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Additive Manufactured Pressure Vessel Shell

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Keywords

Additive Manufacturing, Additive Manufacture, Propellant Tank, Diaphragm Tank, Fracture Critical Inspection

Acronyms

AM = Additive Manufacturing
DMLS = Direct Metal Laser Sintering
EBM = Electron Beam Melting
PMD = Propellant Management Device

Abstract

Additive manufacturing (AM) is an exciting new technology with great potential to revolutionize space systems component design and manufacture. Investigative efforts on the application of AM technology for pressure vessels have been ongoing for several years. However, space borne pressure vessels are high-risk items. Engineers and researchers must assess all risks and rewards when considering replacing or substituting a long-standing proven technology with a promising new technology. It would be inappropriate to extend preferences to additive manufactured components without a thorough and impartial investigation.

This summary paper is a review of a recent ATK study on the development of a propellant tank with additive manufactured tank shell. The summary paper has three sections. Section 1 is an introduction with a description of the tank development program. In Section 2, we identify areas that require additional research. In Section 3, we conclude with a summary of our current state of adaptation on AM technology.

1. Introduction

Additive manufacturing is an exciting new technology with great potential to revolutionize space systems component design and manufacture [1]. Some favorable attributes of additive manufactured products include simplified hardware design, shortened delivery schedule, and lowered recurring cost. Although these positive attributes are attractive for hardware designers, adapting a new, untested, and unproven manufacturing technology has inherent short-term and long-terms risks. This is especially true in space borne pressure vessel application.

Space borne pressure vessels are high-risk items. They hold corrosive fluids under pressurized and thus highly stressed conditions. During launch, tank interfaces could be subject to severe mechanical loads. In addition, propellant tanks are often the single point failure on many space missions. Given these technical challenges, engineers and researchers must evaluate all risks and rewards when considering replacing or substituting a long-standing and proven pressure vessel manufacture technology with a promising new technology.

The study of AM technology and application is a high priority item within Orbital ATK. Support system is in place for a multi-year effort to conduct a systematic study of the additive manufactured tank shells and propellant management device (PMD) components. Our short-term goal is to evaluate suitability and applicability. If the technology were worth implementing, our long-term goal would be to collect design data in support of tank shell and PMD component design and manufacture.

Given the criticality of the hardware and the immense implications of hardware failure, our researchers are adopting a disciplined approach towards the study of tank shells made from AM techniques. In this review paper, we describe our efforts to gain confidence in the technology. We do so by examining one of our pathfinder development programs whose goal was to evaluate the design and manufacture of a new diaphragm propellant tank with an additive manufactured tank shell. Our studies included development of A and B basis design allowables, proof of concept development activities, and culminated in the fabrication of two qualification tanks (QTs). QT1 was an assembly of conventionally machined domes made from titanium bars. QT2 was an assembly of additive manufactured domes. The two QTs have the same overall configuration and the same 6Al-4V titanium bulk material. We conducted the two development programs in parallel to ensure proper comparative value. Figure 1 is an interface drawing of the QT configuration.

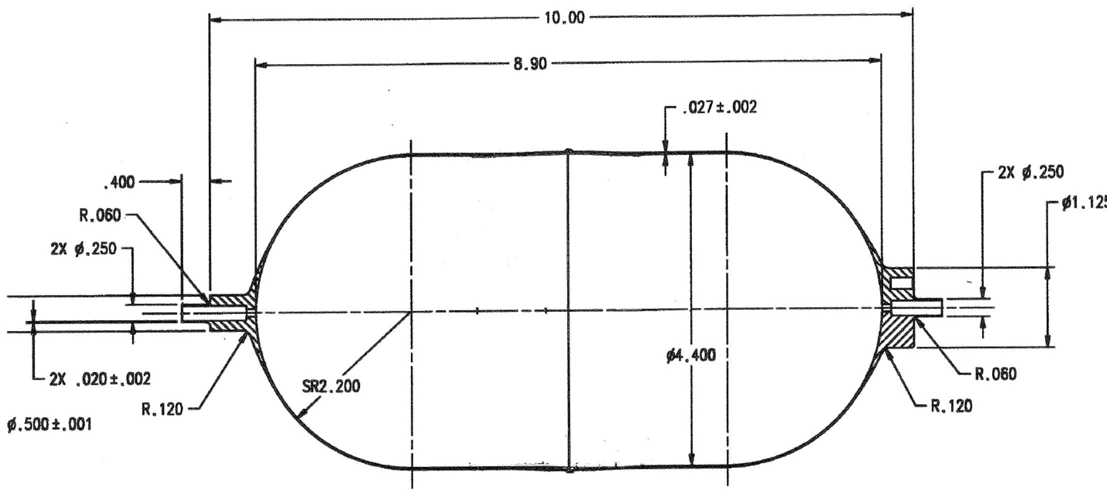

Figure 1: Diaphragm tank interface drawing (dimensions in inches)

A primary objective of the investigative effort was to ensure that the additive manufactured shells undergo the same intense scrutiny that the space industry stakeholders impose on conventionally manufactured shells. Running the two QTs in parallel would ensure a meaningful comparison. Another research objective was to assess the as-made properties of additive manufactured domes. One potential advantage of additive manufactured domes over conventionally machined domes is the reduced machining and processing time. During our investigation, we refrained from altering the as-made additive manufactured domes as much as practical to minimize post processing that might alter the tank dome properties.

As mentioned previously, we fabricated the QT1 domes from titanium bars using conventional material removal process. We fabricated the QT2 domes using AM techniques. Some specifics of the QT2 tank include:

- 6Al-4V titanium domes
- Domes made from laser powder bed fusion or Direct Metal Laser Sintering (DMLS) process
- ∅112 mm (∅4.4 in) inside diameter
- ∅6.35 mm (∅0.25 in) interface tubes
- Girth welding using electron beam welding process
- Incorporates an elastomeric diaphragm
- 1.8 liter (108 in^3) tank volume
- 1.3 liter (80.5 in^3) propellant compartment volume

Figure 2 is a photo of the additive manufactured shells (left two domes) and conventionally machined shells (right two domes). Both sets of shells have near identical dimensions. Each tank would incorporate an elastomeric diaphragm, also shown in Figure 2. The processing time was longer for QT1, including purchasing the titanium bars and machining the domes and interface features. The processing time for the QT2 domes was shorter by several weeks.

Figure 2: Additive manufactured shells (left) and conventionally machined shells (right)

The diaphragm tank design includes an electron beam weld as the tank closure weld. Figure 3 is a photo of the welded QT2 tank. The photo indicates no post processing of the tank domes because the domes had retained their dull surface finish. The only dome alteration was the customary surface preparation at the weld region for pre-weld cleaning. Both the QT1 and QT2 welds had the same weld schedule. We intentionally did not perform any optimization of the additive manufactured tank to ensure a valid side-by-side comparison with the traditionally manufactured tank. Internal processing specification standards were applicable to both tanks, including NDE standards. The only difference between the two tanks was that QT1 has a machined shell from material removal processing, and the manufacture of QT2 shell used additive manufacturing technologies.

Figure 3: The welded QT2 tank with two additive manufactured domes

Both QT1 and QT2 underwent pressure cycle testing, including 51 MEOP cycles at 41.4 bar (600 psi), and 17 proof pressure cycles at 62.1 bar (900 psi). See Figure 4 for the QT2 test setup for pressure cycle testing.

Figure 4: Pressure test setup

Both QT1 and QT2 underwent successful burst pressure tests. QT1 has annealed titanium 6Al-4V properties, and the design burst pressure was 110 bar (1600 psi). The tank ruptured at 168.8 bar (2448 psi).

Each tank was subject to a full test program per the following test sequence:

1. Preliminary Examination and Dimensional assessment
2. Radiographic and Penetrant Inspection
3. Volumetric Capacity, Pre-proof
4. Hydrostatic Proof Test
5. Volumetric Capacity, Post Proof
6. Cyclic Pressurization Life
7. External Leakage Check
8. NDE (Radiographic and Penetrant)
9. Final Examination of Product and Dimensional Assessment
10. Burst Pressure

The QT2 additive manufactured shell has higher mechanical properties. The predicted burst pressure was >241 bar (>3500 psi). The actual burst pressure was at 255 bar (3699 psi). Figure 5 is a photo of both QT1 and QT2 after rupture. Both tanks failed in the dome membrane as predicted by analysis.

Figure 5: The two burst tanks. The additive manufactured tank shell is on the right.

Both QT1 and QT2 have similar mass. The gross mass of QT1 is 0.622 kg. Subtracting the tubing and swageloks, the net mass is 0.565 kg. The net mass of QT2 is 0.55 kg. The mass difference between the two tanks is 0.015 kg, or 2.7%, with the additively manufactured unit being both lighter and higher performing.

2. Discussion

The successful development testing of a propellant tank with an additive manufactured shell is an encouraging first step in a long product development process. The research results suggest that it is possible to use the AM process to achieve material properties that mimic, or in certain instances exceed, traditionally forged titanium products. In addition, it is possible to apply the technology and maintain the necessary tank shell geometric profiles to achieve component capability. While the qualification testing concluded with successful rupture test, there remained many critical issues for further examination, including:

The development of a material database to support structural analysis.

AM vendors and suppliers, as well as other AM researchers, have been studying material properties and collecting material data. Our studies had also collected small samples of mechanical properties. Nevertheless, it will be necessary to conduct a disciplined data gathering campaign to collect statistically based material properties in support of structural design. For space applications, using A-basis design allowables is the norm. With the current efforts, both A and B basis material properties development is underway and showing consistent and exceptional mechanical properties for DMLS processing when compared to traditionally forged products.

The development of the material properties and in process monitoring of those properties is integral to the success of developing and implementing additive manufacturing technologies in space applications. One important lesson learned is that material properties are not only vendor specific but may be machine and process specific. It is imperative to maintain control of the process by processing witness tensile coupons with each part build and maintaining traceability to specific print parameters, post processing activities, and base powder constituents. This process control requirement is in alignment with industry-accepted standards for additively manufactured components, including NASA MSFC-STD-3716 [2].

The development of fracture inspection techniques for additive manufactured components.

Fracture critical dye penetrant and radiographic inspections are key components of space tank manufacture. Recent research efforts had included conducting conventional fracture critical dye penetrant inspection of additive manufactured components. Research results indicate that the bulk printed material could pass fracture critical inspection. Although visual examination of printed material cross sections under a metallurgical microscope had revealed areas of lack of fusion or internal porosity, their size and shape were orders of magnitude smaller than standard fracture inspection initial flaw sizes and undetectable by conventional fracture critical inspection techniques. This suggests that the defects are below the detection capability of the fraction inspection process. As such, additive manufactured components could be candidates for fracture critical applications. A comprehensive research program focusing on fracture critical inspection methodology on additive manufactured parts is necessary to determine the proper inspection techniques for space borne tank shell application. In addition to the work already performed, additional research and development activities are underway to address this critical knowledge gap.

The development of fracture data to support fracture mechanics analysis.

Fracture analysis is a critical and mandatory component in pressure vessel design. A set of fracture data, including the determination of the rate of increase in stress intensity factor of the membrane material in propellant, is necessary for any combination of propellant and tank shell material. Given that additive manufactured shells are from new material processes and have their own material characteristics, it is essential that we collect new fracture data for additive manufactured shells to support pressure vessel design. This is currently under investigation.

The assessment of consistency in material properties from technique to technique and from machine to machine.

There are multiple technologies used in metal additive manufacturing, including DMLS, Electron Beam Melting (EBM), Selective Laser Melting (SLM), and others. The starting raw material could include metal power, wire, or sheets. Sorting through a myriad of potential AM sources and gaining knowledge on the consistencies of each technology is a major challenge. Nevertheless, understanding the consistencies and deviations is a pathway to maintain high reliability and a critical factor in pressure vessel design. Currently, we are focusing on the DMLS process and the EBM process, including omnidirectional print properties.

Results of our investigative efforts indicate that the material properties are different between each type of process. Within each process, it is possible to maintain repeatable results to within 5% when comparing a 3σ standard deviation to the average nominal properties. This condition is applicable for both yield strength and ultimate strength while maintaining acceptable elasticity. We also noted that the material property exceeds the current statistical mechanical performance results within our traditionally forged titanium databased. Additionally, our assessment of omnidirectional properties indicates <5% variance between in plane and out of plane mechanical properties, suggesting the material is more isotropic than industry research efforts have revealed.

The examination of potential material shedding.

Space borne pressure vessels must have clean internal surfaces free of contamination. The rough surfaces of additive manufactured domes could be a source of concern regarding particle shedding. Material shedding might occur during launch, and subjecting additive manufactured parts to vibration or other excitation tests could be an appropriate method of examining potential shedding of small particulates. Although we have no indications of a problem with current processing technologies, further work is underway to quantify and compare various processing outcomes, including quantitative analyses and tests assessing particulate contamination for various post processing efforts.

Short-term Applicability.

Although our study had revealed that more research is necessary on fracture critical tank shell applications, we had made breakthrough progress on the development of additive manufactured propellant management device

(PMD) components and for non-fracture critical vessel designs. For example, the part shown in Figure 6 is traditionally a complex welded assembly of many machined parts. The PMD component is now a one-piece construction with no weldment and no expensive machining. PMD components and assemblies are not pressure bearing and are not subject to the same design requirements as load-bearing tank shells. There are fewer obstacles in implementing additive manufactured components for PMD assemblies than for tank shells, and we expect to incorporate such components in the near future.

Figure 6: A PMD component manufactured using AM technique.

Our current research and development focus is for drop in replacement of components. However, designs for traditionally manufactured components do not transition to additive manufactured processes directly, and our future work scope shall focus on redesigning components to take advantage of AM printing capabilities; reducing part complexity; and reducing part mass, lead time, and cost. In one instance, we redesigned a traditionally manufactured PMD component, fabricated it using AM technology, and compared it directly with its traditionally manufactured variant. This redesign effort resulted in a component that met all critical form, fit, and function requirements while reducing the mass by 70%, the cost by 50%, and the lead-time by 90%. Secondarily, the redesign resulted in a more efficient propellant flow path. The updated design would contribute to reduced pressure loss and reduced residual propellant for the tank assembly.

With regard to tank shell application, we are developing hardware from additive manufactured domes. Figure 7 is a photo of such domes. Currently, these domes are suitable for non-fracture critical applications with 4 to 1 burst designs. Our assessment is that the technology is not yet ready for ultra-lightweight fracture critical tank shell applications because the support mechanisms such as analysis data and non-destructive inspection are not yet in place, and the inherent risks we identified are not yet quantifiable.

Figure 7: Additive manufactured domes.

3. Conclusion

This review paper is the first in a series of papers we plan to contribute to the literature on developing pressure vessels using AM technology. In the coming years, we will continue to document our research findings and provide progress updates on our development effort. Our study indicates that the use of additive manufactured components for pressure vessel application is at an exploratory stage. We found advantages on the use of AM technology, including simplified design and shortened production schedule. Nevertheless, we also found, by subjecting hardware to the production process, that there are design and manufacturing risk items requiring mitigation. While engineers and designers might be enthusiastic about the positive attributes of AM, its implementation must undergo a systematic and holistic review. It would be inappropriate to extend preferences and implement additive manufactured components into production without a thorough and methodical investigation.

Exploratory research is still on going, and it is too early to pass judgment on the applicability of additive manufactured fracture critical pressure containment shells for space applications. We also note that a systematic and holistic review would require significant commitment of resources, including time, money and talent. Nevertheless, we did find that non-pressure bearing components might be suitable candidates for the application of AM technology. As of April 2018, we are only months away from designing new PMD parts or substituting existing PMD parts using this new manufacturing technique.

Reference

1. Frazier, W. E. (2014). Metal additive manufacturing: A review. *Journal of Material Engineering and Performance, 23*(6), 1917-1928. doi:10.1007/s.11665-014-0958-z

2. NASA Marshall Space Flight Center. (2017). Standard for additively manufactured spaceflight hardware by laser powder bed fusion in metals. *MSFC Technical Standard*. Retrieved from https://www.nasa.gov/sites /default/files/atoms/files/msfcstd3716baseline. pdf