

USING INNOVATIVE TECHNOLOGIES FOR MANUFACTURING ROCKET ENGINE HARDWARE

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ABSTRACT

Many of the manufacturing techniques that are currently used for rocket engine component production are traditional methods that have been proven through years of experience and historical precedence. As the United States enters into the next space age where new launch vehicles are being designed and propulsion systems are being improved upon, it is sometimes necessary to adopt innovative techniques for manufacturing hardware. With a heavy emphasis on cost reduction and improvements in manufacturing time, rapid manufacturing techniques such as Direct Metal Laser Sintering (DMLS) are being adopted and evaluated for their use on NASA's Space Launch System (SLS) upper stage engine, J-2X, with hopes of employing this technology on a wide variety of future projects. DMLS has the potential to significantly reduce the processing time and cost of engine hardware, while achieving desirable material properties by using a layered powder metal manufacturing process in order to produce complex part geometries. Marshall Space Flight Center (MSFC) has recently hot-fire tested a J-2X gas generator (GG) discharge duct that was manufactured using DMLS. The duct was inspected and proof tested prior to the hot-fire test. Using a workhorse gas generator (WHGG) test fixture at MSFC's East Test Area, the duct was subjected to extreme J-2X hot gas environments during 7 tests for a total of 537 seconds of hot-fire time. The duct underwent extensive post-test evaluation and showed no signs of degradation. DMLS manufacturing has proven to be a viable option for manufacturing rocket engine hardware, and further development and use of this manufacturing method is recommended.

INTRODUCTION

Rocket engine hardware is exposed to harsh environments, extreme temperatures, high pressures, and is required to meet uncompromising standards against failure. While many different manufacturing processes are used for rocket engine hardware, such as casting, forging, roll forming, spinning, and welding, sometimes the hardware design is such that these standard processes do not work well and alternative methods are required. This occurred in the case of the J-2X gas generator hot gas discharge duct. Because of the wall thickness and duct geometry, tube bending proved to be very difficult in the manufacture of this duct; therefore, the team sought out DMLS as a method for manufacturing a test article.

Throughout this activity, the DMLS duct demonstrated robust capabilities while being subjected to extreme J-2X operating environments. As a result, the team recommends further work and characterization of the DMLS process in order to bring this method into mainstream manufacturing for rocket engine hardware.

This paper discusses the work performed by the Marshall Space Flight Center Propulsion Directorate, Pratt & Whitney Rocketdyne (PWR), and Morris Technologies to characterize a J-2X gas generator discharge duct that was manufactured using the Direct Metal Laser Sintering process. Non-destructive evaluations were performed on the duct and the duct was hot-fire tested in the Marshall test area using a workhorse gas generator test fixture.



Figure 1: DMLS Duct As Received at MSFC

RESULTS AND DISCUSSION

SUMMARY AND PURPOSE

The purpose of this project is to evaluate DMLS as a manufacturing option for rocket engine components, in particular the J-2X gas generator discharge duct. DMLS is evaluated by assessing the following metrics:

- Manufacturing quality and tolerance compliance (as compared to the PWR drawing).
- Material properties of the witness samples compared to the cataloged DMLS material database.
- Comparison of the material property samples to the Aerospace Material Specification (AMS) wrought material properties.
- Comparison of the DMLS alloy 625 microstructure, chemical makeup, and density to the properties expected of alloy 625.
- DMLS part performance under hot-fire conditions, high-temperature and high-pressure environments provided by the WHGG testing.

For this project, Morris Technologies built the DMLS duct section per PWR's drawing. MSFC provided two flanges to PWR to be welded onto the DMLS duct section. After PWR welded the flanges to the duct section and inspected the welds, the duct was shipped to MSFC. Once the duct was received at MSFC, a series of Non-Destructive Evaluation (NDE) inspections were performed. Figure 1 shows the duct as it was received by MSFC.

While the duct was under-going NDE at MSFC, PWR sent out material samples for tensile and High Cycle Fatigue (HCF) testing for comparison to the PWR DMLS alloy 625 database. MSFC performed an integrated Ground Support Equipment (GSE) and test article Finite Element Model (FEM) analysis in order to design the test stand and determine the appropriate fixturing. PWR performed a structural analysis using conservative properties for hot-fire test rationale.

After the NDE inspections, test stand analysis, and the material sample testing indicated that the duct material and condition were acceptable for hot-fire, the duct was proof pressure tested and then hot-fire tested for a total of 537 seconds over a series of 7 tests. Upon completion of the test series borescope, dye penetrant, x-ray, and white light inspections were performed, and plans were made for further destructive testing. A top-level process flow of the work performed for this Manufacturing Technology Demonstration (MTD) is shown in Figure 2.

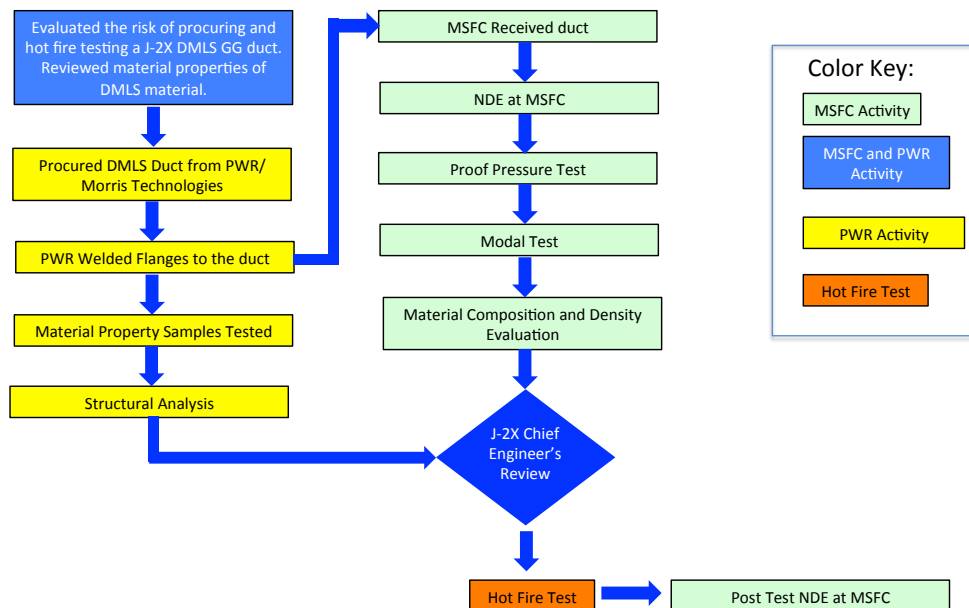


Figure 2: DMLS Duct Process Flow

BACKGROUND

The J-2X gas generator discharge duct length was originally long and had generous bend radii such that it could be easily manufactured by bending an alloy 625 tube into the desired shape. During WHGG testing at MSFC in 2009,¹ a longitudinal combustion stability mode was excited due to a coupling between the injector mode and the natural frequency of the combustion chamber longitudinal mode. As a direct result of the WHGG testing, the GG discharge duct length was modified to generate a more stable, shorter chamber length.

In order to shorten the GG duct while maintaining the existing J-2X engine layout, the approximately 4-inch diameter GG duct design was updated to incorporate a thicker wall and a 1-D bend radius. This design proved to be very difficult for the manufacturer to bend. As a result, the current J-2X E10001 GG duct is made by welding 3 separate 60-degree duct sections together. This process is not optimal due to the potential for mismatch of the welded duct sections. The duct sections could have different wall thickness at the weld interface due to the bending process. Also, the welds are difficult to inspect, and the manufacturing process is time and labor intensive. A picture of the E10001 bent duct section is shown in Figure 3.

Due to the difficulties in bending the J-2X GG duct, alternate manufacturing processes were being discussed. DMLS was one alternative, albeit not one seriously considered. After further evaluation, however, it was decided that it would be a worthwhile activity to procure and test an MTD duct and evaluate it for use on the J-2X.

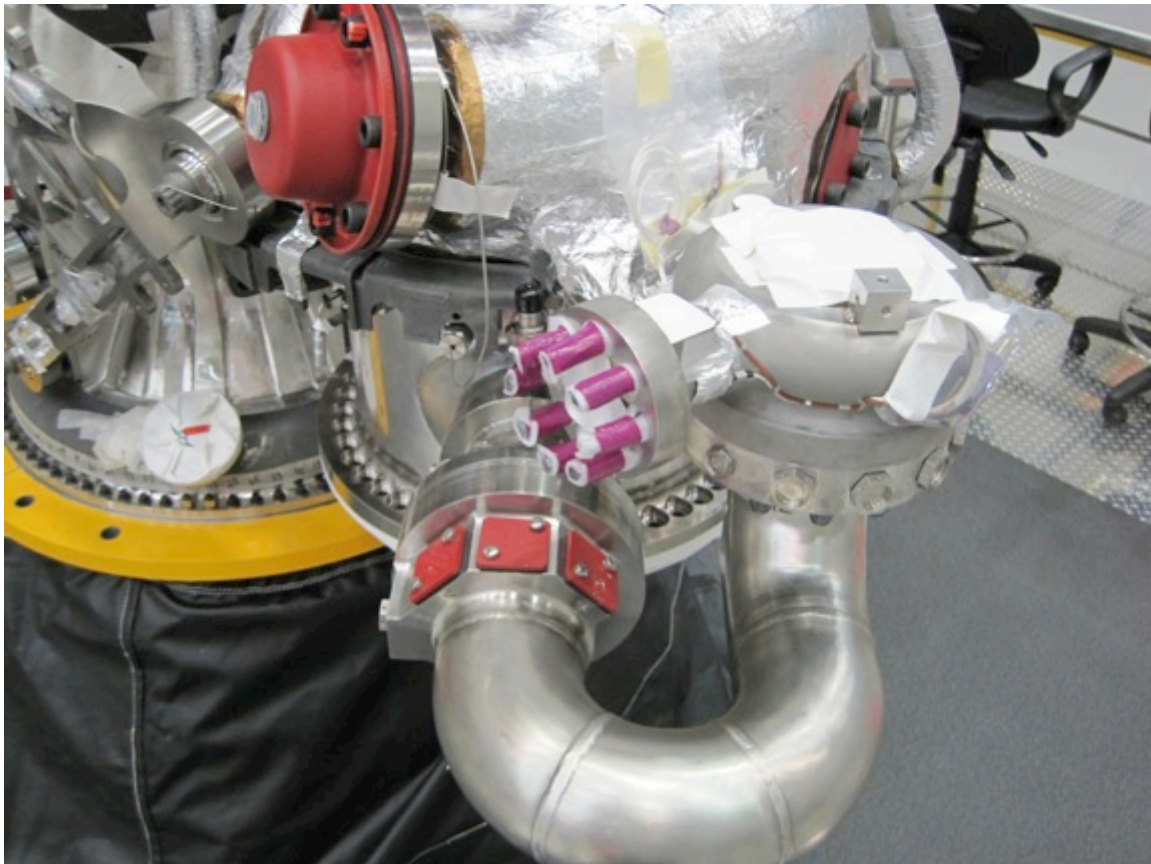


Figure 3: J-2X E10001 Gas Generator Discharge Duct

THE DMLS MANUFACTURING PROCESS

DMLS is an additive technology that uses a focused laser to locally fuse very thin layers, on the order of 20 microns of powdered metal, layer by layer. Morris Technologies based in Cincinnati, Ohio, uses DMLS machines that are made by Electro Optical Systems (EOS). After the part is built in the DMLS machine, post-processing techniques such as Hot Isostatic Press (HIP) and the Microtek[®] Micro-Machining Process (MMP) are used to achieve the desired material properties, grain structure, surface finish, and final dimensions. A variety of materials can be used with DMLS manufacturing, including Cobalt Chrome, Stainless Steel, Aluminum alloys, Titanium alloys, Nickel alloys, Maraging Steel, and Bronze alloys.

DMLS manufacturing of a duct does not come without concern. In the past, techniques similar to DMLS have had issues with porosity and internal voids, which can lead to a reduced strength of the part. Layer delamination is also a concern. However, recent developments in DMLS manufacturing and post-processing techniques have increased the confidence in the process. Post manufacturing heat treat can bring the DMLS part's tensile properties (ultimate tensile strength, yield strength, elongation) to be comparable to wrought properties; HIP can eliminate voids and porosity. Morris' proprietary techniques for reducing carbon and oxygen levels in the sintering powder, along with lower vacuum levels and reduced oxygen content in the sintering chamber, can greatly improve material strength. Post-process machining and the Microtek[®] Micro-Machining Process can be used to achieve the desired surface finish, while minimizing touch labor. The laser scanning process has also been improved to provide for a much better surface finish directly out of the sintering chamber. This involves scanning the contour of each layer first, then scanning the fill area between contours.

The total time from issue of the purchase order to receipt of the duct at PWR was less than 2 months. This included 3 build trials, each build trial taking one week to set up and complete. After the final build was completed, the duct was subject to a vacuum stress relief, rough removal of the build supports, weld repair in a region where there was a short feed, fluorescent penetrant inspection, x-ray inspection, HIP, solution heat treatment, final support removal, and the MMP finishing process. This compares to roughly 4.5 months for manufacturing the 3-piece welded duct.

Although NASA is in the early stages of using DMLS as an accepted process, it is recognized that numerous benefits can be gained from DMLS hardware:

- Complex geometries can be built without the need for welds,
- No special tooling (such as molds or mandrels) is required,
- The designer is not limited by standard manufacturing techniques,
- For a duct application, uniform wall thickness can be achieved when this cannot be achieved using tube bending, and
- Complex geometries can be built at a low cost and with a short lead-time.

This test activity is important since this was the first time DMLS components had been hot-fire tested in a rocket engine structural application. The high temperature and high-pressure environment that the duct experienced in the WHGG test setup truly tested the durability and strength of the material.

NON-DESTRUCTIVE EVALUATION

After the GG duct was manufactured and PWR welded the flanges on, it was shipped to MSFC for evaluation and test. Several methods were used to evaluate the duct and to determine if it was safe to hot-fire test the duct. These methods include: X-Ray Inspection, Computed Tomography (CT) Scan, Ultrasonic Test (UT), Chemical Etch, Penetrant Inspection, White Light Scan, Material Chemical Analysis (X-Ray Fluorescence), and a density calculation. Proof pressure testing was also performed as a final confirmation prior to hot-fire testing.

The X-ray inspection consisted of both single and double wall images. No indication of internal porosity was noted. The CT scan provided wall thickness measurements, and again provided confirmation that the overall part density was acceptable. There were no voids noted internal to the DMLS duct section. An example of one of the CT scans through the mid-section of the duct is shown in Figure 4.

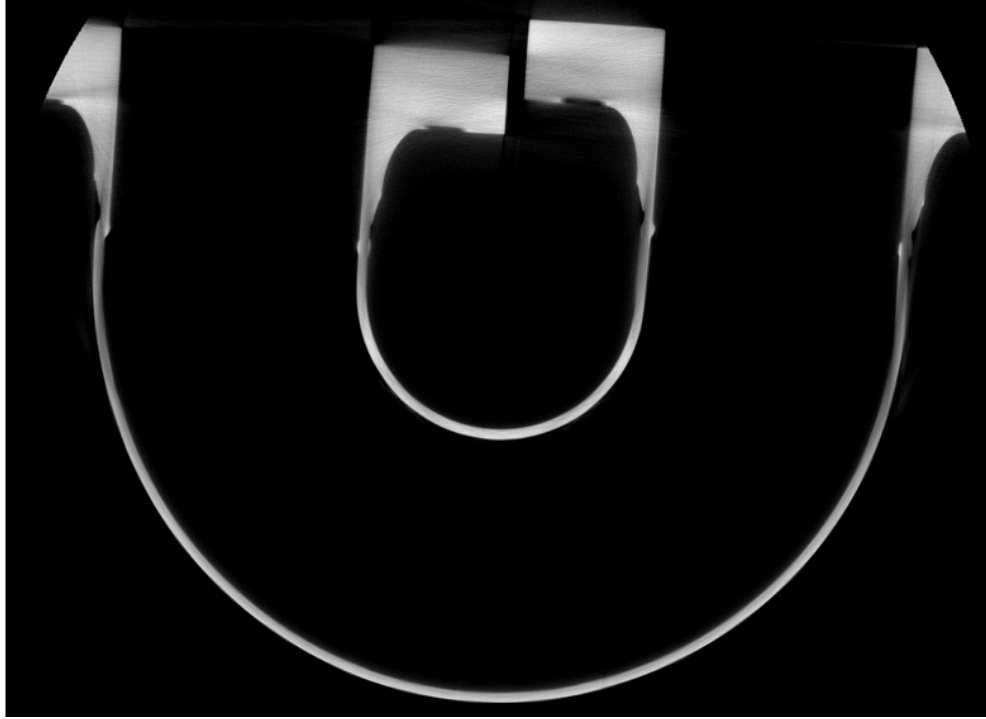


Figure 4: CT Scan through Mid-Section of the Duct

Ultrasonic Testing was also used to quantify the wall thickness variation of the duct. The results from UT compared very well with the results from the CT scan. It is noted that the PWR drawing specified a wall thickness tolerance of $\pm .005$ inches. The actual duct dimensions were measured to be $+0.012/-0.010$ inches. This is not a concern for this duct application, but tolerance studies are recommended for future evaluation.

In order to achieve an understanding of the duct surface and to ensure that there are no surface flaws present that could open up and cause the duct to rupture during testing, a fluorescent penetrant inspection was performed. Because the surface roughness of the duct was around 1-2 microinches, it was necessary to perform an acid etch on the duct to achieve a reliable penetrant inspection. The duct was etched using a solution of nitric acid (225 gm/L) and hydrofluoric acid (12.9 gm/L). It proved to be very difficult to etch the duct due to the very low initial surface roughness.

The results from the dye penetrant inspection revealed some surface porosity. Since the X-ray and CT scan revealed no internal part porosity, it was determined that the duct would be hot-fire tested, and the surface porosity would be evaluated post test and compared to the pre test results.

Shape Fidelity, Inc. scanned the duct using a white light scanning system. The purpose of scanning the duct was to evaluate the overall contour of the duct to compare with the original ProE model of the duct. Also, the white light scanning system was able to generate a ProE model of the outer mold line of the duct, which was used in the facility assembly model to ensure proper fit in the WHGG test setup. The results from the white light scan are shown in Figure 5. The white light to CAD model comparison showed that the “as-built” duct appeared to deviate no more than

0.078" from the CAD model, which is typical of parts that have been subject to the HIP process. This deviation was in the curved contour of the duct, rather than a deviation in wall thickness. This is not significant compared to the amount of curvature deviation that would be expected in a bent duct.

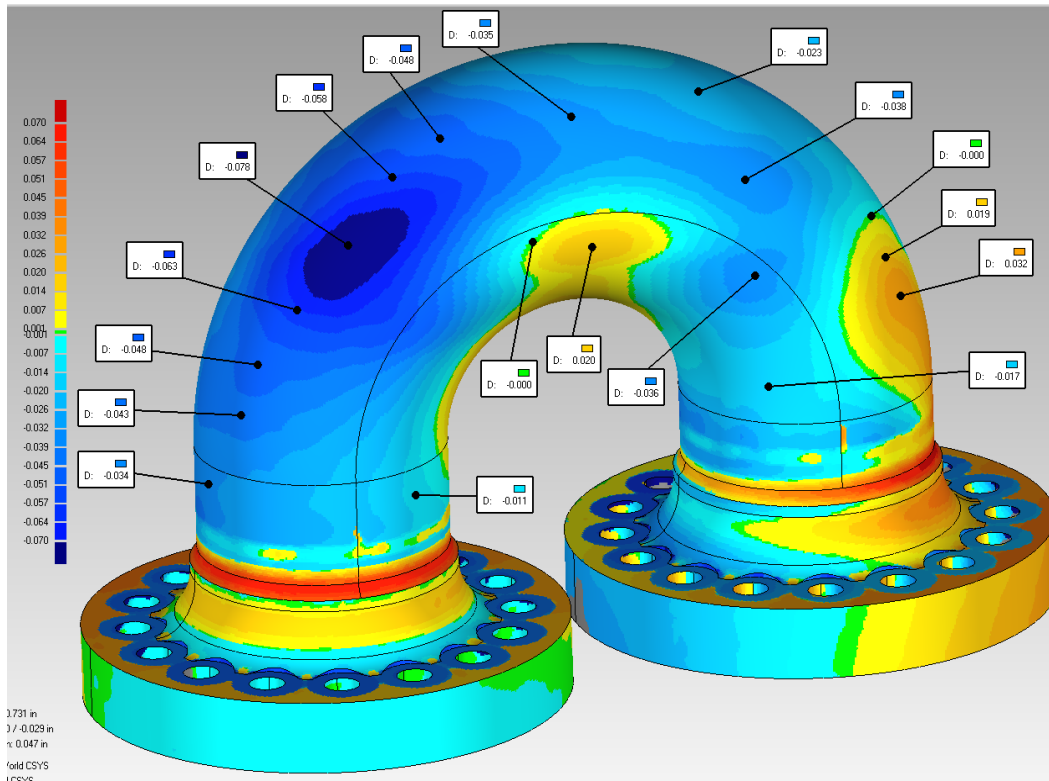


Figure 5: White Light Scan Results, As-built compared to As-designed CAD Model

To compliment the NDE performed at MSFC, PWR performed a structural analysis using conservative properties. This analysis showed that the DMLS duct met all the primary factors of safety on strength and endurance, and gave the team confidence that the duct was safe to proof pressure test and hot-fire test.

Prior to any hot-fire testing, the duct was required to be proof tested to demonstrate material quality and workmanship. Proof pressure for the duct was based on operating pressure, operating temperature, and required safety factor. The duct was pressurized for five 60-second cycles to 2,155 +/- 50 psig. No visible evidence of yielding, distortion or structural damage was noted after the proof pressurization sequence was completed. The duct was also subjected to a post proof test dye penetrant inspection to look for any cracks that may have formed due to pressure cycling. The duct appeared to be unchanged from the dye penetrant inspection performed prior to proof.

Material density and composition tests were completed in order to confirm the composition of the duct compared with what was expected. The actual duct could not be used for these tests, so two large sample pieces were used. These samples were pieces that were manufactured during the DMLS build with the duct. These samples were also heat treated with the duct. All density testing was performed with the material at 25°C. The density values returned from testing were 8.358, 8.354, and 8.430 g/cm³, for an average of 8.381g/cm³. These density readings are consistent with the predicted density of alloy 625. For material composition determination, a hand-held X-ray Fluorescence device (XRF) was used. The XRF database identified all sections tested to be alloy 625 with a high degree of certainty.

MATERIAL PROPERTY TEST RESULTS

Several witness samples were built in the DMLS chamber at the same time the duct was built. These samples were sent out for material property testing in order to confirm that these samples were within family with PWR's DMLS database. The results from the material property tests confirmed that the DMLS duct Ultimate Tensile Strength (UTS) and Percent Elongation exceeded minimal AMS 5666 wrought material properties, while the Yield Strength was just shy of wrought properties.² The tensile test results are shown in Figure 6.

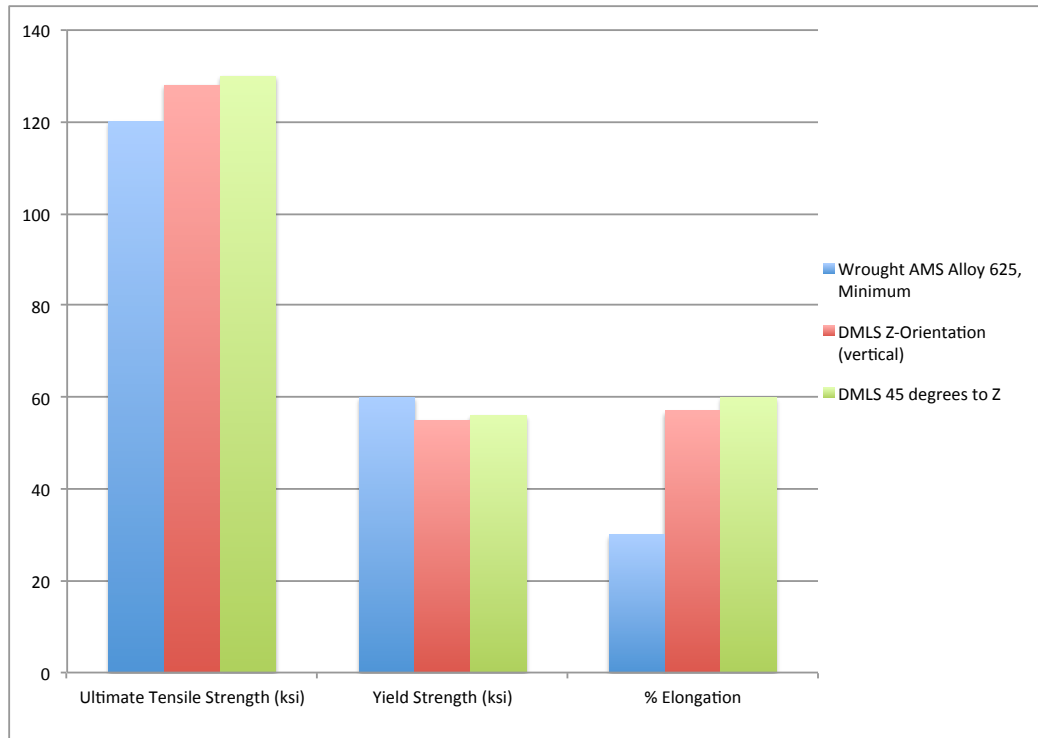


Figure 6: DMLS Witness Sample Tensile Results Compared to Minimal AMS Wrought Properties²

HOT-FIRE TESTING

After all the results of NDE were evaluated and a review was held with the J-2X and PWR chief engineers, the duct was approved for hot-fire testing using the MSFC WHGG test setup. Engineers from the Combustion Devices branch provided the test requests; the tests were conducted at the MSFC East Test Area on Test Stand 116.³

The objective of the WHGG DMLS duct testing was to characterize the performance of the DMLS J-2X GG hot gas duct in an engine-like configuration. Over the course of three days, June 1-3, 2011, the test program conducted seven starts, for a total firing time duration of 537 seconds. The duct was inspected periodically for damage. Performance data was evaluated, and the duct material condition was documented throughout the test program.

Table 1 is the test matrix that shows the conditions and durations that were tested. The "high" mixture ratio (MR) and "high" chamber pressure (P_c) tests exposed the duct to an environment that exceeded the J-2X environment. The test conductor cut Test 3 due to rising fuel temperatures, which were caused by a low fuel level in the fuel tank. Tests 6 and 7 included a 2-grain bomb, which was used to achieve 23-30% overpressure to fatigue the duct even further.

Table 1: DMLS WHGG Duct Test Matrix

Test #	Power Level	MR	Pc	Time (s)	Notes
1	240K	Low	Low	5	
2	294K	High	High	90	
3	294K	High	High	82	Planned 90 seconds, Observer Cut
4	294K	High	High	90	
5	294K	High	High	90	
6	294K	High	High	90	Bomb, 2 grain, 23% overpressure
7	294K	High	High	90	Bomb, 2 grain, 30% overpressure
			Total	537	

The gas generator hardware used is considered to be “workhorse” hardware because the weight and external features are not consistent with a flight weight GG. However, the hydraulic pathways and geometry internal to the hardware are similar to the flight GG, with some exceptions. The hardware consists of a 43 element shear-coaxial injector, a 90-degree elbow chamber with an integral acoustic cavity near the injector interface, two thermocouple rakes, the DMLS duct, a chamber spool, and a nozzle. The length of the hardware was selected to mimic the effective length of the gas generator combustion chamber on the J-2X engine, as shown in Figure 7.

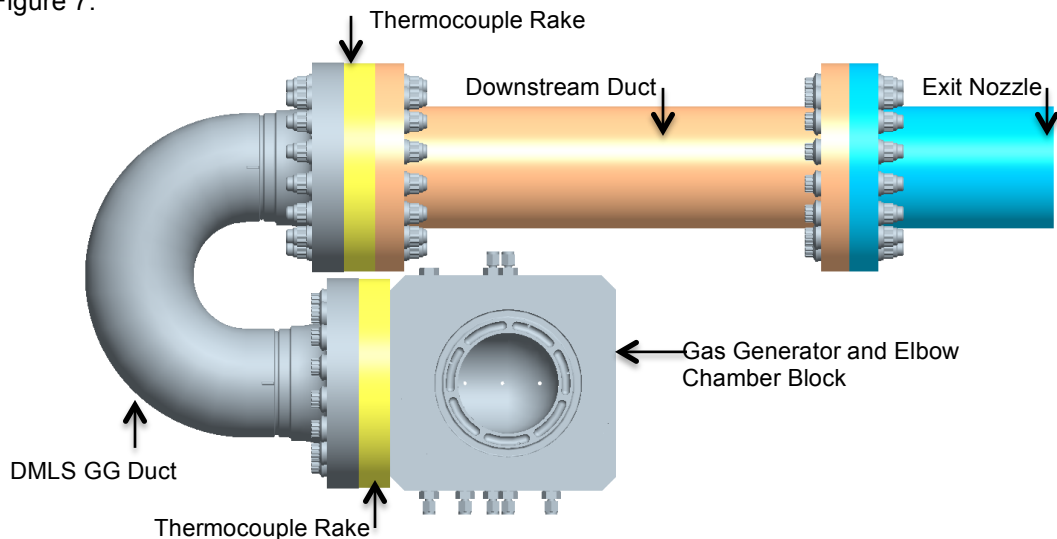


Figure 7: WHGG Duct Test Setup

Instrumentation used for the test series included the standard suite of WHGG instrumentation,³ and the additional duct instrumentation outlined in Table 2. The hot gas temperatures and pressures were characterized in two thermocouple rakes, one upstream and one downstream of the duct. On the duct surface, skin thermocouples and strain gages were used to characterize the skin temperatures and the dynamic response of the duct. An Infrared (IR) camera was also used to evaluate the skin temperature on the bottom side of the duct.

TEST RESULTS

Overall, the tests yielded very consistent results. The primary objective of the testing was to evaluate the durability of the duct and to assess the duct condition throughout the test program. Structurally, the duct was able to withstand the test environment. Post-test visual inspections showed no indication of cracking, and the dynamic response of the duct compared well to the model predictions.

The duct was externally inspected visually after each test, and internally inspected using a borescope periodically during the test series. Figure 8 depicts the condition of the duct before and after hot-fire testing. There was some discoloration from surface oxidation of the duct after the test series, which was expected. The visual and borescope inspections revealed one significant observation, a grid pattern of the material on the duct inner intrados bend. This is believed to be a surface artifact of the DMLS manufacturing process specific to this duct. In order to form the duct's geometry, a honeycomb support structure was built up in the DMLS chamber. During the post-build processing of the duct this honeycomb structure was removed. Morris Technologies confirmed that the grid marks are indications of the honeycomb supports.

Table 2: WHGG Duct Instrumentation

Instrumentation	QTY	Sample Rate
High temperature stain gauge	4	100,000 sps
Standard foil type strain gauge	1	100 sps
Skin temperature	6	100 sps



Figure 8: DMLS Duct Before (Left) and After (Right) Hot-Fire Test

POST-TEST NON-DESTRUCTIVE EVALUATIONS

After the hot-fire test program, the duct was again evaluated via fluorescent penetrant, CT, and white light scan. The post-test results from all three methods compared very well with pre-test evaluations.

The dye penetrant inspection revealed roughly the same amount of surface porosity that was noted in the pre-test inspection. Figure 9 shows the post-test results. Note that the flanges were made from forged alloy 625 material, while the bent duct section was DMLS material. There is a distinct difference between the forged and DMLS material, but it is believed that the observed porosity is superficial. The porosity did not impact the duct's performance during hot-fire testing. The high temperature strain gages are still attached to the duct in Figure 9; one of the gage locations and the lead wires are identified in the Figure.

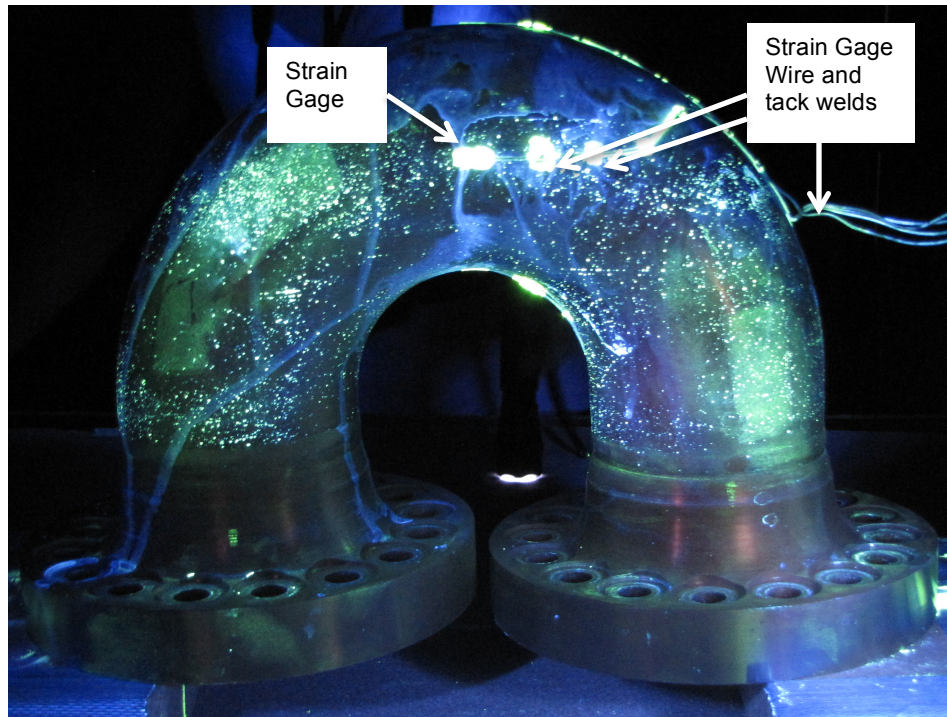


Figure 9: Post-Test Fluorescent Penetrant Inspection

SUMMARY AND CONCLUSIONS

Overall, the J-2X DMLS GG Duct test program was a significant step forward in using the DMLS process for manufacturing rocket engine hardware. DMLS has many advantages that can result in significant cost and schedule savings for hardware, and can allow engineering designers to create more functionally optimal hardware that can be more easily manufactured with fewer constraints than commonly used manufacturing processes.

The J-2X DMLS duct was subjected to a significant amount of NDE, witness samples were evaluated, and the duct was tested in a J-2X gas generator hot gas environment. Referring back to the metrics used for evaluating the DMLS process in this activity, the following conclusions are drawn:

- The duct was slightly outside the specified engineering tolerances when compared to the PWR drawing. Tolerance studies are recommended for future evaluation.
- The material property samples are consistent with the DMLS material database.
- The material property results confirm that the build properties exceed minimal AMS wrought material properties for UTS and Elongation for alloy 625, while falling just shy on Yield Strength.
- The DMLS alloy 625 microstructure, chemical makeup, and density match well with properties expected of alloy 625.
- The DMLS duct survived the high-temperature and high-pressure environments provided by the WHGG testing, which simulated a J-2X hot gas environment.

Since the duct passed this evaluation, it is recommended that DMLS be considered for future applications and that it be evaluated for use as a standard manufacturing method for flight rocket engine hardware. In order for this to occur, it is necessary to define the critical manufacturing parameters, powder requirements, and to understand the process variability.

Even though the US rocket industry is in the early stages of using DMLS as a viable manufacturing technique, the potential benefits are recognized to be substantial. Rocket engine hardware typically has a low production rate, which can drive traditional manufacturing prices up. DMLS is an attractive option for low production rate hardware that currently requires complex geometries, tightly controlled tolerances, or a large number of piece parts, machining operations, and welds that can be combined into fewer simple parts. DMLS is also a very quick process; hardware lead times could be significantly reduced.

FUTURE WORK

Concerning future work, the next two steps would ideally occur in parallel. The first step is to further develop the DMLS database to fully understand the material properties and the variation in material properties when applying different build parameters. The second is to implement DMLS technology in a development test program. Using a DMLS part on a full-scale rocket engine rather than a workhorse component test article will build greater understanding of the performance of DMLS material in a rocket engine environment.

Ultimately, the goal is to implement DMLS technology on a flight program, and to define the DMLS process as a standard, NASA approved process in NASA-STD-6016.

ACKNOWLEDGMENTS

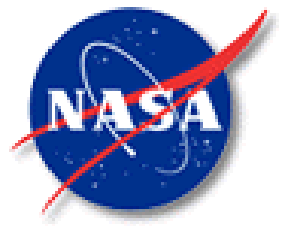
The authors would like to acknowledge PWR, in particular Don Miller for suggesting the use of DMLS for this duct and for providing materials expertise throughout this activity, Michael Lauer, and Jon Volkmann for providing project leadership; the MSFC ET-116 test crew, in particular Cynthia Sprader for executing the hot-fire tests; the MSFC EM materials engineers Frank Zimmerman and Jeramie Broadway for materials expertise; the MSFC EM non-destructive evaluation team, in particular Michael Suits, Dr. Samuel Russell, Dr. Ronald Beshears, Rhonda Lash, David F. Brown, and Jacobs-ESTS employees John Swieder, Richard Money, Chris Palmer, and APL-ESTS employee Allen Kinworthy; Morris Technologies; MSFC ET10 for their work in testing the material samples for density and composition; MSFC ET engineers Russel Parks and Adam Lacock for their work characterizing the dynamic response of the duct; and Shape Fidelity Incorporated for providing the white light scanning service to the team. Additional contributions were made by MSFC engineers Michael Ian Johnston, Dr. Jeremy Kenny, Elizabeth Esther, summer intern Eric Kachel, and Jacobs-ESTS engineers Paul LaSarge and Nicholas Werner.

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ER21 Engine Systems



Using Innovative Technologies for Manufacturing Rocket Engine Hardware

Presented at the JANNAF
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Introduction

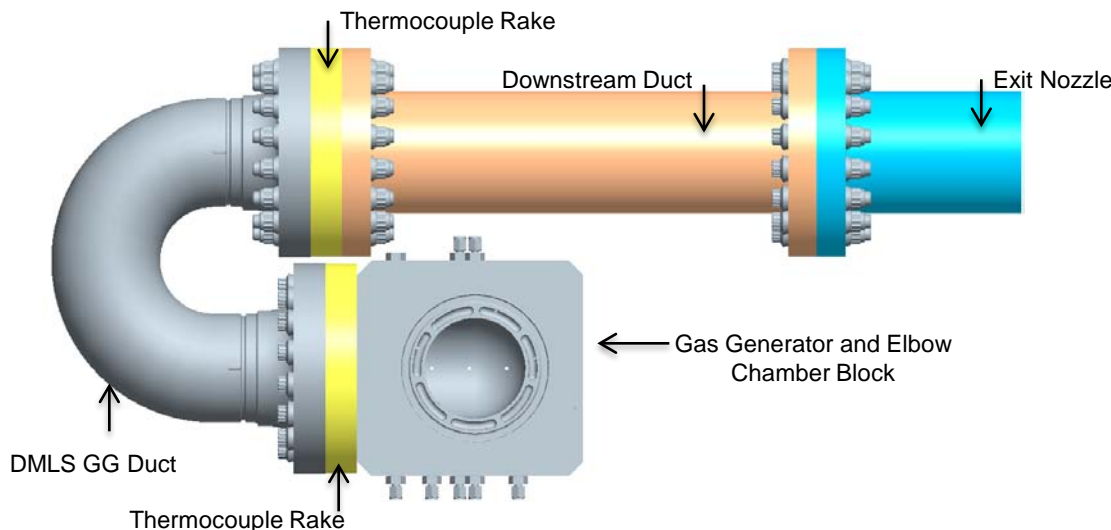


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- Rocket engine hardware is exposed to harsh environments, extreme temperatures, high pressures, and is required to meet uncompromising standards against failure.
- Traditional manufacturing techniques sometimes do not work well
 - Casting, forging, roll forming, spinning, welding
 - This occurred on J-2X during the manufacture of the Gas Generator (GG) discharge duct
 - The J-2X team sought out Direct Metal Laser Sintering (DMLS) as a method for manufacturing a test article
- DMLS duct demonstrated robust capabilities while subjected to extreme J-2X operating environments.
 - Team recommends further work and characterization of DMLS to bring this process into mainstream manufacturing for rocket engine hardware.



- Main objectives evaluated:
 - Manufacturing quality and tolerance compliance (as compared to the PWR drawing).
 - Material properties of the witness samples compared to the cataloged DMLS material database.
 - Comparison of the material property samples to the Aerospace Material Specification (AMS) wrought material properties.
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 - DMLS part performance under hot-fire conditions, high-temperature and high-pressure environments provided by the WHGG testing.





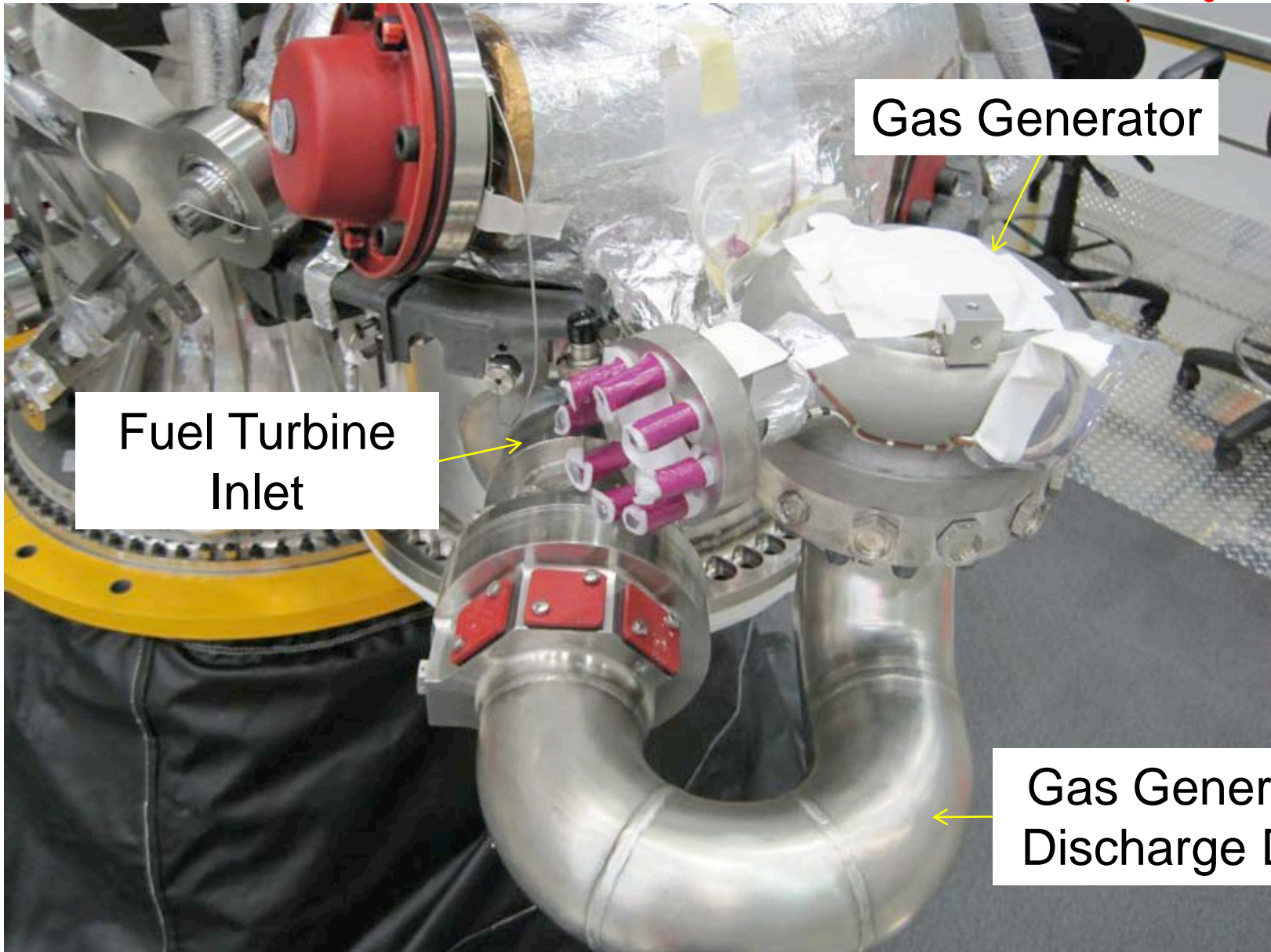
Background



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- The J-2X GG Duct length was originally long enough such that it could be easily manufactured by bending an alloy 625 tube into the desired shape.
- During Workhorse Gas Generator (WHGG) testing at MSFC in 2009, a longitudinal combustion stability mode was excited due to a coupling between the injector mode and the natural frequency of the combustion chamber longitudinal mode.
- As a direct result of the WHGG testing, the GG discharge duct length was modified to generate a more stable, shorter chamber length.
- This short duct with a 180 degree bend became very difficult to manufacture using standard manufacturing techniques.
 - Tube diameter (less than 4 inches)
 - Material strength (alloy 625)
 - Wall thickness (wall thinning during tube bending)
- Current solution is to manufacture the duct as 3 separate pieces that are welded together.
 - Labor intensive
 - Difficult to weld and inspect
 - One weld cannot be inspected



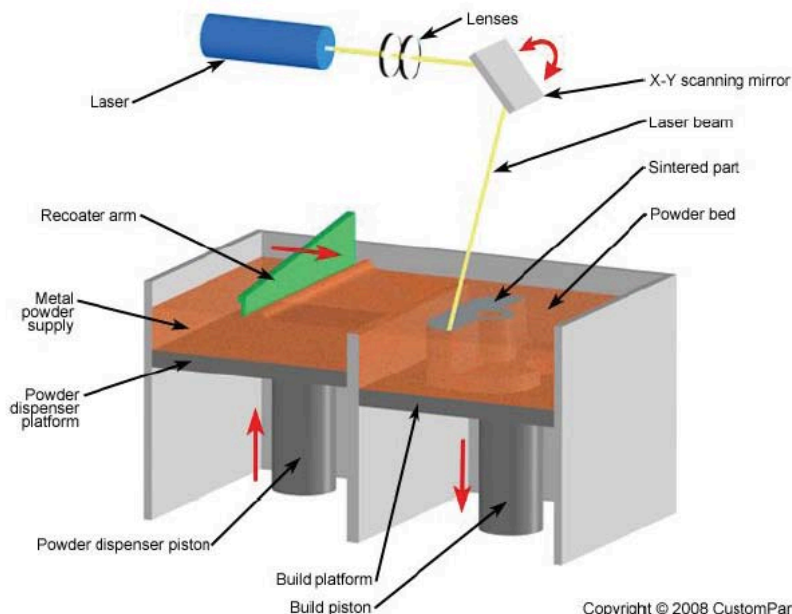


Gas Generator

Fuel Turbine Inlet

Gas Generator Discharge Duct

- DMLS is an “additive” technology
 - Uses a focused laser to locally fuse very thin layers (~20 microns) of powdered metal, layer-by-layer, from a CAD model.
 - Machine runs 24 hours a day, unattended after the initial setup
 - Post-processing is used to achieve the desired material properties, grain structure, surface finish, and final dimensions
 - Hot Isostatic Press (HIP) eliminates voids, increases material density, creates uniform microstructure
 - Final Machining, vacuum stress relief, heat treat, polishing
- A variety of metals can be used with DMLS manufacturing
 - Cobalt Chrome, Stainless steel, Aluminum Alloys, Titanium Alloys, Nickel Alloys (alloy 625 and 718), Maraging Steel (Tooling steel), Bronze Alloys



Inconel 625 sample from Morris Technologies



DMLS and the GG Duct



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- Numerous benefits can be gained from using DMLS:
 - Complex geometries can be built without the need for welds,
 - No special tooling (such as molds or mandrels) is required,
 - The designer is not limited by standard manufacturing techniques,
 - For a duct application, uniform wall thickness can be achieved when this cannot be achieved using tube bending, and
 - Complex geometries can be built at a low cost and with a short lead-time.
- Making the duct using DMLS was fast and cheap (~\$26K, less than 2 months); next, we had to prove it could withstand the hot fire environment.
 - Extensive NDE – looked at part consistency, indications of voids or surface flaws, wall thickness variation
 - Material coupon testing
 - Proof pressure testing
 - Hot fire testing
 - More NDE after hot fire testing

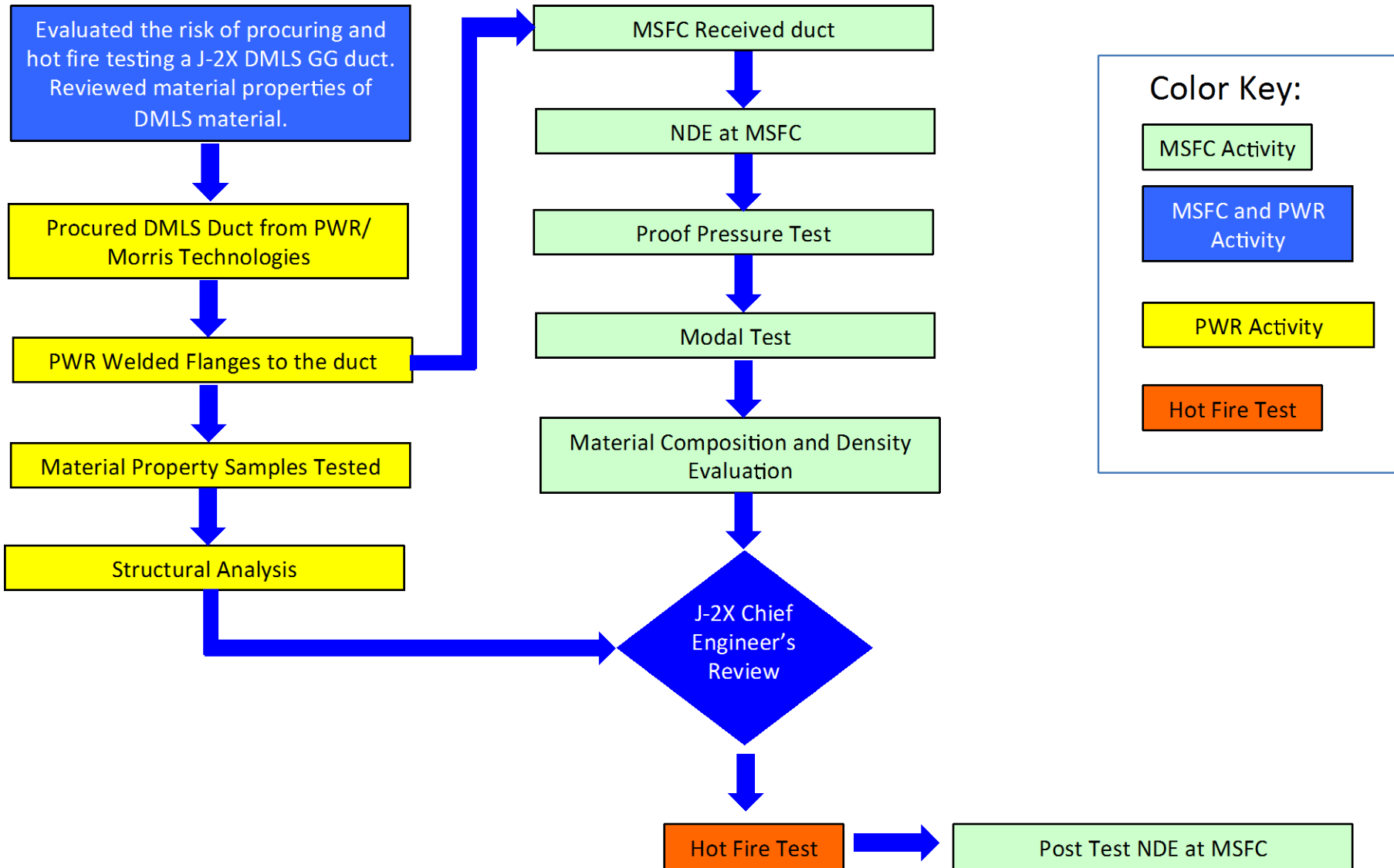




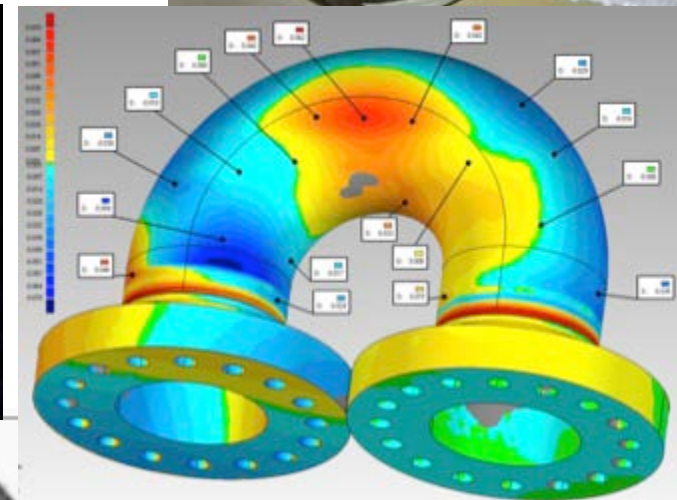
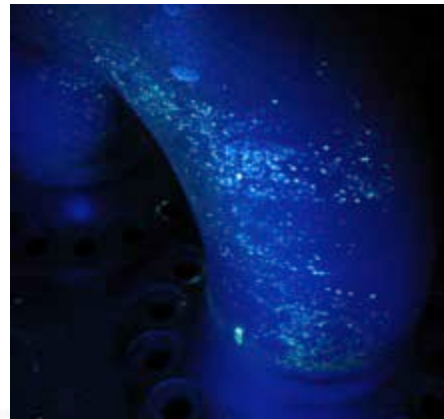
DMLS MTD Process Flow



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- An extensive amount of NDE was performed at MSFC
 - X-Ray
 - Acid Etch
 - Dye Penetrant
 - Ultrasonic Test
 - CT Scan
 - White Light scan
 - Material Composition & Density
- Proof Pressure test up to 2155 psig, followed by dye penetrant
- Modal Test

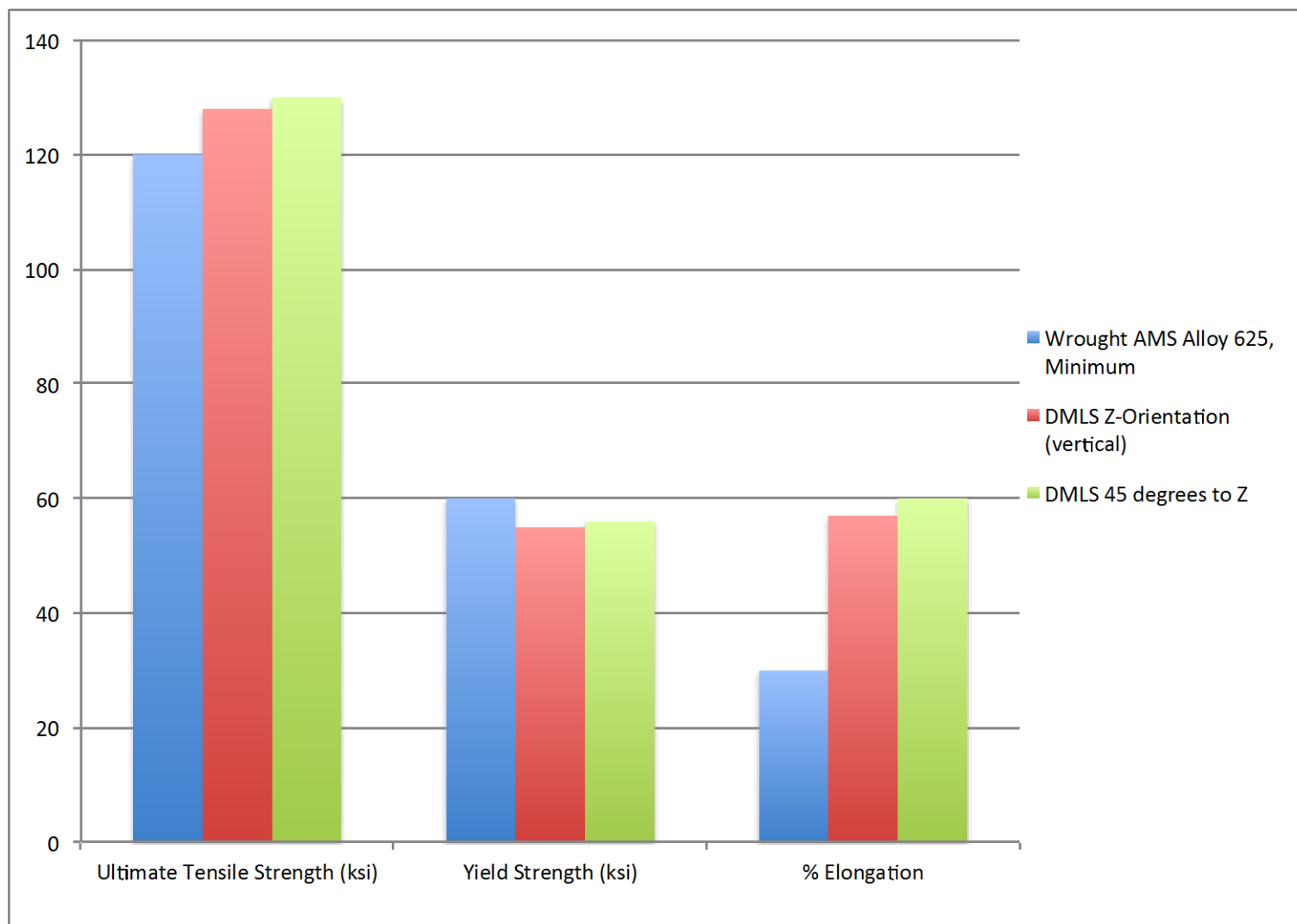




DMLS Material Property Test Results



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Hot Fire Test Program



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- The duct was installed on the WHGG test position, east test area TS116, LOX and LH₂ propellants
- Conditions well above J-2X run box
- 3 days of testing, June 1-3, 2011
- The duct condition was documented between tests

Test #	Power Level	MR	Pc	Time (s)	Notes
1	240K	Low	Low	5	
2	294K	High	High	90	
3	294K	High	High	82	Planned 90 seconds, Observer Cut
4	294K	High	High	90	
5	294K	High	High	90	
6	294K	High	High	90	Bomb, 2 grain, 23% overpressure
7	294K	High	High	90	Bomb, 2 grain, 30% overpressure
Total				537	

Instrumentation	QTY	Sample Rate
High temperature stain gauge	4	100,000 sps
Standard foil type strain gauge	1	100 sps
Skin temperature	6	100 sps





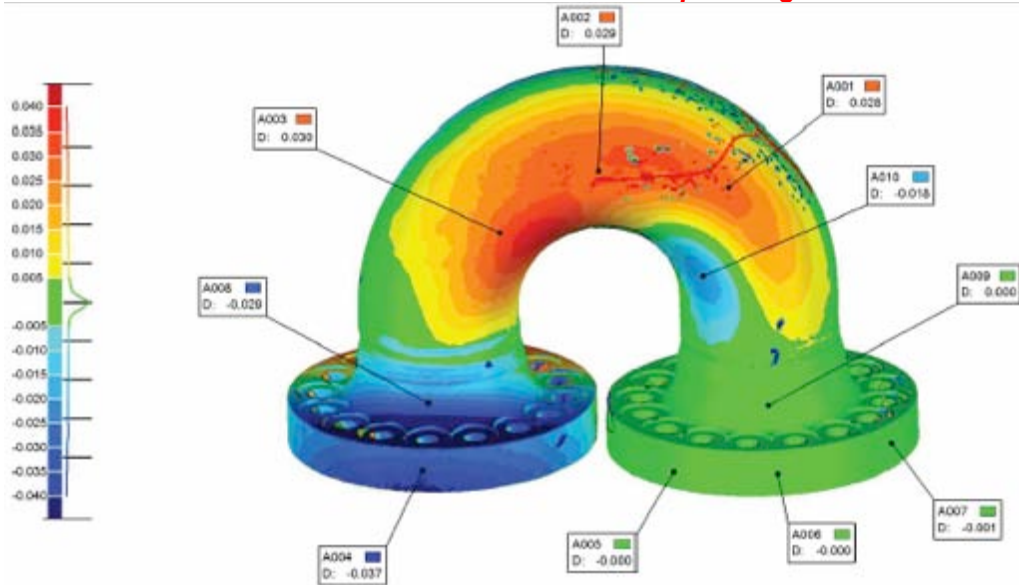
Before and After Test Photos



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- After testing, the following were performed:
 - Dye penetrant
 - CT scan
 - White light scan
- Compared pre-test to post-test
- Destructive test plan is in work
 - Section the duct
 - Surface mapping
 - Material property testing





Conclusions



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- The duct was slightly outside the specified engineering tolerances when compared to the PWR drawing. Tolerance studies are recommended for future evaluation.
- The material property samples are consistent with the DMLS material database.
- The material property results confirm that the build properties exceed minimal AMS wrought material properties for UTS and % Elongation for alloy 625, while falling just shy on Yield Strength.
- The DMLS alloy 625 microstructure, chemical makeup, and density match well with properties expected of alloy 625.
- The DMLS duct survived the high-temperature and high-pressure environments provided by the WHGG testing, which simulated a J-2X hot gas environment.
- Vendor demonstrated schedule and cost benefits over existing manufacturing processes
 - For future applications, significant cost savings could be achieved, especially on parts with a complex geometry requiring extensive machining.
 - Rocket engine hardware typically has a low production rate, which can drive traditional manufacturing prices up. DMLS is an attractive option for low production rate hardware that requires tightly controlled tolerances.
 - DMLS is also a very quick process; hardware lead times could be significantly reduced.
 - The amount of touch labor required to build hardware is significantly reduced.
 - DMLS can allow engineering designers to create more functionally optimal hardware that can be more easily manufactured with fewer constraints than commonly used manufacturing processes.



Future Work



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- Overall, the J-2X DMLS GG Duct test program was a significant step forward in using the DMLS process for manufacturing rocket engine hardware.
- Concerning future work, the next two steps would ideally occur in parallel.
 - The first step is to further develop the DMLS database to fully understand the material properties and the variation in material properties when applying different build parameters.
 - The second step is to implement DMLS technology in a development test program. Using a DMLS part on a full-scale rocket engine rather than a workhorse component test article will build greater understanding of the performance of DMLS material in a rocket engine environment.
 - This is under consideration for J-2X cost savings on selected part(s)
 - It will be important to define the critical manufacturing parameters, powder requirements, and to understand the process variability.
- Ultimately, the goal is to implement DMLS technology on a flight program, and to define the DMLS process as a standard, NASA approved process in NASA-STD-6016, "Standard Materials and Processes Requirements for Spacecraft."