

ADDITIVE MANUFACTURING A LIQUID HYDROGEN ROCKET ENGINE

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Abstract

NASA, Marshall Space Flight Center is working on new manufacturing techniques for producing liquid propulsion systems hardware. The use of additive manufacturing processes offer great promise in reducing manufacturing turnaround times and ultimately overall product cost. This paper will detail Marshall's efforts to produce the world's first fully additively manufactured rocket engine. Metrics thus far obtained on manufacturing cycle times, component and part count reductions, testing to date, and estimated and actual cost comparisons will be presented. Marshall engineering's approach and planning for certification of these new manufacturing process for liquid rocket engines will be overviewed.

Introduction

Additive manufacturing has the potential to revolutionize liquid rocket engine design and development. From reducing lead times and costs, to minimizing part counts and welds, when engineers design for additive manufacturing the design space is wide open. A significant amount of work is currently underway to better characterize material properties and provide rationale for certification of parts made using powder bed fusion. In parallel, engineers are working to use the technology in their designs and test the hardware in relevant environments. A team of propulsion engineers at NASA's Marshall Space Flight Center (MSFC) has worked to design, build and test a rocket engine and rocket engine components that take advantage of additive manufacturing. As illustrated in Figure 1, the parallel efforts of material development, working with the industrial base and development of propulsion components benefit many of NASA's efforts in spaceflight. Through this effort, engineers have gained valuable insight into the cost, schedule, and technical benefits of using additive manufacturing.

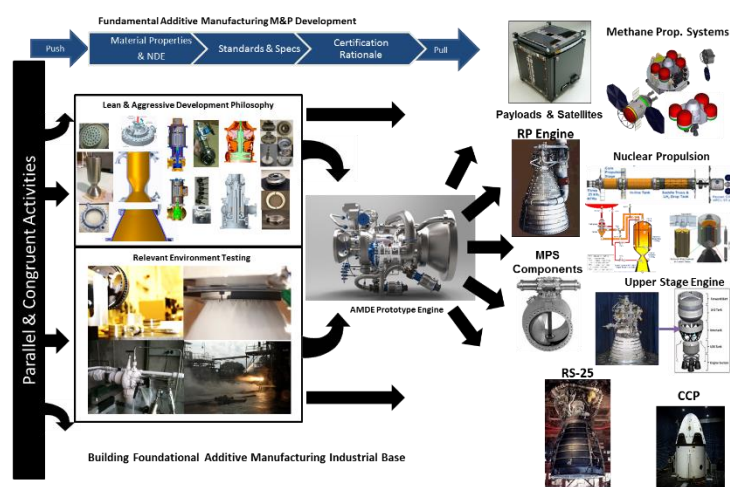


Figure 1: Parallel paths to Develop Additive Manufacturing for Propulsion

Frequently, cost and schedule savings of additively manufactured parts is thought of as the cost and schedule to produce a single component or piece part. The issue with this line of thinking is that the benefits of using additive reach well beyond the hardware cost; if additive manufacturing influences the design from its inception, it can change every aspect from layout to the number of drawings to the number of assembly steps. Using additive manufacturing to influence the design of a system changes the entire product life cycle. Reduced part counts translate to reduced drawings, process developments and configuration management support. It also means increased reliability and simplified assembly of historically complex components and systems. The shorter lead times over some traditional manufacturing techniques, mean earlier risk reduction testing, reducing the need for upfront analysis, while providing real data for improved analytical models as the design matures. While additive manufacturing properties are still being collected and questions remain about repeatability and a path to certification, additive manufacturing, particularly powder bed fusion, opens the door for a new approach to design and development.

Additive Manufacturing Demonstrator Engine (AMDE) Overview

The AMDE project began in 2012 as an effort to prove that additive manufacturing could reduce the time and cost to develop rocket engines. The objectives of the project were to reduce the cost and schedule required for new engine development and demonstrate it through a complete development cycle, advance the technology readiness level of additively manufactured parts through component and system testing, and to develop a cost effective prototype engine whose basic design could be used as the first development unit for an in-space propulsion class engine. With limited personnel, in less than 3 years the team built over 100 additively manufactured parts, tested injectors, turbomachinery, and valves in both component and system tests, and designed a prototype engine.

The AMDE is a liquid oxygen (LOX)/liquid hydrogen (LH2) open expander cycle engine designed to operate at 35,000 lbf of vacuum thrust with an estimated Isp of 452 seconds. The engine was developed for sea level testing and due to limited resources, controllers, valve actuators and gimbaling were excluded from the design effort. Using additive manufacturing the overall part count of the major components designed and built was reduced by 80%. Figure 2 shows the part count by component. In addition to reducing the part count, there are only 30 welds estimated for the engine. The total effort lasted approximately 3 years, cost \$10million, and an average of 20 to 25 equivalent full-time employees were devoted to the effort.

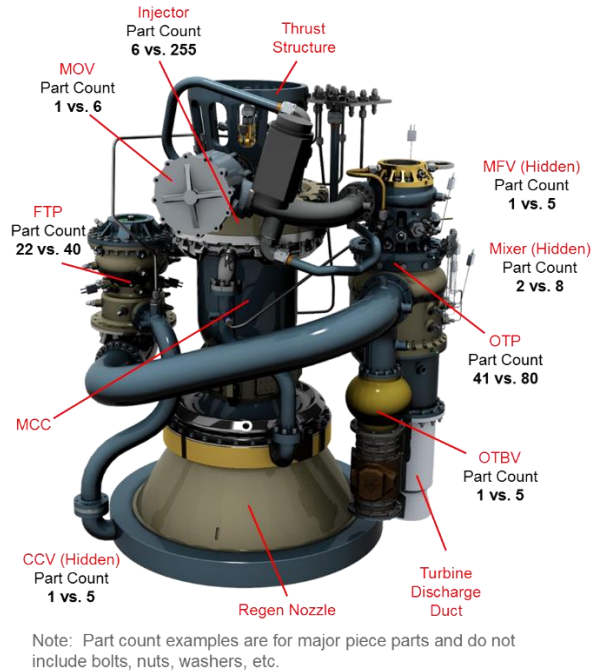


Figure 2: Additive Manufacturing Demonstrator Engine Design and Part Count

Additive Manufacturing Benefits to Propulsion System Design and Hardware

Impact of Additive Manufacturing on the Design Cycle

Due to the high cost and complexity of aerospace hardware and ever increasing analytical capabilities, it is often the practice to delay procurement and testing of components until after the critical design review is complete. This reduces the risk of a redesign or costly failure during test. Also, for parts that were traditionally cast, or involved complex process development, the time invested to develop the casting often does not allow for multiple design iterations. The AMDE effort leveraged the low cost and quick turnaround times for additively manufactured hardware to shift from a traditionally serial development cycle, to a more concurrent cycle as illustrated in Figure 3. This allows for earlier hardware build and test that impacts system design and analysis.

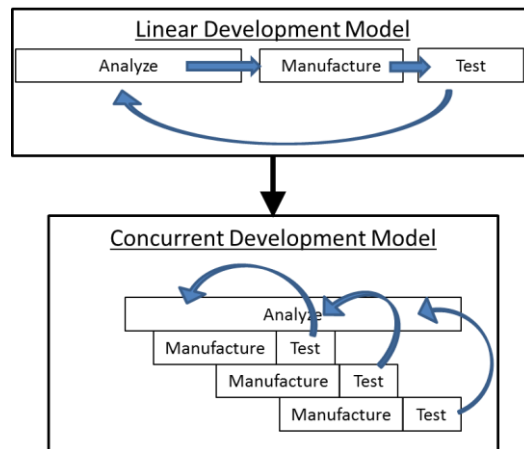


Figure 3: Shifting Development Model

The AMDE effort spent approximately \$500K during the first year procuring hardware based on preliminary designs. This was to satisfy two primary objectives: determine “buildability” of hardware by additive manufacturing vendors across the United States and to test as much hardware as possible. At the conclusion of the first year, sub-scale engine injector testing, shown in Figure 4, was performed that provided assurance that the technology was capable of producing hardware with acceptable performance and durability. Prior to the sub-scale testing, multiple single element prototypes, Figure 5, were produced and used for water flow testing as well as sectioned to examine internal passages. The information gathered early in the design cycle, allowed for build, assembly and test of the final units to occur without significant increases to projected costs or schedules. Early test data also gave analysts and designers confidence in the performance of the component and system.



Figure 4: Sub-scale injector hot fire test



Figure 5: Single injector element

Procuring hardware with preliminary designs also allowed for multiple iterations with additive manufacturing vendors without detrimentally affecting the overall schedule. For example, the complex fuel turbopump shaft and blisk was originally built with features that were not acceptable. This early unit opened a conversation between the manufacturing vendor and the component engineer. After implementing changes, a new part was ordered for less than \$10,000 and received in less than 2 months. While this part was not the final design, it provided confidence that the hardware could be produced and gave engineers and technicians a component to use for development of tool paths as well as rotor balance and assembly procedures and trials.

Layout Flexibility

During the layout of a rocket engine, it is vital to incorporate flexibility into the system. Historically, the engine layout is constrained by manufacturing techniques, standard tube and pipe wall thicknesses, and thinning at bends. These factors require flexible elements which can often increase cost and schedule,

as well as complexity by introducing bellows, welds and flow induced vibrations into the system. Using additive manufacturing for engine layouts removes line thickness constraints and thinning at the bends. It is possible to customize the line thickness to minimize overall weight. Additionally, as the size of the build boxes increase, the number of welds required will be reduced. The AMDE design included less than 30 welds in the entire engine assembly. Finally, complex line geometries can build flexibility into the system to account for loading during operation. Integrated loads analysis indicates that the AMDE layout includes enough flexibility in the system to eliminate the need for additional flexible ducts. An example of the duct design is shown in **Error! Reference source not found.** and includes complex bends and internal vanes.



Figure 6: Representative Duct Design

While the system flexibility is a benefit, it is not the only benefit of designing with the additive process in mind. The traditional definitions of interfaces can now be blurred. For example, it may sometimes be possible to incorporate valve bodies into lines, or add length to inlets or outlets of combustion devices or turbomachinery. This added flexibility has the potential to reduce seals and leak paths, simplify assemblies and further reduce the number of welds in systems. Reductions in the number of welds not only reduces the amount of “touch labor” on the system, but also reduces the number of inspections, doubling the savings that could be realized in assembly schedules.

Part Count Reduction

Using additive manufacturing to build hardware can allow designers to combine features reducing overall part counts. This reduction in parts has a cascading effect on the system. Reducing the number of parts reduces the number of drawings, the number of total signatures required, and the development of processes for assembly. It also has the potential to simplify some analysis, such as tolerance stack up analysis by reducing the number of parts to be analyzed.

Engineers at MSFC redesigned a typical flex duct using additive manufacturing. The result was a 65% reduction in part count and a 70% reduction in the number of welds.¹ Their efforts also reduced the number of machining operations by 60%.¹ A sample traditional duct and the redesigned parts are shown in Figure 7.

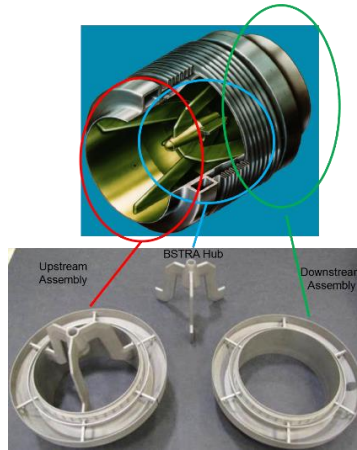


Figure 7: Flexible Element

Another example of significant part count reduction is the AMDE injector. Traditional injectors are made up of elements which consist of multiple parts each. By integrating the elements into the injector body, the part count was reduced from approximately 250 parts to 6 in the injector assembly. Again, not only were part counts reduced, but the development of critical machining operations and brazing operations were eliminated. Also, instrumentation ports could be strategically played into the injector body allowing for measurements in some locations that would not be possible with traditional manufacturing techniques. Figure 8 shows the primary components of the AMDE injector.



Figure 8: AMDE Injector Assembly

The reduction in part count illustrated by the previous examples, also increases the reliability of the component. Fewer parts and assembly steps reduces the likelihood for error during assembly and streamlines the fabrication and assembly procedures. Eliminating welds and braze operations by combining parts, also eliminates the required inspections after the processes are performed.

Efficient Packaging and Design Flexibility

An additional benefit of using additive manufacturing in designs is more efficient packaging and a larger design space from which to find solutions. In the previous example of the part count reduction in the injector, additive manufacturing also allowed for the spacing between the elements to be reduced by allowing for more efficient element designs. In this particular example, additional elements can be added to the same space or the overall size of the part could be reduced. Another example of using additive to overcome a packaging obstacle, is the fuel mixer shown in Figure 9. This component was the focal point of the integrated layout of the engine. The loads were highest at this location requiring

multiple design iterations. In the end, additive manufacturing allowed for a design solution with a customized geometry and varying wall thicknesses to strike a balance between flexibility and strength.



Figure 9: Fuel Mixer

Mass Reductions

Additive manufacturing allows for customized designs that efficiently remove material while maintaining the structural integrity of the component or system. With more traditional manufacturing methods, removal of material for mass reduction could be costly depending on the part geometry, but with additive manufacturing, optimizing the design is easier because some of the traditional manufacturing hurdles can be avoided.

While the material properties of parts made using powder bed fusion are not fully characterized as compared to forgings or cast parts, for Inconel, the properties are an improvement over traditional cast properties. This allows for more efficient designs for parts that were previously cast.

Conclusion

Powder bed fusion is a new technology for aerospace applications and therefore many unknowns remain. For example, repeatability and consistency of material properties is not yet fully understood. The impacts of minor changes to powder chemistry, the methodology to certify hardware for human rated applications and cleaning and inspection techniques are still being explored. Given all these challenges and many others not mentioned, the benefits of incorporating additive manufacturing into aerospace systems outweigh the concerns. Reductions in part count, increases in reliability, streamlining of fabrication and assembly, increased design flexibility and earlier testing all help to inform the designer and engineer. Designers who embrace the unique aspects of additive manufacturing and incorporate them into their designs and use the schedule benefits to gather data early in the design process should see better performance and higher reliability parts in their final assemblies.

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References

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