM. After the key functional features have been defined, the main body of the head is created by adding a material thickness around their volumetric shapes. Extra material adds strength to the part and to dampen vibration. The placement of material can be determined using topological optimization, which is the use of mathematics to optimize the strength-to-weight ratio of a design. It results in using the minimum amount of material for given functional parameters. Using topology optimization, the weight of the cylinder head improved by 66% to 1.76 kg (3.9 lbs).

The cylinder head design is an impressive engineering achievement. Part of the success came from the capabilities of the design software used to create part. FIT chose to use .... This level of design complexity does not come easily or quickly. CFD, topology optimization, and lattice-generation software tools can be expensive and difficult to use. They require a substantial investment in learning how to use the software, coupled with trial and error. In some cases, it is beyond the reach of small companies.

### Design Challenges

AM indeed offers interesting design opportunities, but it also introduces unique design challenges. The mathematically optimized shapes generated by the software are not always feasible to build. For example, it's important to know the minimum wall thickness that is possible. Another example is the smallest hole that the AM process can produce. Overhanging features must be supported by extra structures during the AM build process, which later must be removed. Consequently, the designer must provide access for their removal. The metal powder bed fusion process results in thermal stresses that can lead to warping when the parts are cut away from the built plate. To reduce the possibility, anchors are designed to secure the parts and their features to the build plate. Adding too many can create additional work in their removal and too few can cause curling and

warping. The overall result is usually some compromise on the theoretically optimum shapes, although typically much less than for conventional manufacturing processes such as metal casting.

Another design consideration is the removal of powder. In the case of the cylinder head, all internal cavities and holes are entirely filled with powder when the parts are removed from the build chamber. All of this powder must be removed, so “drain” holes and exit paths must be present to prevent the powder from being trapped inside. This requires the designer to carefully consider the size and location of these holes and paths and then add them to the CAD model. Often, it is necessary to later plug the holes, which adds time and cost to the parts.

Most designers and engineers in the current workforce have not received formal education and training on design for additive manufacturing. Consequently, most companies that are considering the use of AM for production applications are encountering it for the first time. Some of them have developed “tribal” knowledge from the experience of a small group of pioneers within the company, so they are a helpful but often limited resource. The bottom line is that the demand for education and training on design for additive manufacturing exceeds the supply.

To meet a need in one segment of the aerospace industry, Wohlers Associates has conducted two formal classes on design for additive manufacturing for NASA Marshall Space Flight Center in the recent past. The first was four days in length and involved hands-on learning with advanced methods of design, including part consolidation (combining many parts into one or fewer parts), topology optimization, and lattice and mesh structures. The second class was three days in length and focused mostly on metal AM. In both classes, interesting parts were designed by the participants—in this case, rocket scientists—and produced on the machines at NASA for evaluation.

Additive manufacturing offers many opportunities to improve the performance and weight of a design. Using special software tools and techniques, it is possible to make major improvements that are impossible with conventional methods of manufacturing. Meanwhile, AM also comes with design considerations, similar to conventional manufacturing, although design freedom is much greater with AM. For these reasons, we believe that AM will be used increasingly for entirely new types of parts and products, such as automobile engines, that will be superior to their predecessors in many ways.